Deep inelastic scattering conference Hamburg, 2016

Inclusive jet cross section measurements with the CMS detector

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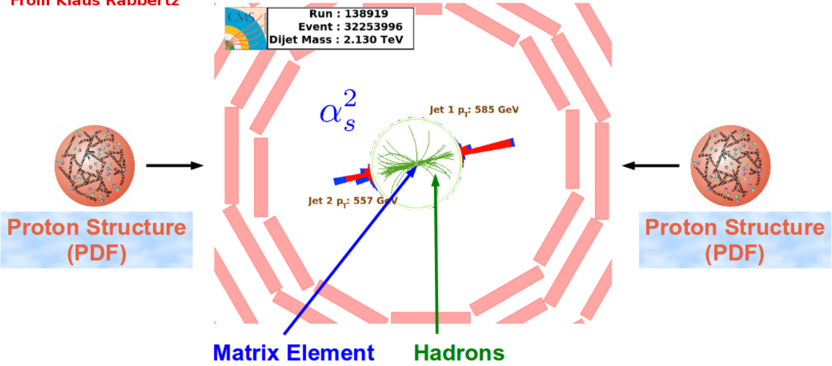
- Introduction: jets, LHC and CMS
- Jet reconstruction and calibration
- Analysis strategy
- Jet measurements at various energies
- Summary

Introduction: jet measurements in CMS

Abundant production of jets in pp collisions: access hard QCD, α_S, PDF..

From Klaus Rabbertz



Text-book measurement of jet cross sections

- Understand performance of available models
  1. Pure matrix-element calculations corrected for nonperturbative and electroweak effects
  2. MC generators with matrix elements at different order in α_S interfaced to UE sim.
- Measurement of α_S running up to TeV scale **(→ see Engin's talk)**
- Better constrain of PDF at high scale and x values **(→ see Engin's talk)**
- Search for New Physics, e.g. contact interactions

The Large Hadron Collider at CERN, Geneva

- 27-km underground ring collider
- Bending magnetic field of 8.4 T
- Proton beams accelerated up to 6.5 TeV

Three years of data taking in Run I:

$\sqrt{s} = 7\text{-}8$ TeV

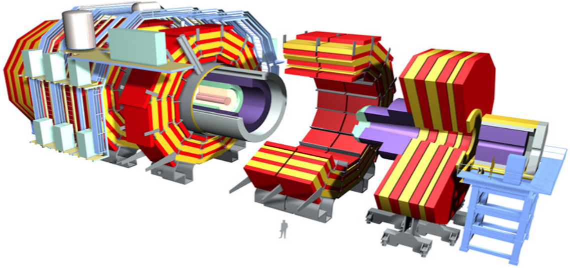
Three-day run in 2013:

$\sqrt{s} = 2.76$ TeV

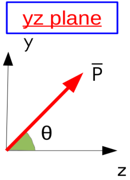
Run II started in 2015

$\sqrt{s} = 13$ TeV

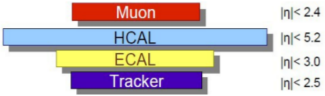
The Compact Muon Solenoid experiment



- Length: 21 m
- Diameter: 15 m
- Weight: 12500 ton

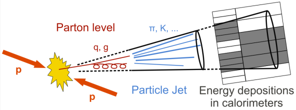


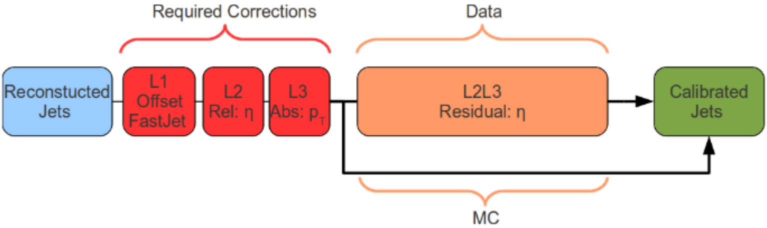
- Tracking system for measurement of the momentum of charged particles
- Calorimeter system for measurement of the particle energy
- Muon system for the muon identification



Jet reconstruction and calibration

- A jet in CMS is seen as a bunch of particles in the detector
- Information from the subdetectors is combined through the Particle Flow algorithm
- The reconstructed particles are clustered with the anti-k_T algorithm





Double differential inclusive jet cross section

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\mathrm{d}y} = \frac{1}{\epsilon L}\frac{\mathrm{N_j}}{\Delta p_T \cdot \Delta y}$$

ϵ = trig.efficiency
N_j = number of jets
L = eff. luminosity
Δp_T, Δy = bin widths

Trigger strategy

Exclusive division method: phase space is divided in regions according to the leading jet p_T and independent triggers are used in each region

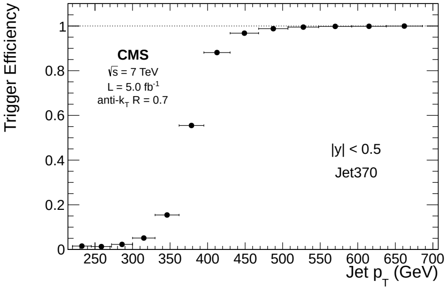
The trigger efficiency is defined as:

$$\epsilon^{trig} = \frac{InclusiveRecoJet\_P_T(Ref + L1Object\_p_T > Z + HLTObject\_p_T > Y)}{InclusiveRecoJet\_p_T(Ref)}$$

Single jet triggers in CMS

Two-level trigger:

- L1: use of raw calorimetric information
- HLT: use of more sophisticated clustering of calorimetric towers and tracking infos



→ Fitted to an error function

→ Turn-on point: 99% efficiency

Phys. Rev. D 87 (2013) 112002

Trigger strategy

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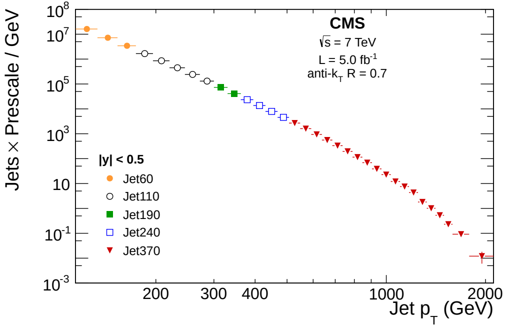
Example: inclusive jet cross section at 7 TeV



Trigger p_T threshold (GeV)	Leading jet p_T (GeV)
60	114-196
110	196-300
190	300-362
240	362-507
370	$>$ 507

→ Trigger ranges in terms of leading jet p_T

Phys. Rev. D 87 (2013) 112002

Performing the data unfolding

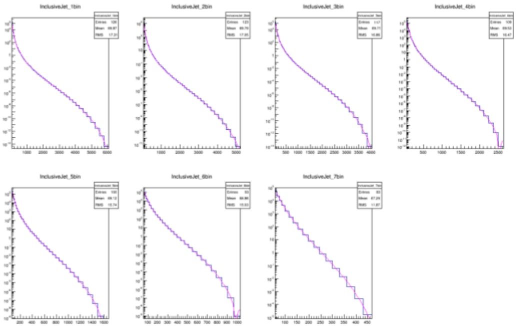
MC | Generator Level → Detector Simulation → Detector Level

Response Matrix

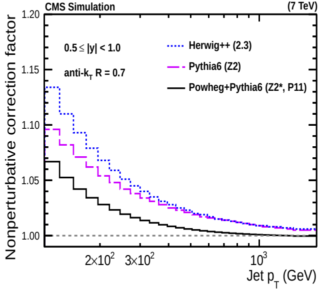
DATA | True Level ← **D'Agostini method** ← Detector Level

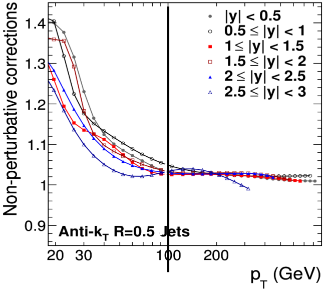
In detail:

- Fit of the generator spectrum from NLO calc.
- Jet resolution obtained from simulated sample in each y and p_T bin
- Smearing (toy MC) of the gen. spectrum for response matrix construction
- Iterative unfolding method optimized for the considered distributions



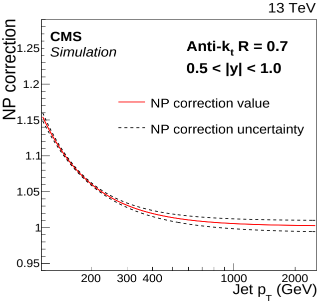
Nonperturbative corrections

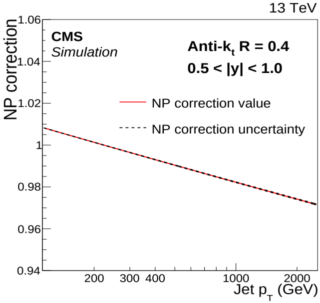




Evaluation of effects from MPI and HAD

$$C_{NP} = \frac{\frac{d\sigma^{nom.}}{dp_T}}{\frac{d\sigma^{MPI,Had\ off}}{dp_T}}$$



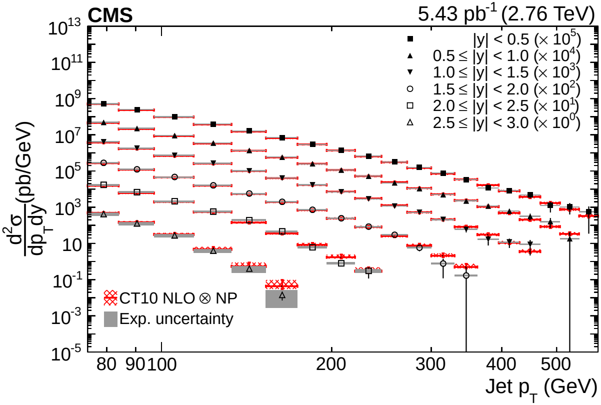


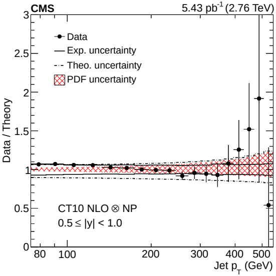
→ Flattening at 1 from ∼ 200-400 GeV

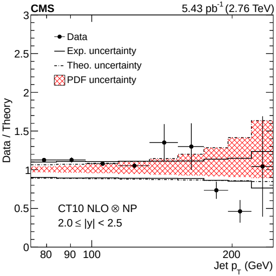
→ Higher for larger jet sizes

LEFT: ak7, RIGHT: ak5 (4) jets
TOP: 7 TeV, BOTTOM: 13 TeV

Inclusive jet cross section at 2.76 TeV





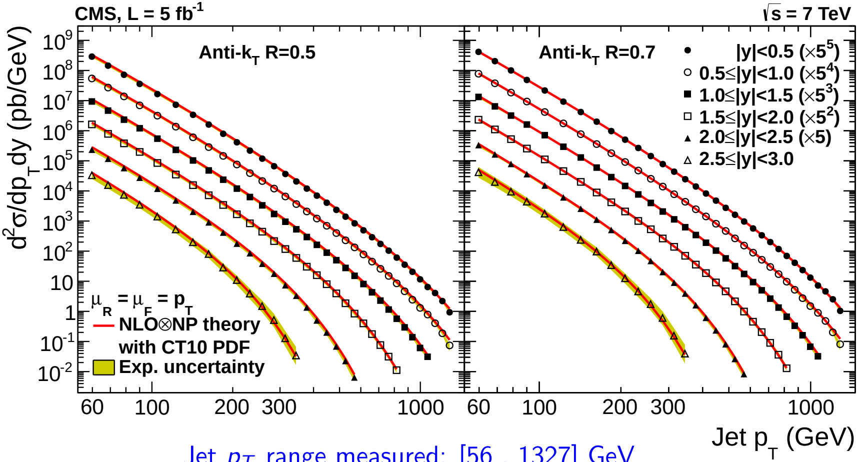


Jet p_T range measured: [74 , 592] GeV

Fixed-order NLO calculations corrected for NP effects describe the measurement very well over the whole p_T and y range

arXiv 1512.06212, subm. to EPJC

Inclusive jet cross section at 7 TeV

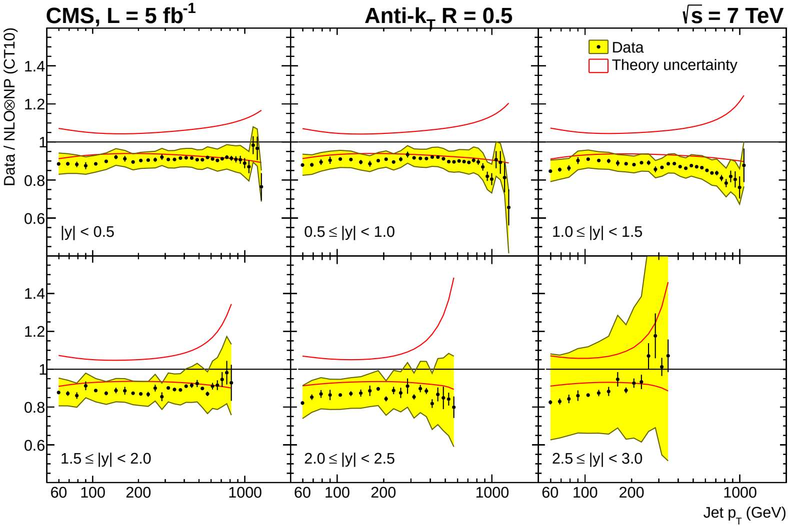


Jet p_T range measured: [56 , 1327] GeV

Jets with two different distance parameters help to understand in a deeper way the details of the parton evolution

PRD 90 (2014) 072006

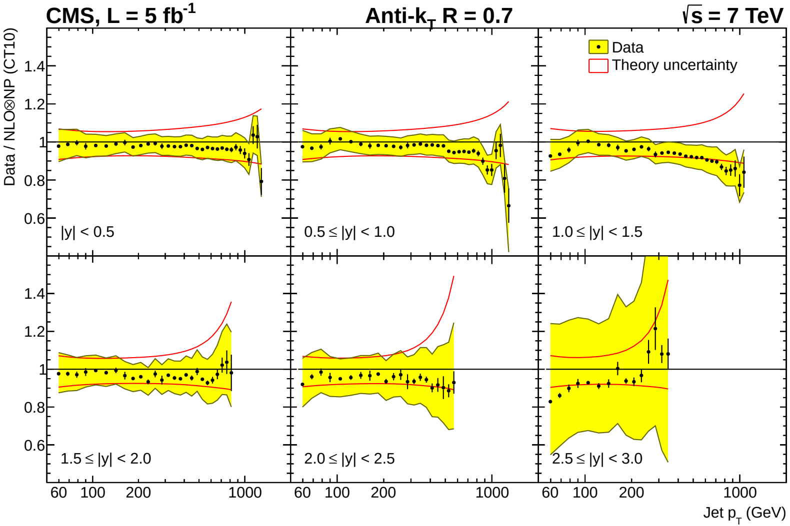
Inclusive jet cross section at 7 TeV: ratios (I)



Not optimal performance of fixed-order calculations for jets with smaller cone size

PRD 90 (2014) 072006

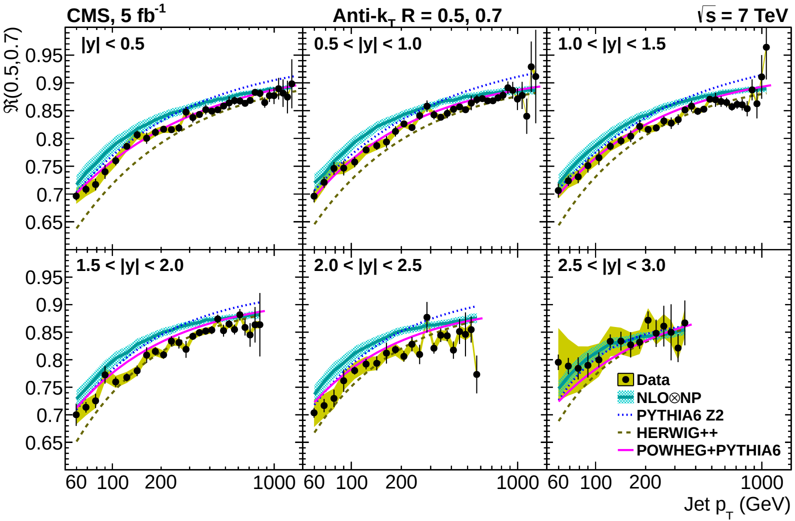
Inclusive jet cross section at 7 TeV: ratios (II)



Very good data description for fixed-order calculations for jets with larger cone size

PRD 90 (2014) 072006

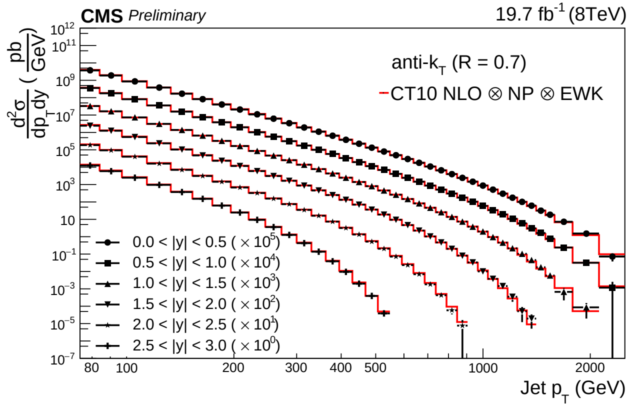
Inclusive jet cross section at 7 TeV: ratios (III)

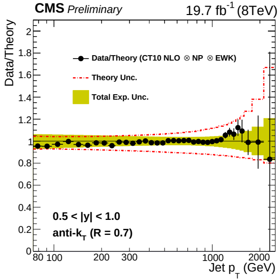


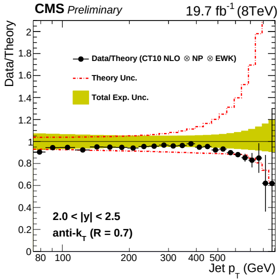
Cross section ratio between the two cone sizes well reproduced by NLO matrix elements interfaced to PS and MPI simulation

PRD 90 (2014) 072006

Inclusive jet cross section at 8 TeV





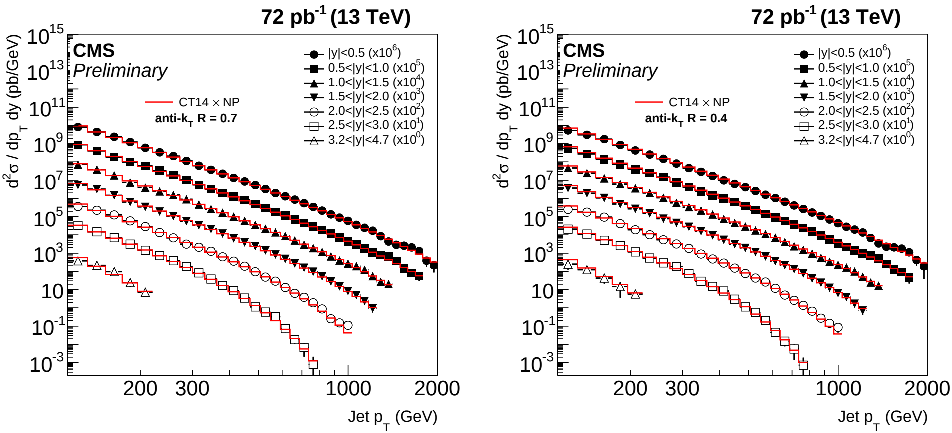


Jet p_T range measured: [74 , 2500] GeV

Very good agreement over the whole p_T and rapidity range for fixed-order calculations corrected for NP and EW effects

CMS-PAS-SMP-14-001 - CMS-PAS-FSQ-12-032

Inclusive jet cross section at 13 TeV

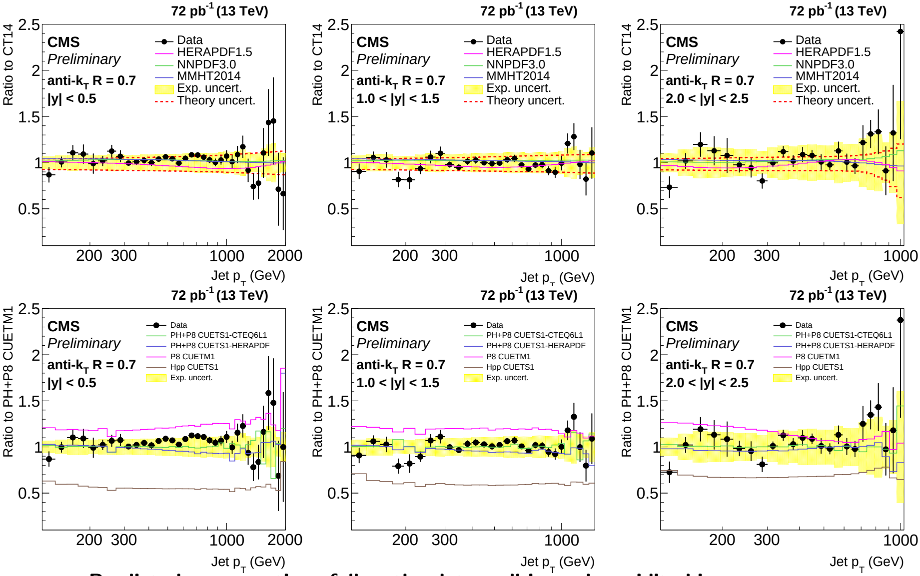


Unfolded results compared to predictions from:

- NLOJet++ corrected for non-perturbative effects
- POWHEG NLO dijet matrix element + PYTHIA8 underlying event simulation
- PYTHIA 8 and HERWIG++ LO predictions

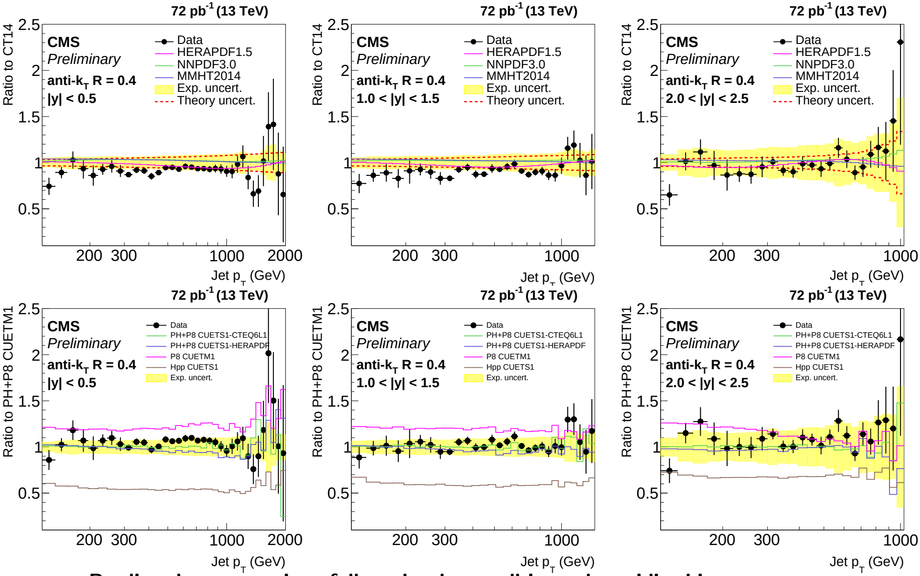
For the first time HF region included! CMS-PAS-SMP-15-007

Inclusive jet cross section at 13 TeV: ratios



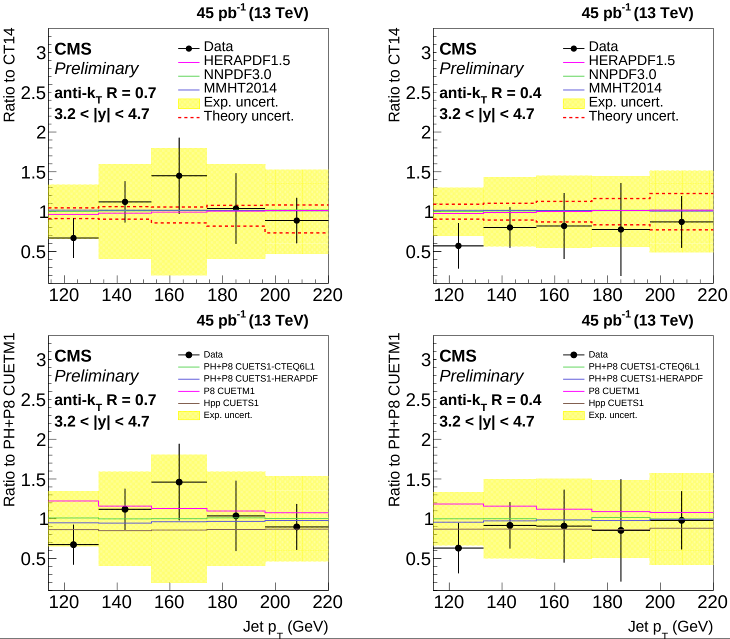
- **Predicted cross sections follow the data well in each rapidity bin**
- **Similar performance of predictions from pure ME calc. and MC generators**

Inclusive jet cross section at 13 TeV: ratios



- **Predicted cross sections follow the data well in each rapidity bin**
- **Better performance of predictions from MC generators than pure ME calc.**

Inclusive jet cross section at 13 TeV: very forward region



Predicted cross sections follow the data well in the outermost rapidity region

LEFT: ak7,
RIGHT: ak4

Summary

- The CMS experiment performed a wide range of jet measurements at various collision energies and is ready for the new 13 TeV phase
- Double-differential cross section distributions are measured for inclusive jets in $p_T \in$ [30-2500] GeV, up to $|y| < 4.7$
- Systematic effects are evaluated and main contributions come from JES uncertainties at each energy
- Fixed-order NLO calculations reproduce well jet cross sections in various rapidity bins but are better for large R for the clustering algorithm
- MC event generators with NLO matrix element follow slightly better the data for jets clustered with small R
- Jet measurements are becoming precision physics and exploring new phase space territory and are challenging the precision of theoretical predictions

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THANK YOU FOR YOUR ATTENTION!

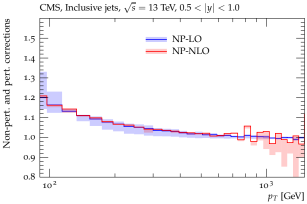
Non-perturbative corrections

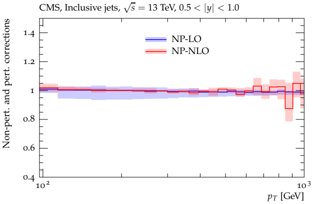
Corrections evaluated for various $|y|$ bins (p_T: 97-3000 GeV)

Considered MC event generators:

- POWHEG (CT10) + PYTHIA 8 - tune CUETP8M1
- POWHEG (HERAPDFNLO) + PYTHIA 8 - tune CUETP8S1-HERAPDF1.5LO
- POWHEG (CT10) + PYTHIA 8 - tune CUETP8M1
- PYTHIA8 + tune CUETP8M1
- HERWIG++ + tune CUETHppS1

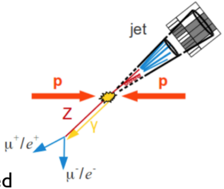
$$C_{NP} = \frac{\frac{d\sigma^{nom.}}{dp_T}}{\frac{d\sigma^{MPI,Had\ off}}{dp_T}}$$

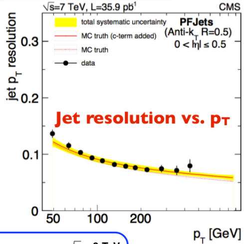




Jet Energy Calibration and Resolution

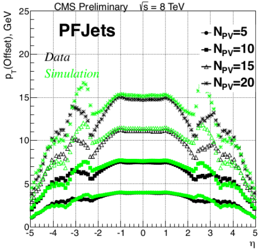
- Jet energies are calibrated to particle (hadron) level
- A factorized methodology is employed



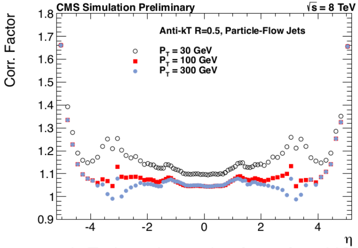


JINST 6 P11002

CMS-DP-2013-033



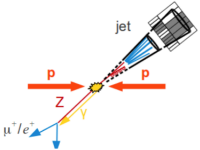
Additional energy due to pileup as a function of η (AK5 PFJets)

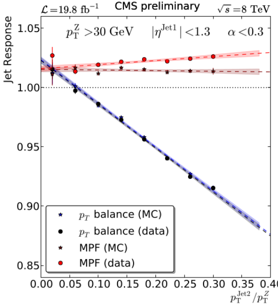


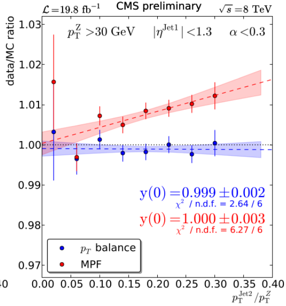
η and pT -dependent scaling factor from MC after applying pileup corrections

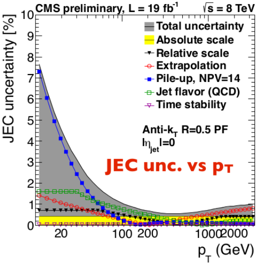
Jet Energy Scale Uncertainty

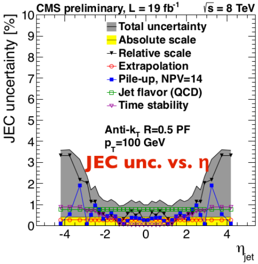
- JEC (Jet Energy Correction) uncertainty ~1% for central high-pT jets
- Good agreement between MC and DATA











p_T balance

- $$R_{\text{balance}} = \frac{p_T^{\text{jet}}}{p_T^{\gamma}}$$

MPF (Missing $\vec{E}_T$ Projection Fraction)

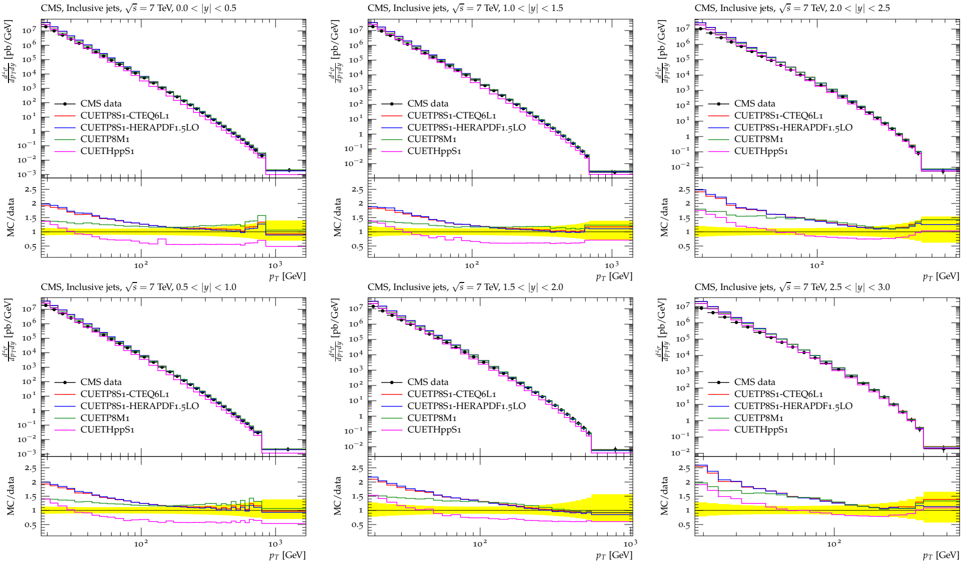
- $$R_{\text{MPF}} = 1 + \frac{\vec{E}_T^{\text{miss}} \cdot \vec{p}_T^{\gamma}}{(p_T^{\gamma})^2}$$

Summary of assigned uncertainties

Systematic effect	2.76 TeV	7 TeV	8 TeV	13 TeV
JES	5-78%	8-35%	6-45%	8-65%
JER-unfolding	2-3%	5%	1-5%	1-2%
Luminosity	3.7%	2.2%	2.6%	4.8%
Trigger efficiency	1%	1%	1%	1%
Pile-up	negl.	negl.	negl.	negl.
Model-unfolding	negl.	negl.	negl.	negl.
PDF	1-20%	1-30%	5-30%	1-10%
Scale	1-10%	5-40%	5-30%	1-12%
NP Corrections	2-5%	1-5%	0.06-1.4%	2%

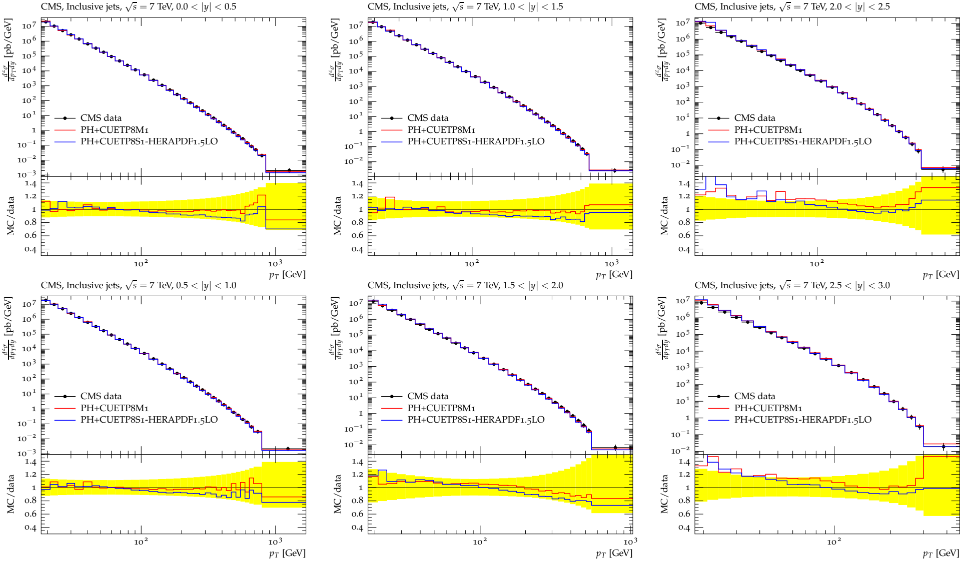
Validation plots (III): Jets

Inclusive jet cross sections measured by CMS in rapidity bins



Interface with NLO matrix element (I): Jets

Inclusive jet cross sections measured by CMS in rapidity bins



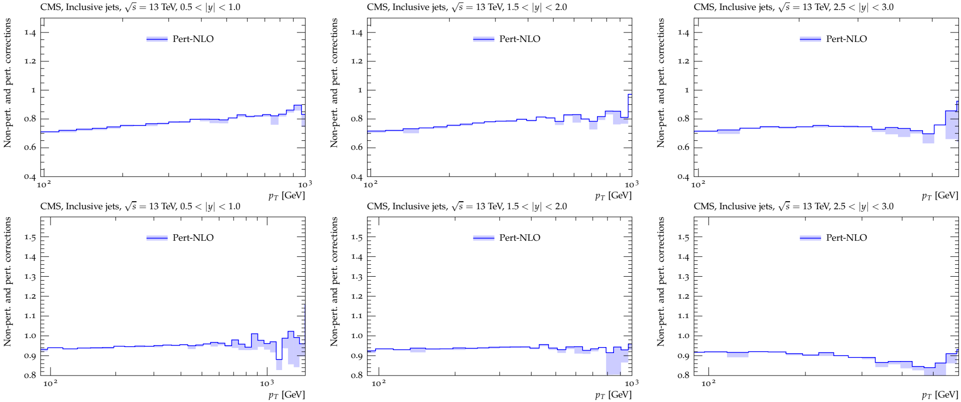
Perturbative corrections

$$C_{PS} = \frac{\frac{d\sigma^{MPI,Had\ off}}{dp_T}}{\frac{d\sigma^{MPI,Had,PS\ off}}{dp_T}}$$

Pert. corrections with NLO matrix element

Three different UE tunes accounted for

AK4 (top), AK7 (bottom)



This correction seems to be too high for accounting for NLO discrepancies for AK4