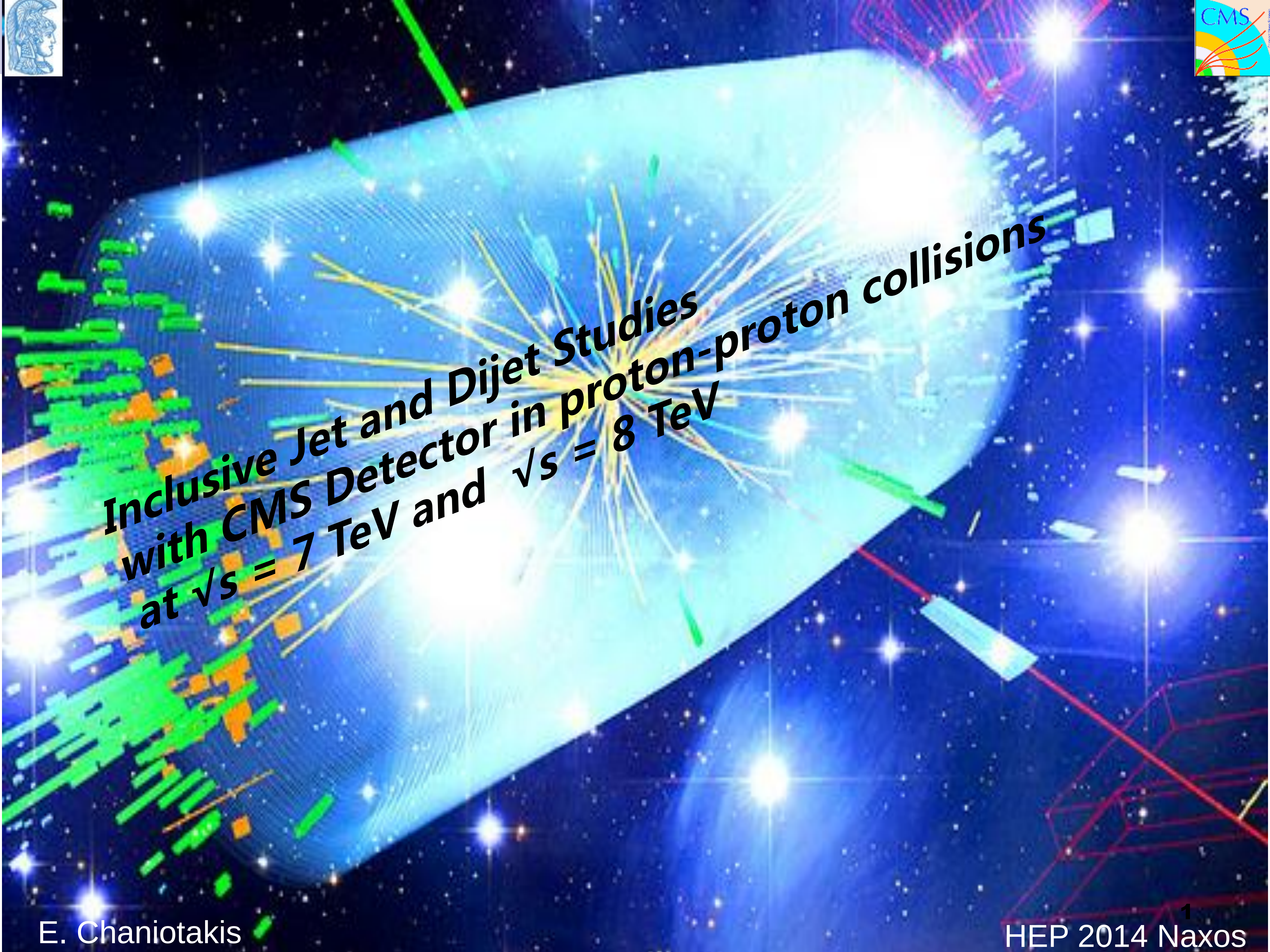
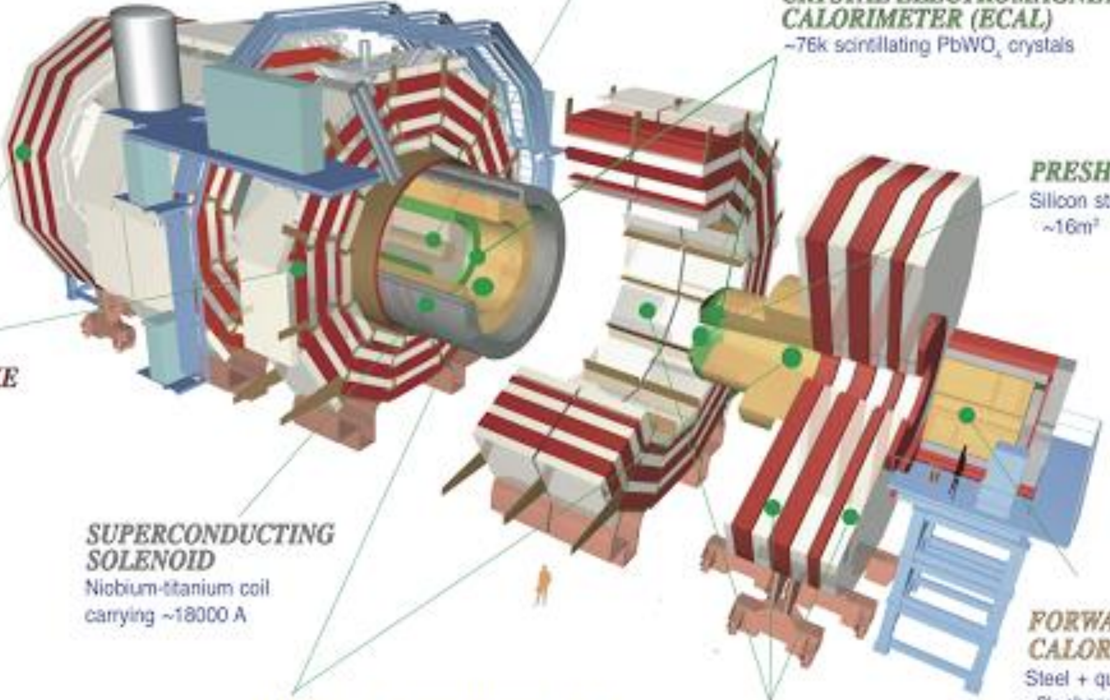


Inclusive Jet and Dijet Studies with CMS Detector in proton-proton collisions at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV

E. Chaniotakis

HEP 2014 Naxos

CMS Detector



Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

SILICON TRACKER
Pixels (100 x 150 μm^2)
~1m^2 ~66M channels
Microstrips (80-180μm)
~200m^2 ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO$_4$ crystals

PRESHOWER
Silicon strips
~16m^2 ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Physics Motivation

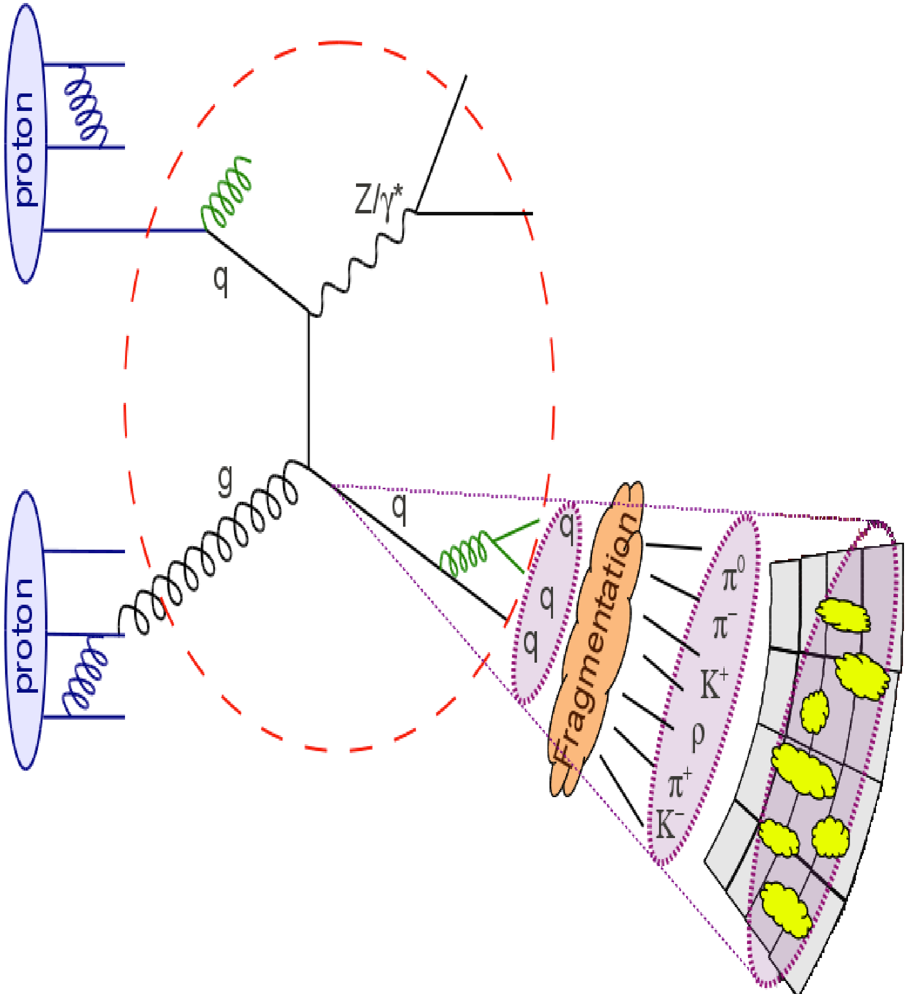
- **Test pQCD in a new energy regime, in a totally unexplored kinematic region.**

- **Provide constraints on PDFs,**

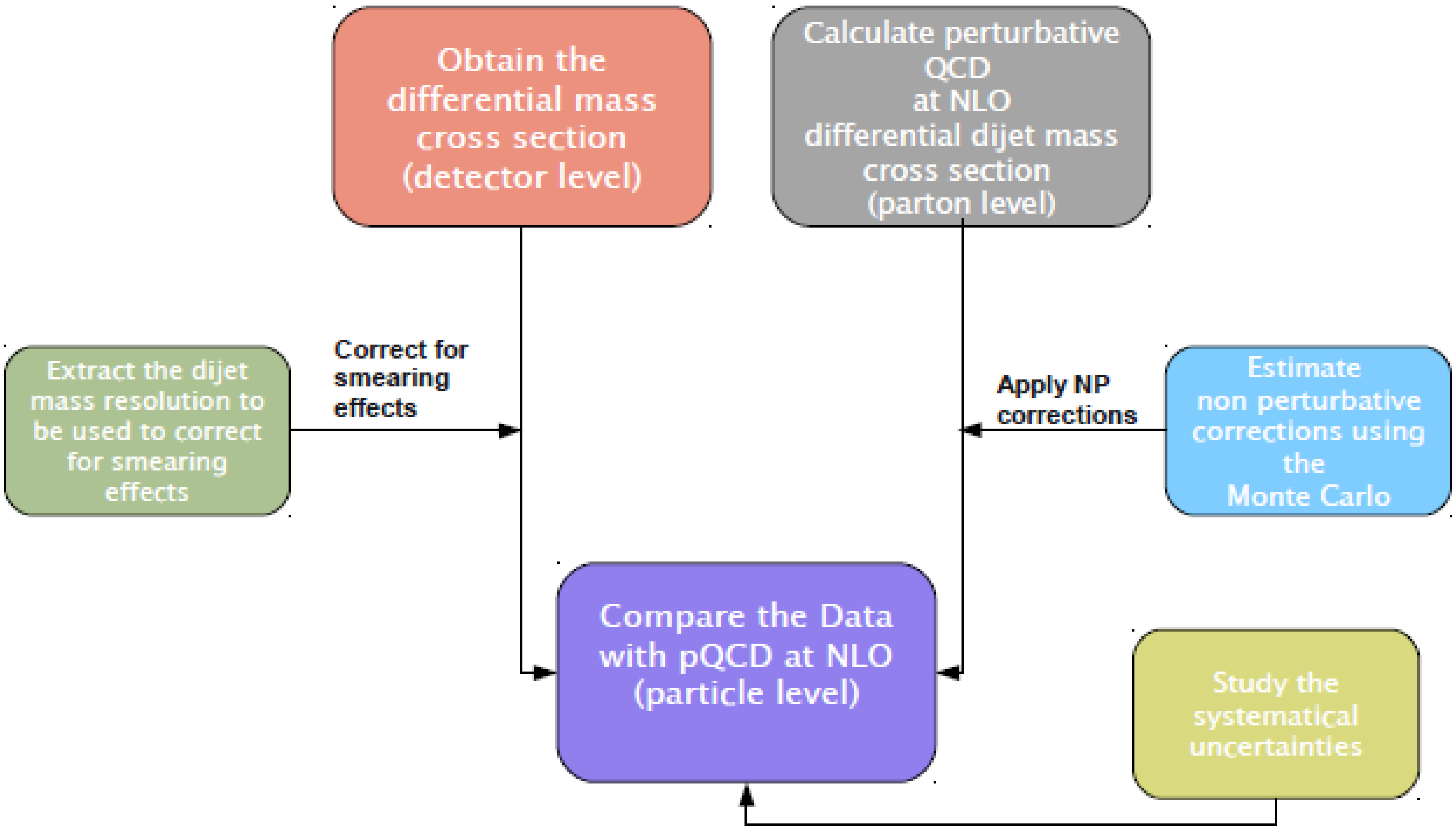
- **Differentiate between PDF sets**

- **Tune Monte Carlo generators in order to better describe the data.**

- **Measure and understand the main background to most new physics searches, *or get a chance to have a first glimpse of something new and unexpected*.**



Steps of the Analysis



Obtain the differential mass cross section (detector level)

Calculate perturbative QCD at NLO differential dijet mass cross section (parton level)

Extract the dijet mass resolution to be used to correct for smearing effects

Correct for smearing effects

Apply NP corrections

Estimate non perturbative corrections using the Monte Carlo

Compare the Data with pQCD at NLO (particle level)

Study the systematical uncertainties

Experimental Measurement

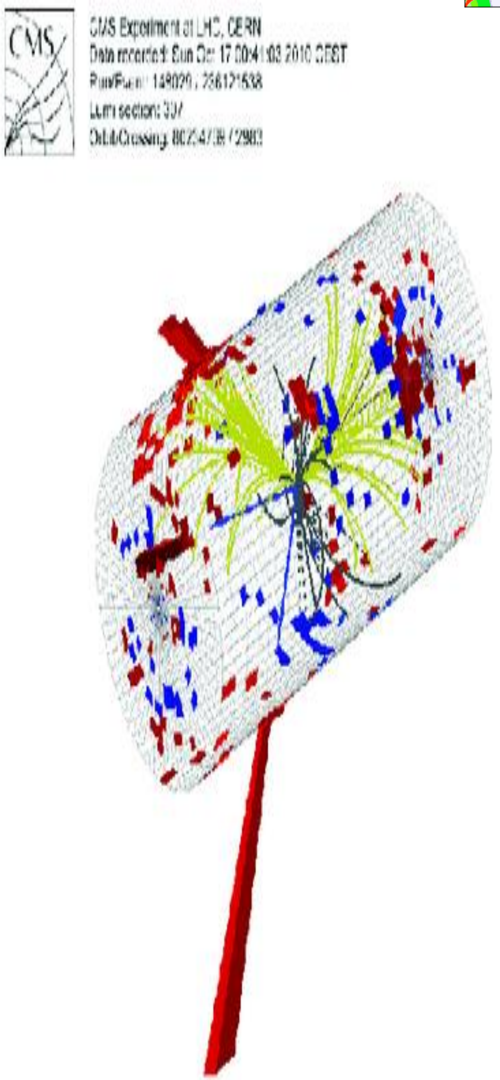
Event selection

- Primary vertex |z|<24cm

- Number of primary vertex tracks >4

- Inclusive jet measurement :At least 1jet with |y|<2.5

- Inclusive dijet measurement: At least 2 jets with ymax = max(|y1|,|y2|) < 2.5
- Corrected jet p_T : 60 GeV (primary jet)
- Corrected jet p_T : 30 GeV (secondary jet)



▪After applying the selection criteria we have a very clean data set and reject <<1% of our events

In order to suppress unphysical jets coming from calorimeter noise, the following Jet-ID criteria are applied:

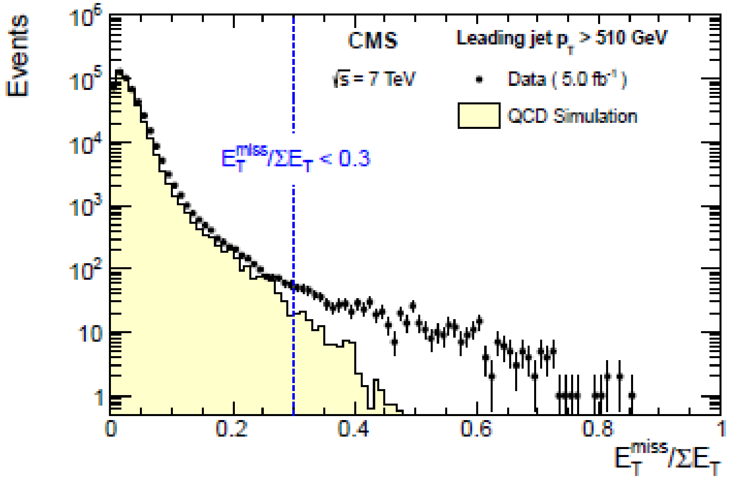
- Each jet should have at least 2 particles one of which is a charged hadron
- Jet energy fraction carried by photons and neutral hadrons should be less than 90%
- These criteria have an efficiency greater than 99% for physical jets whereas unphysical jets pass the criteria with a probability less than 10^{-6}

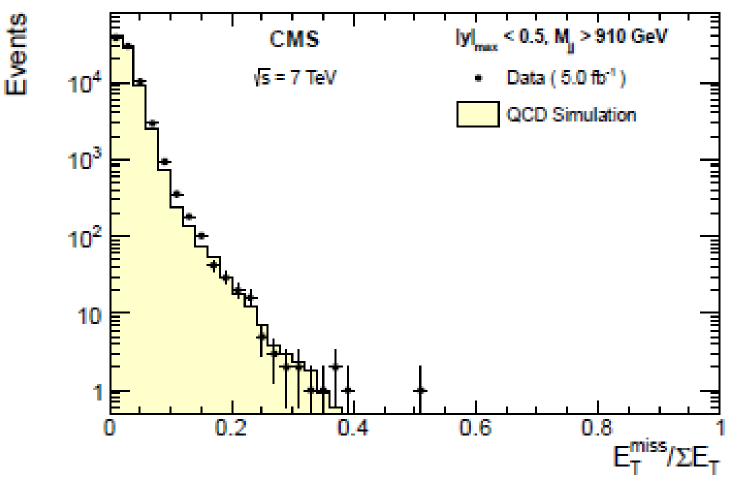
Data Quality

To ensure the quality of our data and the robustness of the selection criteria against noise, detector pathologies, reconstruction failures etc. a series of tests is being performed.

These tests include the comparison between Data and MC
of jet related quantities (Charged Hadron Fraction , Neutral Hadron Fraction etc.),
and event related quantities ($E_T^{miss} / \sum E_T$, Jet pT , $\Delta\varphi$ between the two jets in the dijet analysis etc.)

They also include the stability of measured quantities over time (such as the dijet mass, the event rate, the jet and event characteristics).



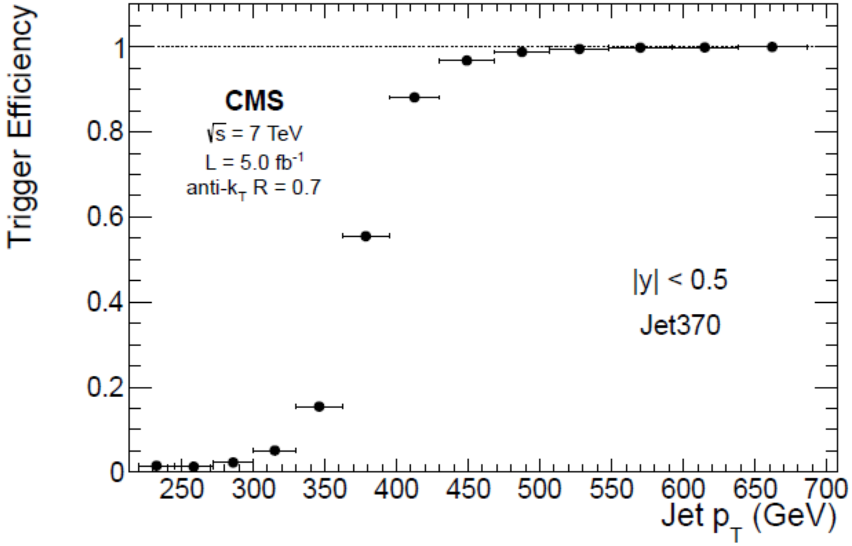


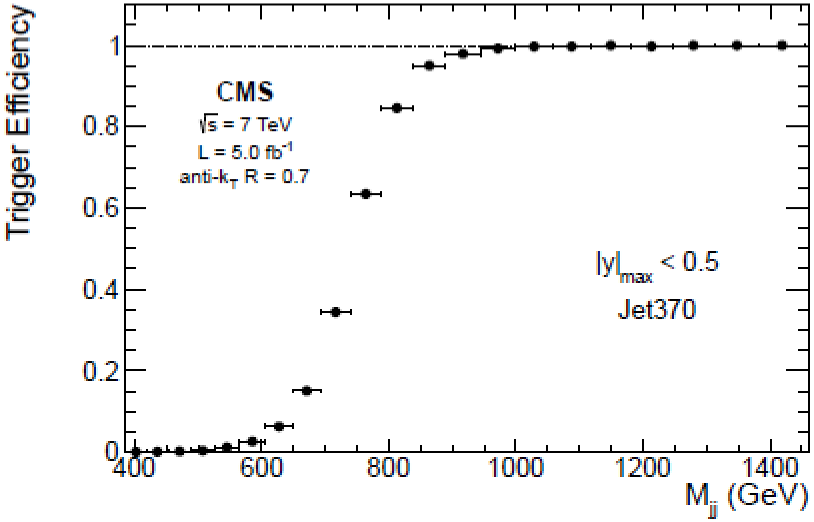
Trigger Studies

For all available samples we determine the lower limit in the parameter of interest, in order for them to be at least 99% efficient.
Each sample's efficiency curve is determined from the sample composed of triggers with lower thresholds according to the formula:

$$\varepsilon_{\mathrm{A}} = \frac{L_B}{L_A}\frac{N_{trigA}}{N_{trigB}}$$

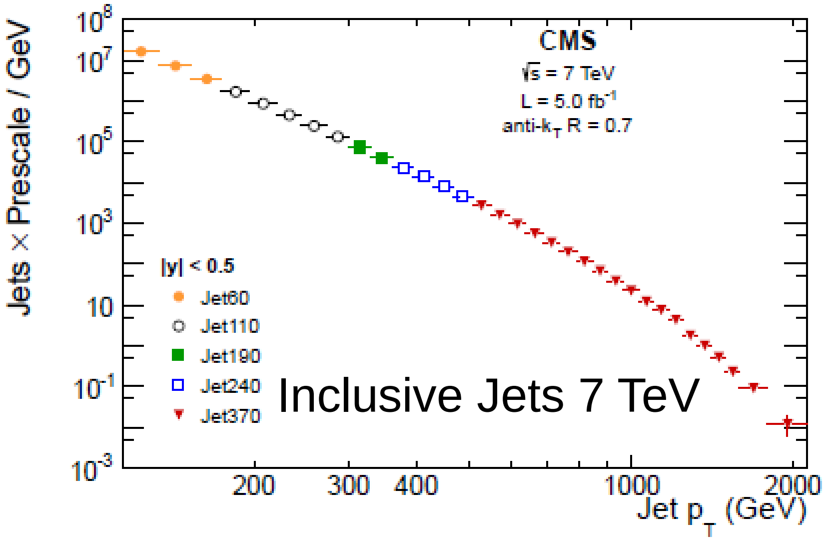
ε_A : efficiency of the higher threshold sample
N : Nr of triggers
L : effective luminosity

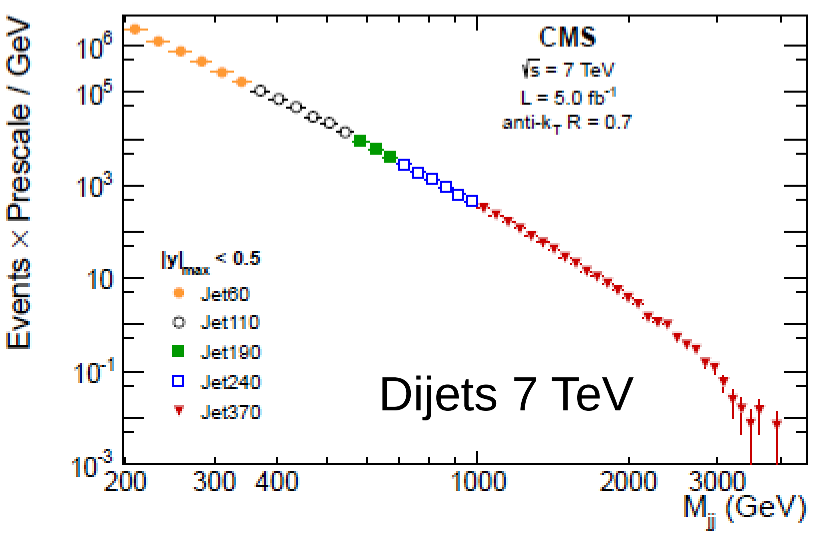




Spectrum Construction

The spectrum construction is achieved by combining the inclusive jet pT (dijet mass) spectra from individual trigger paths. Each trigger starts from the value where it is 99% efficient.





$$\frac{d^2\sigma}{dp_T d\,|y|} = \frac{C}{\varepsilon L_{equiv.}} \frac{N}{\Delta p_T \Delta |y|}$$

$$\frac{d^2\sigma}{dM_{JJ} d|y|_{max}} = \frac{C}{\varepsilon L_{equiv}} \frac{N}{\Delta M_{JJ} \Delta |y|_{max}}$$

N : the number of jets in the bin

$L_{equiv.}$: the integrated luminosity of the data sample from which the events are taken

ε : the product of the trigger and event selection efficiencies

C : correction factor for the smearing effect

ΔMjj : mass bin

ΔpT : pT bin.

Δ|y| : the rapidity bin width

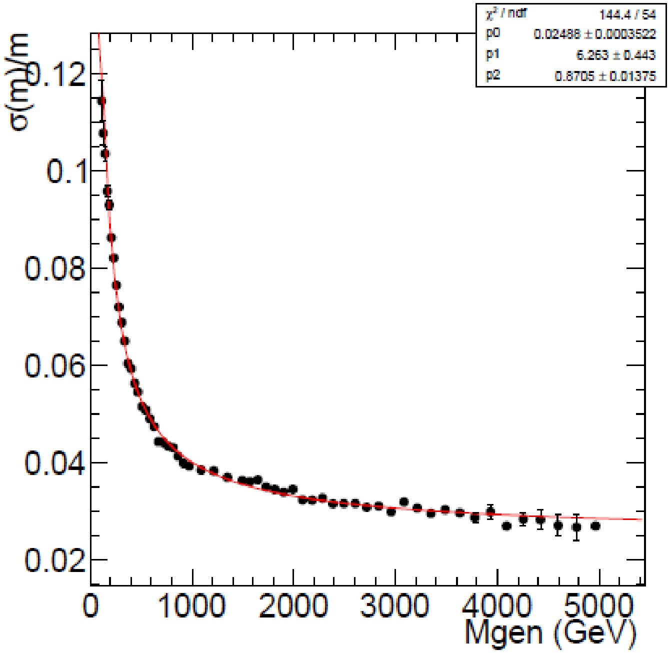
Unsmearing

Due to the steeply falling spectrum and the finite detector resolution, the measured cross section is smeared with respect to the particle level cross section. In every bin there are migrations , and due to the steeply falling nature of the spectrum more events migrate in than out of a bin.

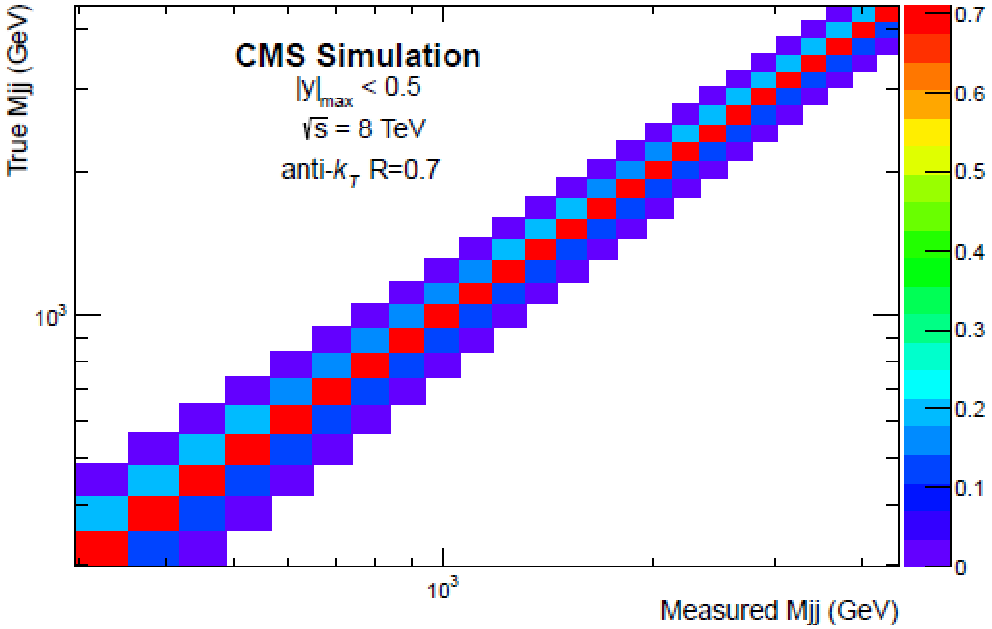
The unsmearing is done in the following steps:

- Extract the resolution using Monte Carlo and parametrise it with a smooth function of pT (mass).
- Obtain the Response Matrix for the Unfolding with a toy MC using the RooUnfold Package. The pT (mass) values are generated randomly. Spectrum predicted by Pythia6 smeared with a gaussian function centred in the pT (mass) with sigma determined by the resolution parametrisation.
- Iterative Bayesian method written by D'Agostini applied to unfold the data spectrum.

Dijet Mass Resolution at 8 TeV for the central rapidity bin



Dijet Mass Response Matrix at 8 TeV



Theoretical Prediction

NLO predictions

- The theoretical prediction for the jet cross sections consist of a Next to Leading Order (NLO) calculation and a nonperturbative correction to account for multi-parton interactions and hadronization.

- The NLO calculations are performed using the NLOJet++ program (v.2.0.1) within the framework of fastNLO.

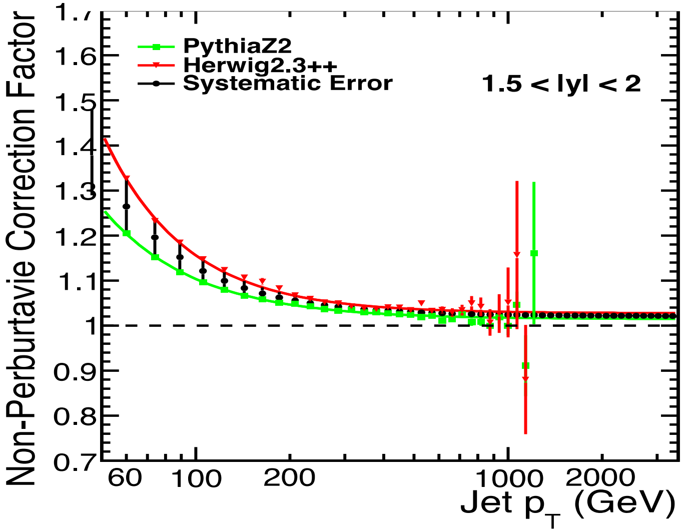
- Renormalization and factorization scales μ_R , μ_F are defined as the p_T for the inclusive jets and the average p_T between the two jets for the dijets.

- The following PDF sets have been used for the calculation: NNPDF2.1 , MSTW2008NLO, CT10, HERAPDF1.5, ABKM09, ABM11.

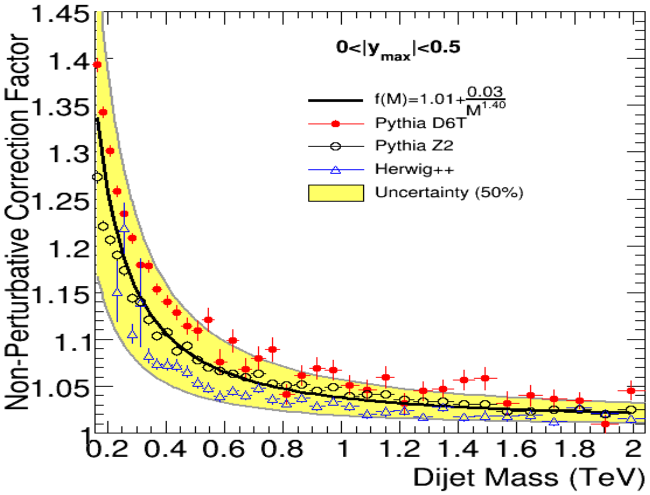
NP corrections

- NP corrections are used to account for MultiParton interactions and Hadronization. The NLO calculations provide predictions at the parton level, whereas the experimental measurement after the unfolding takes us from the detector to the particle level. Therefore the NP correction must be applied to take the theory from parton to particle level.

- The NP corrections are derived from Monte Carlo using Pythia6 and Herwig++ event generators. The correction factor is the average of the two predictions and the systematic uncertainty is their difference.



NP correction for inclusive jets at 7 TeV



NP correction for dijets at 7 TeV

Systematic Uncertainties

Experimental Systematics

- Luminosity uncertainty

  Uncertainty in the luminosity measurement which is directly transferred to the cross section measurement.

- Unsmearing uncertainty

  Uncertainty introduced by the modelling of the jet (dijet) resolution and spectrum shape in the simulation.

- Jet Energy Scale uncertainty

  Dominant experimental uncertainty. Due to the falling nature of the spectra, a small uncertainty in the pT (mass) scale is translated in a big uncertainty in the cross section.

  It is calculated by adding in quadrature the individual contributions of 16 mutually uncorrelated uncertainty sources broadly categorised as :

  PileUp , ***Relative calibration of JES vs η*** , ***absolute scale including pT dependence***, ***Differences between quark and gluon initiated jets***.

Theoretical Systematics

- PDF uncertainty

  Dominant theoretical uncertainty at high pT (mass) values due to PDF dependence.

- Scale uncertainty

  The renormalization and factorization scale uncertainty is estimated as the maximum deviation at the six points

  $(\mu_F/\mu, \mu_R/\mu) = (0.5, 0.5), (2, 2), (1, 0.5), (1, 2), (0.5, 1), (2, 1)$

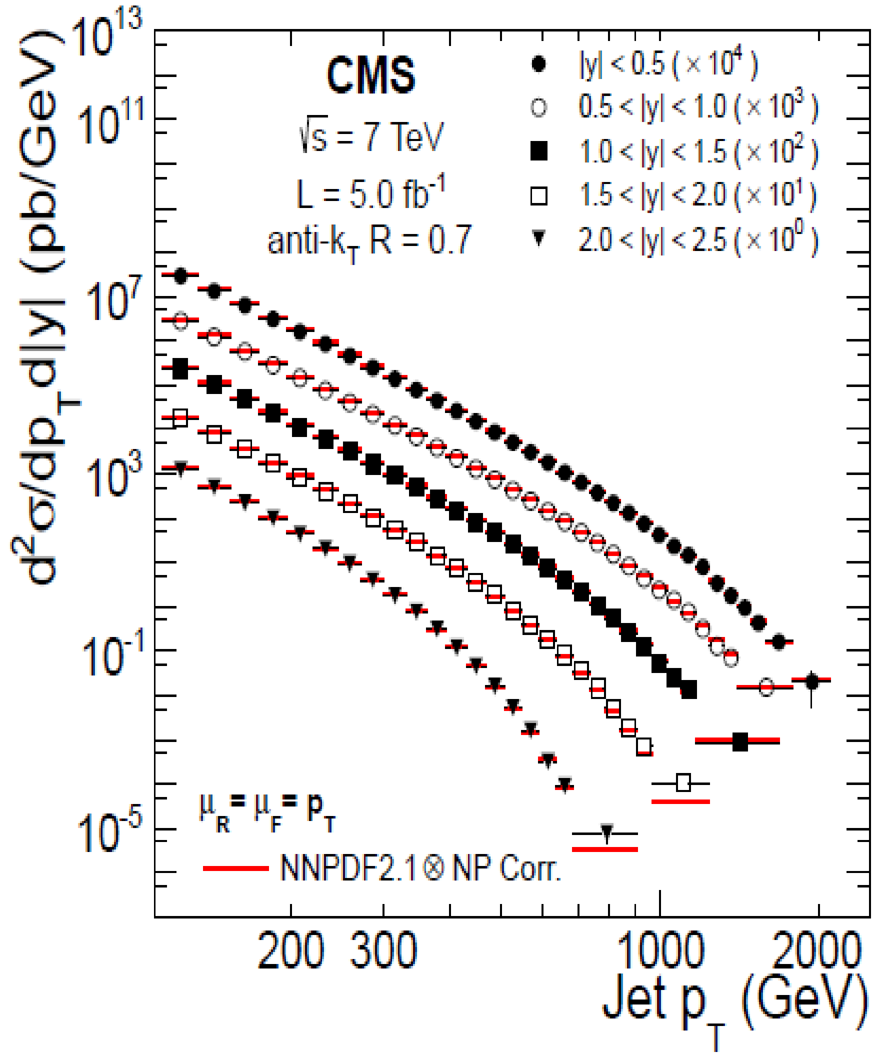
  where μ = pT (inclusive), μ = pTave (dijets)

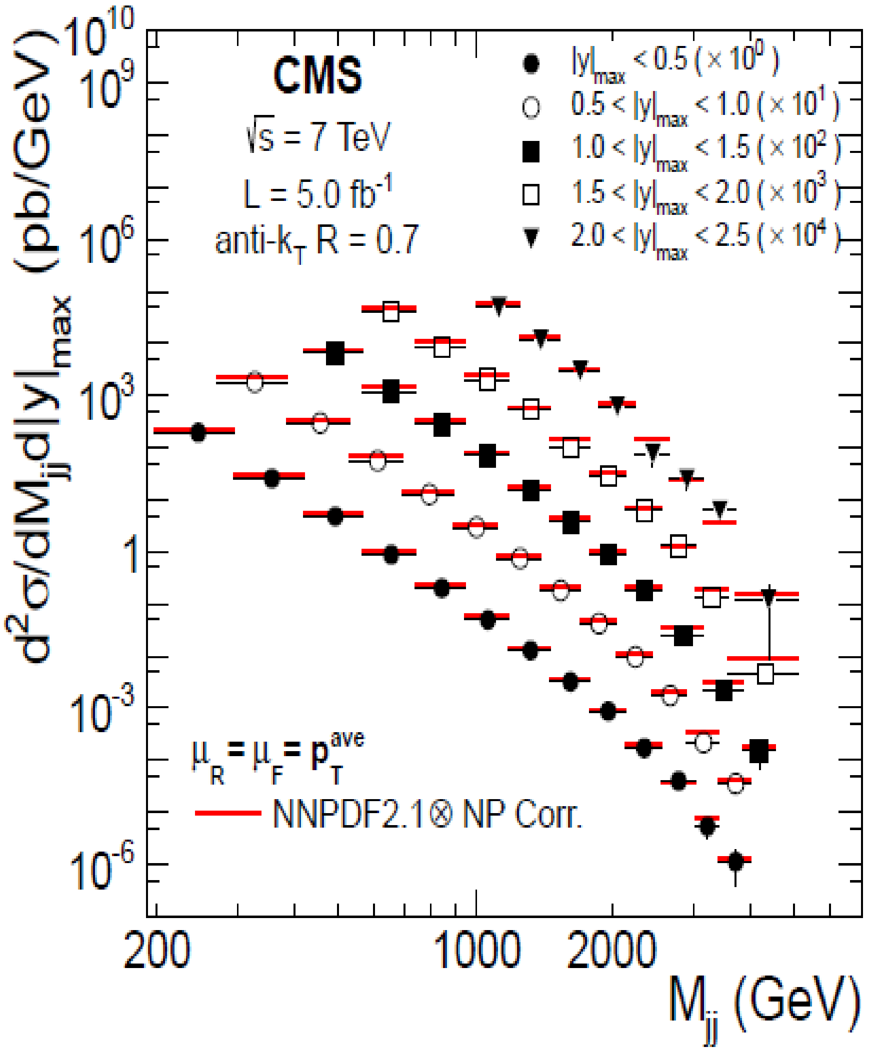
- NP correction uncertainty

  To account for the systematic uncertainty of the NP corrections, different PYTHIA tunes are applied and their difference is taken as the uncertainty. NP uncertainty dominant in low pT (mass).

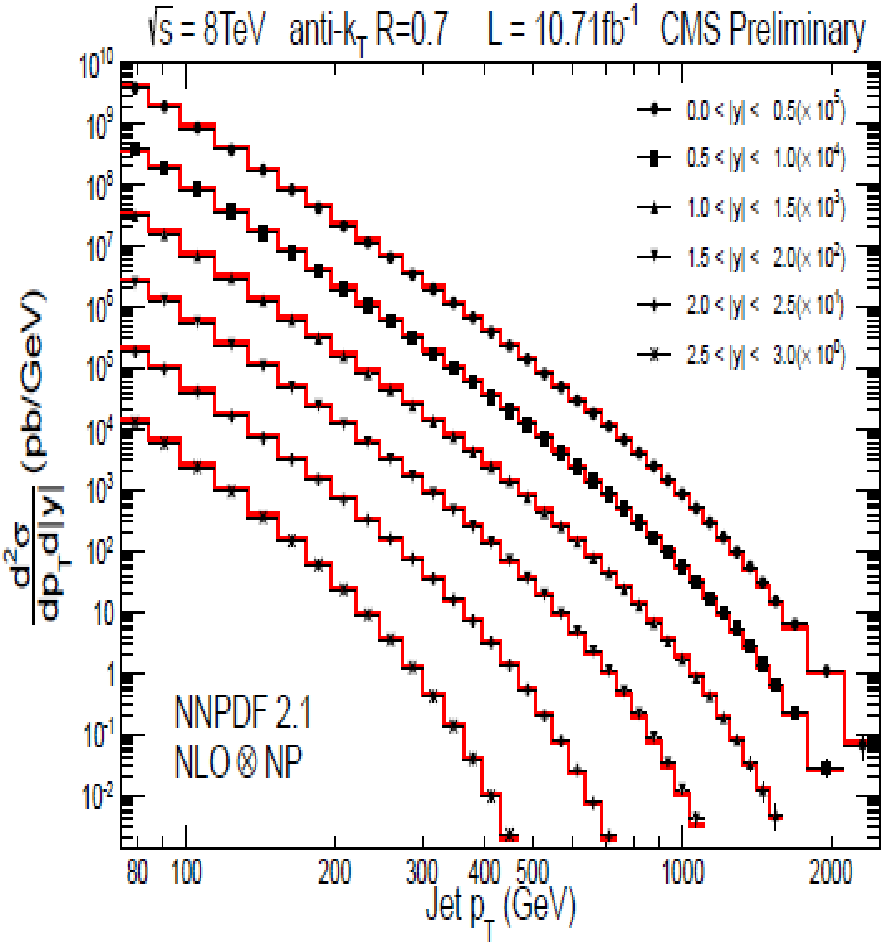
Results

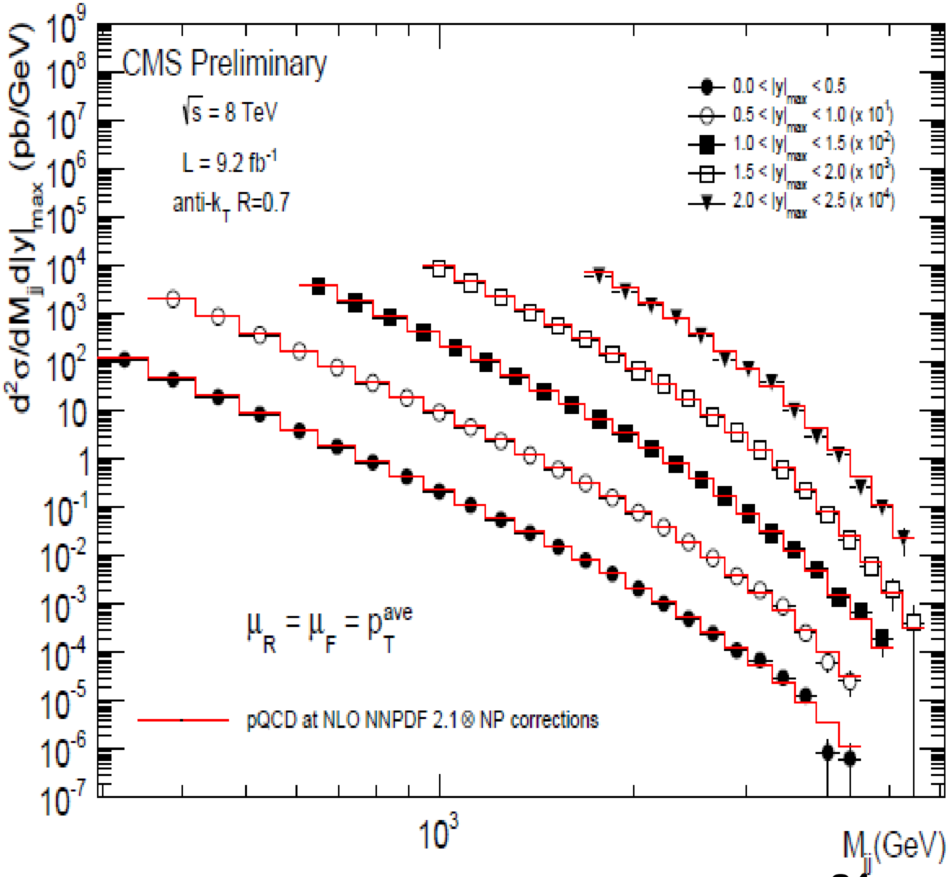
Cross section at 7 TeV



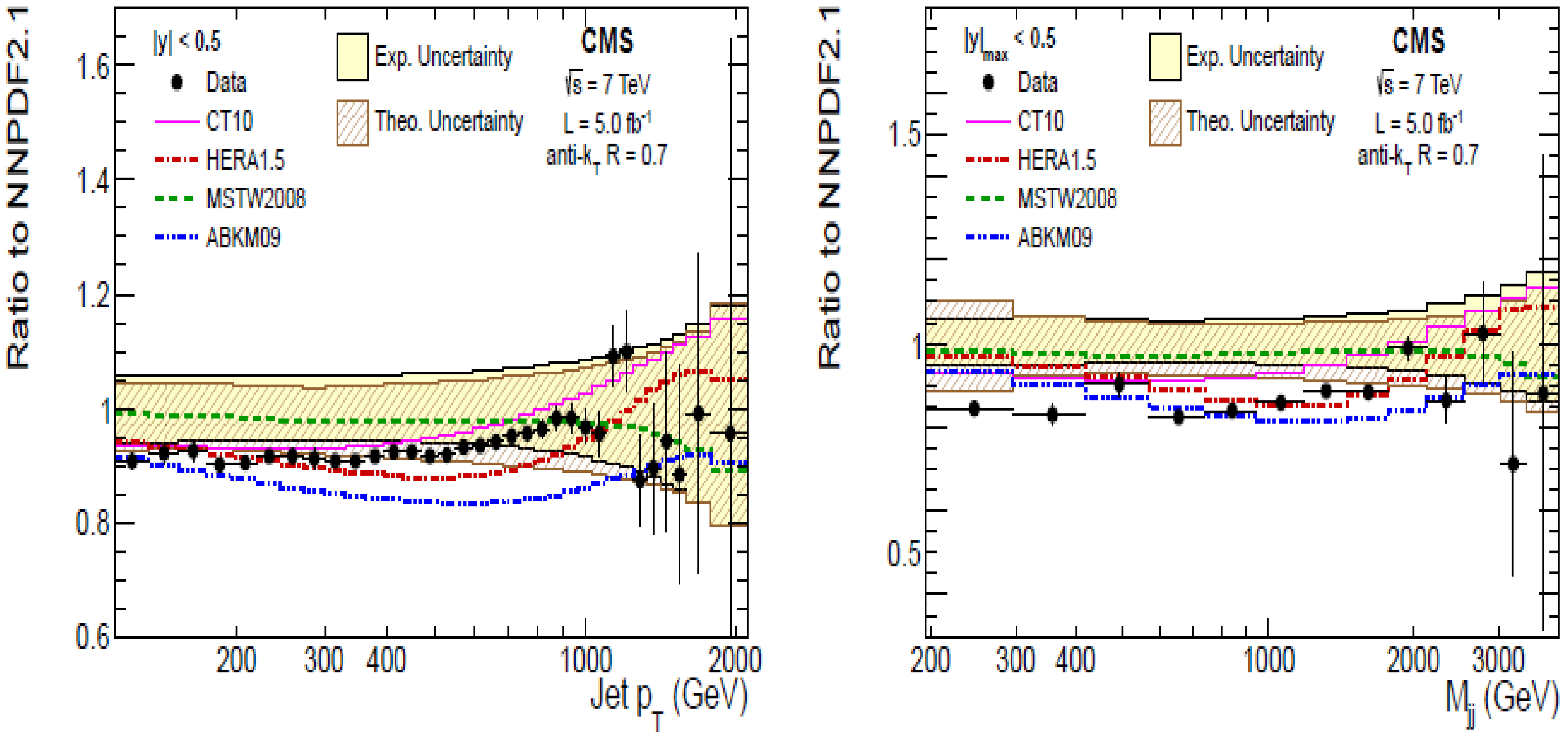


Cross section at 8 TeV (preliminary)

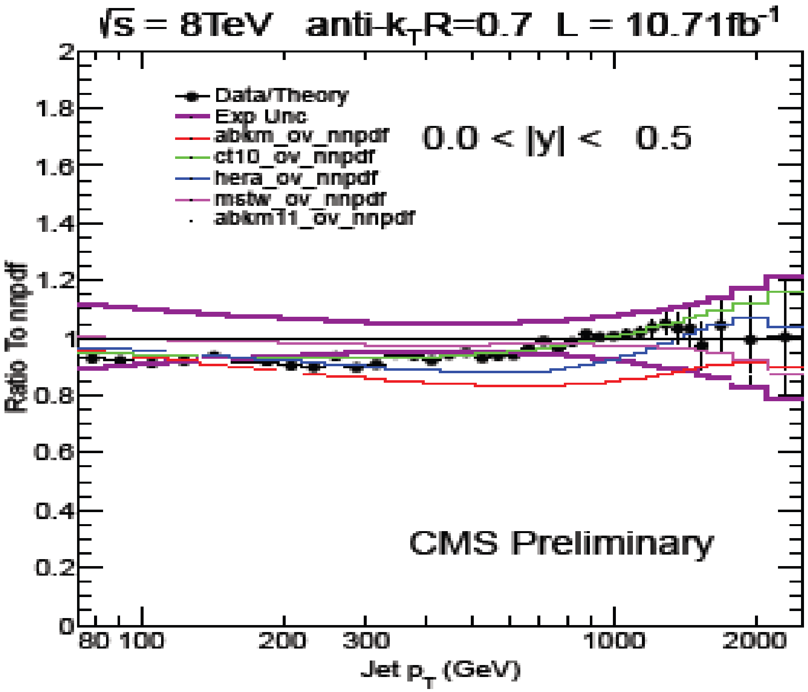


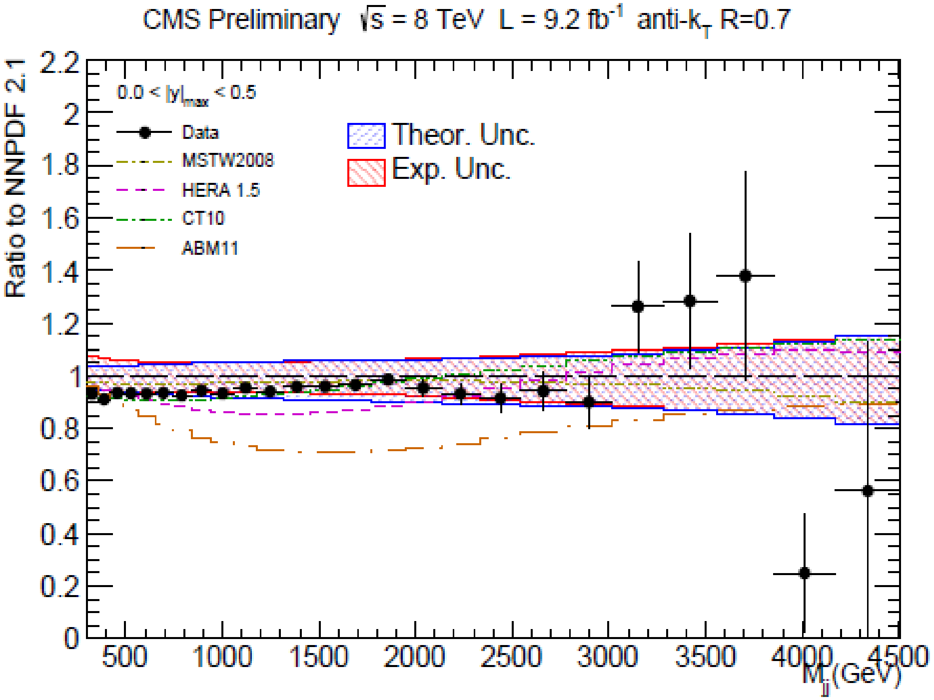


Comparison with theory at 7 TeV



Comparison with theory at 8 TeV (preliminary)





Conclusions

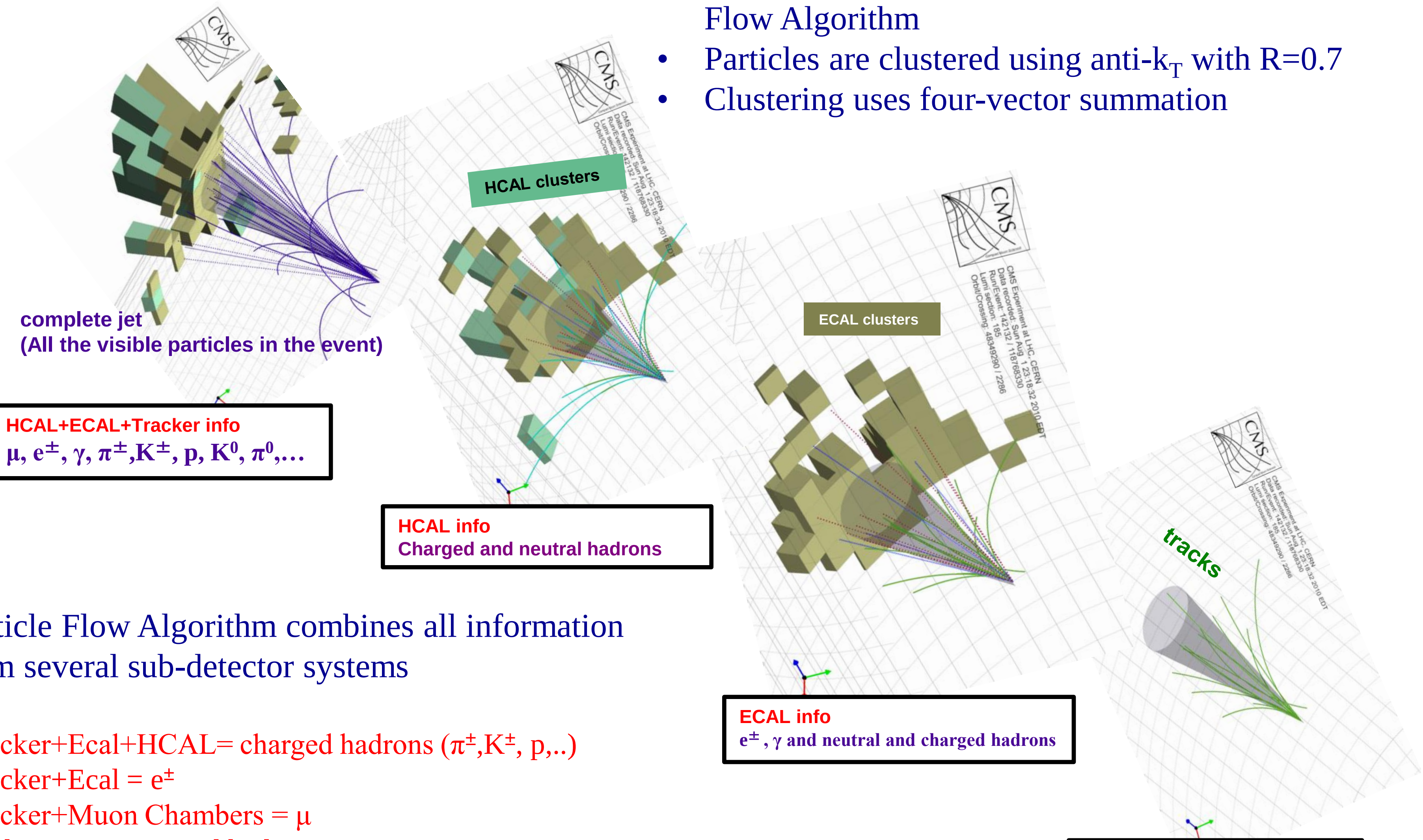
- **A full treatment of the components of an inclusive jet (dijet) cross section measurement have been presented.**
- **Results of the data VS theory comparison at 7 TeV and (preliminary) results at 8 TeV center of mass energy have been demonstrated**
- **Data seem to have good agreement with theoretical prediction indicating that QCD describes well the parton scattering in this kinematical regime.**
- **Theoretical and experimental uncertainties are comparable**
- **By comparing data and theory predictions using different PDF sets we can differentiate between PDF sets.**

THANK YOU!

Back Up

Jet Reconstruction

- Individual particles are reconstructed with Particle Flow Algorithm
- Particles are clustered using anti-k_T with $R=0.7$
- Clustering uses four-vector summation



complete jet
(All the visible particles in the event)

HCAL+ECAL+Tracker info
$\mu, e^{\pm}, \gamma, \pi^{\pm}, K^{\pm}, p, K^0, \pi^0$,…

HCAL info
Charged and neutral hadrons

ECAL info
$e^{\pm}$, γ and neutral and charged hadrons

Silicon Tracker info
μ, $e^{\pm}$, and all charged hadrons

Particle Flow Algorithm combines all information from several sub-detector systems

- Tracker+Ecal+HCAL= charged hadrons ($\pi^{\pm}$,$K^{\pm}$, p,..)
- Tracker+Ecal = $e^{\pm}$
- Tracker+Muon Chambers = μ
- Ecal+HCAL = neutral hadrons
- Ecal = photons

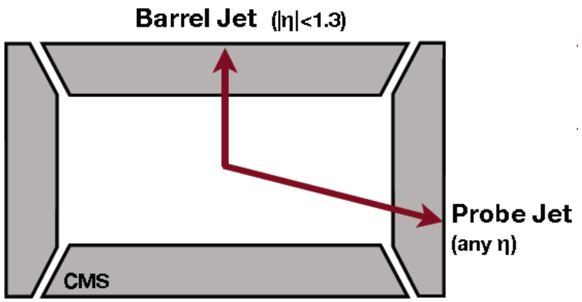
Jet Corrections

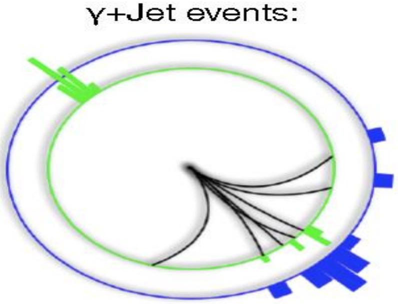
- Jets are corrected at CMS following a factorized scheme, where three corrections are applied sequentially:

- *Offset: pile up and noise correction*

- *Relative: jet response vs η relative to barrel found using dijet balance*

- *Absolute: jet response vs pT found in barrel using γ/Z+jet*





$$p_T^{corrected} = \boxed{Abs(p_T \cdot Rel(\eta, p_T))} \times \boxed{Rel(\eta, p_T)} \times \boxed{p_T - \text{offset}}$$

Absolute correction is applied to the jets which have already been corrected for η dependence

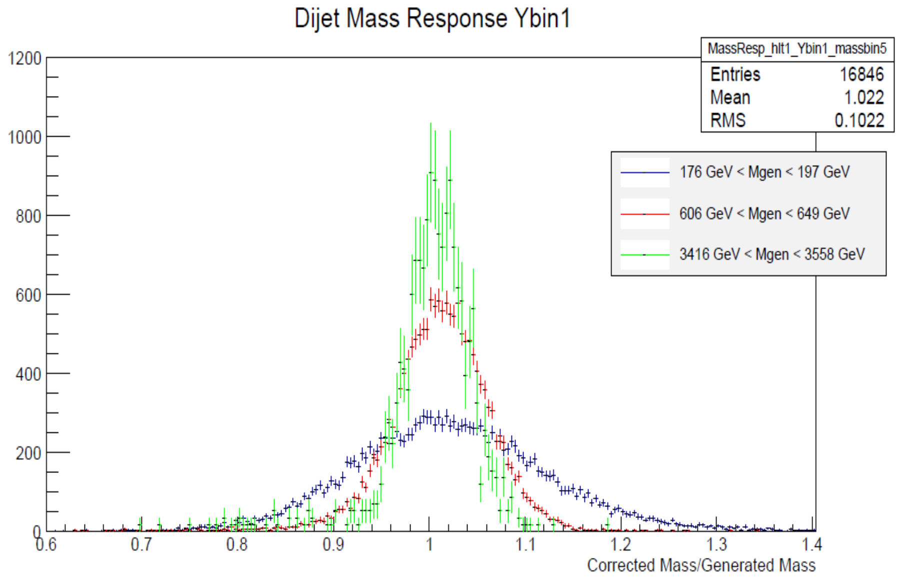
Relative correction is applied to the jets which have already been "offset" corrected

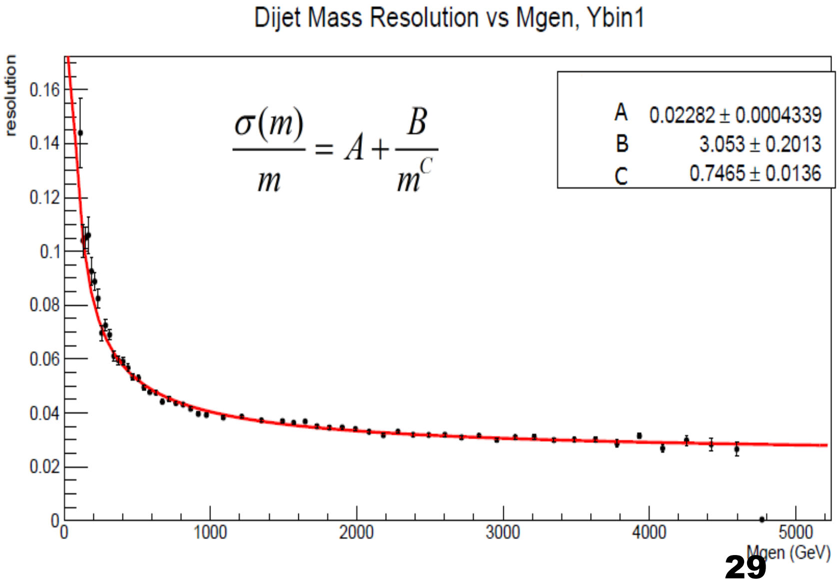
Offset correction is applied to the uncorrected jets

Combined correction brings back the jet to the particle level

Resolution

- Resolution is obtained using Monte Carlo
- We generate jets and divide them in pT bins (inclusive jets) – mass bins (dijets)
- Generated jets are corrected using the GEANT4 simulation of the CMS detector. Identical kinematic selection is applied to both generated and corrected jets.
- For each pT (mass) bin and each rapidity bin we form the response ratio. (Corrected/Generated)
- We fit the response histos with a gaussian. The sigma is the relative resolution.
- We plot the resolution vs the pT (mass).
- The resolution is parametrised using a smooth function of pT(mass).





Unfolding

Due to the steeply falling spectrum and the finite detector resolution, the measured cross section is smeared with respect to the particle level cross section. In every bin there are migrations , and due to the steeply falling nature of the spectrum more events migrate in than out of a bin.

In order to correct for the smearing effects, we obtain the Response Matrix using Toy MC:

- ***Dijet mass (jet pT) values at the particle level are generated randomly. Spectrum predicted by Pythia 6 smeared with a Gaussian function centered at the generated mass.***

- ***The σ of the Gaussian function is determined from the relative resolution parameterization***

- ***These generated and smeared values are used to fill the response matrix object by using the RooUnfold package***

NP corrections

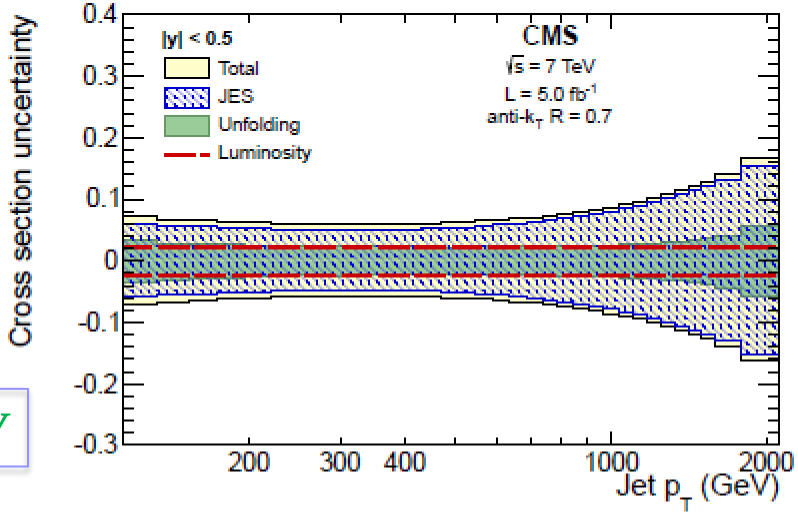
- NP corrections are used to account for MultiParton interactions and Hadronization. The NLO calculations provide predictions at the parton level, whereas the experimental measurement after the unfolding takes us from the detector to the particle level. Therefore the NP correction must be applied to take the theory from parton to particle level.

- The NP corrections are derived from Monte Carlo. The calculation is performed using POWHEG for the hard scattering and the leading emission and PYTHIA6 for the matched showering and hadronization process. These two steps are processed independently.

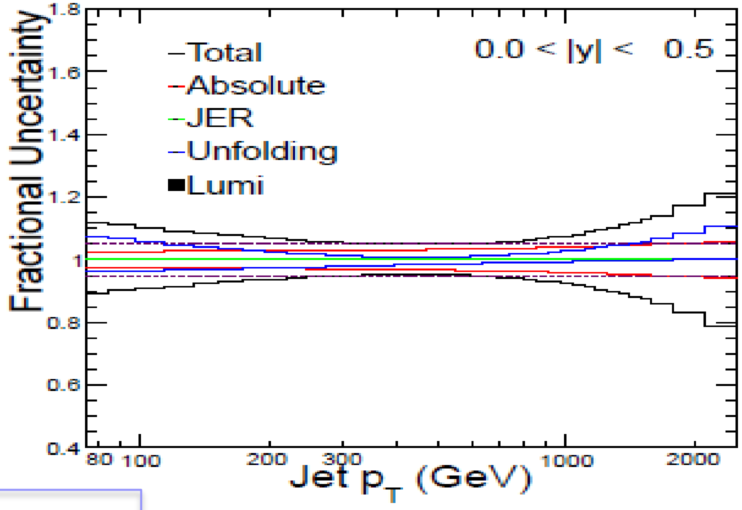
- The correction factor derived is calculated as: $C^{\mathrm{NP}}_{\mathrm{NLO}} = \frac{\sigma_{\mathrm{NLO+PS+HAD+MPI}}}{\sigma_{\mathrm{NLO+PS}}}$ where the numerator is the cross section with parton showering, hadronization and multiparton interaction taken into account and the denominator is the cross section without hadronization and multiparton interactions included.

- The NP correction factor is multiplied with the theoretical NLO prediction to provide the particle level theoretical prediction

Inclusive jet experimental uncertainty

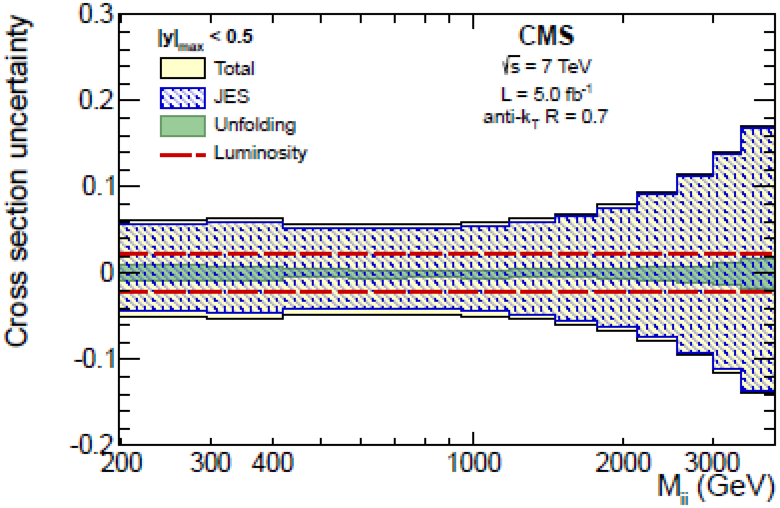


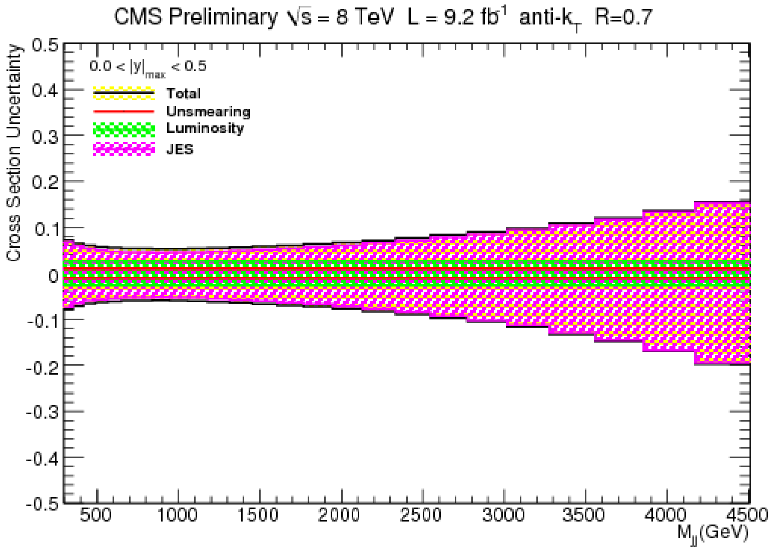
7 TeV



8 TeV (Preliminary)

Dijet experimental uncertainty

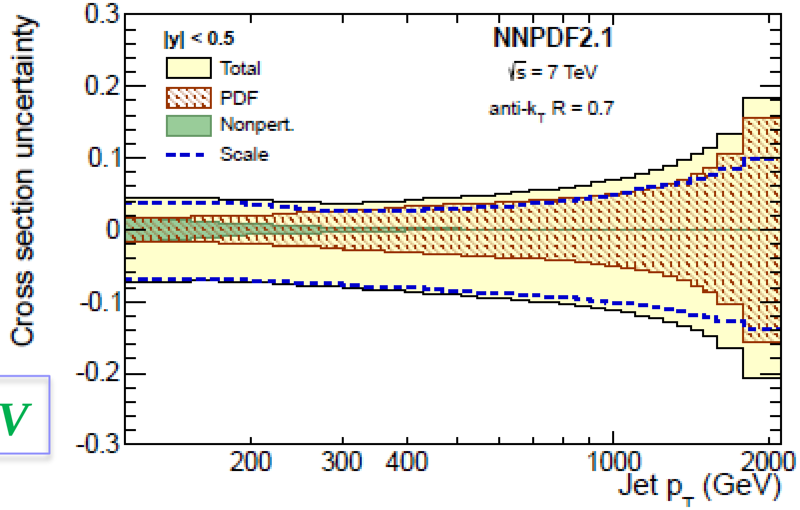


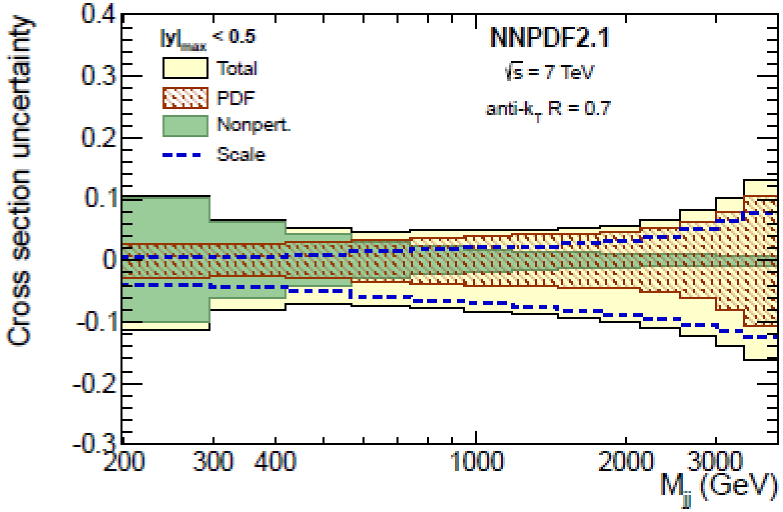


Inclusive jet theoretical uncertainty

Dijet theoretical uncertainty

7 TeV





8 TeV (Preliminary)