SM@LHC 2013

Jet measurements at LHC

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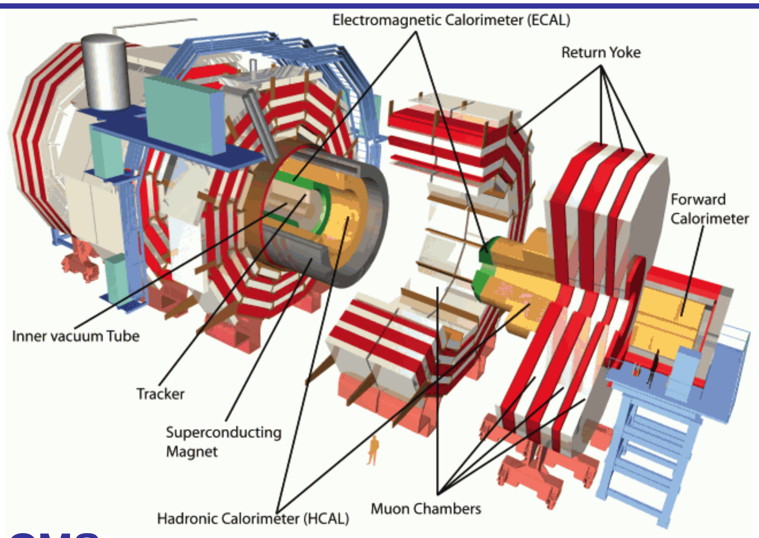
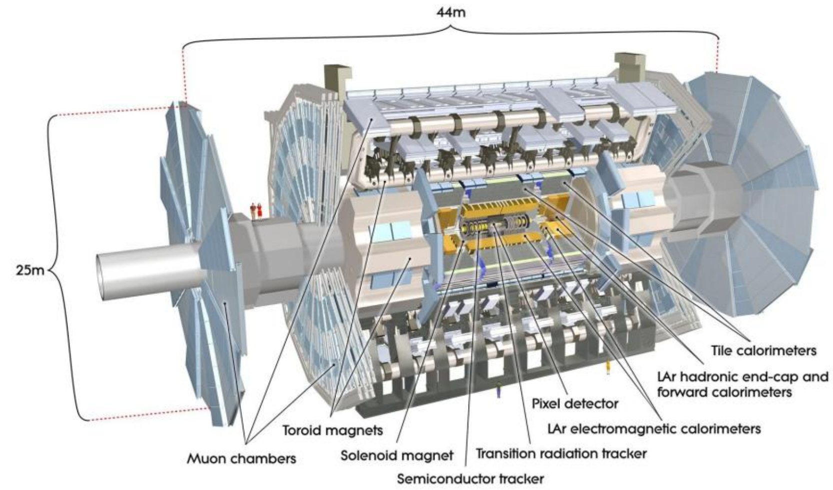
(on behalf of the CMS and ATLAS Collaborations)

Outline

- **Introduction**
- **Jet reconstruction**
- **Jet energy scale and resolution**
- **Jet measurements**
    - Inclusive jet cross section
    - Dijet cross section
    - Three to two jet ratio
    - Jet mass and substructure
    - kT splitting scales
    - Dijet angular distributions
- **Summary - Outlook**

The CMS and ATLAS Detectors





CMS

Magnetic field: 3.8 T

Pixels: σ/pT~ $1.5\cdot10^{-4}$pT(GeV)⊕0.005

Electromagnetic Calorimeter:
σE/E ≈ 2.9%/√E(GeV) ⊕0.5%⊕0.13GeV/E

Hadronic Calorimeter:
σE/E ≈ 120%/√E(GeV) ⊕ 6.9%

Muon Spectrometer:
σpT/pT ≈ 1% for low pT muons
σpT/pT ≈ 5% for 1 TeV muons

ATLAS

Magnetic field: 2.0 T

Pixels, Si strips & Straw tubes:
σ/pT~ $3.8\cdot10^{-4}$pT(GeV)⊕0.015

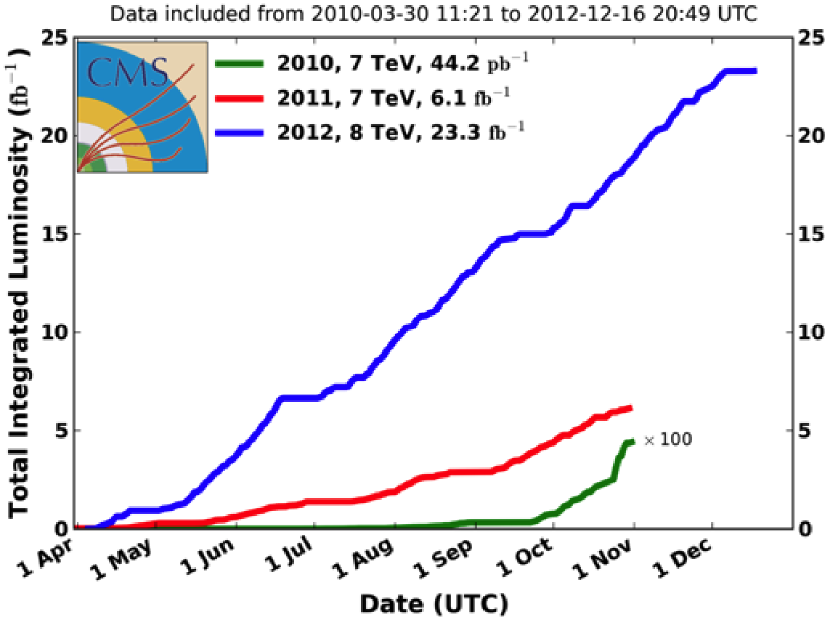
Electromagnetic Calorimeter:
σE/E ≈ 10%/√E(GeV)⊕0.7%⊕0.2GeV/E

Hadronic Calorimeter:
σE/E ≈ 60-100%/√E(GeV) ⊕ 3%

Muon Spectrometer:
σpT/pT <10 % up to 1 TeV muons

Data Collection

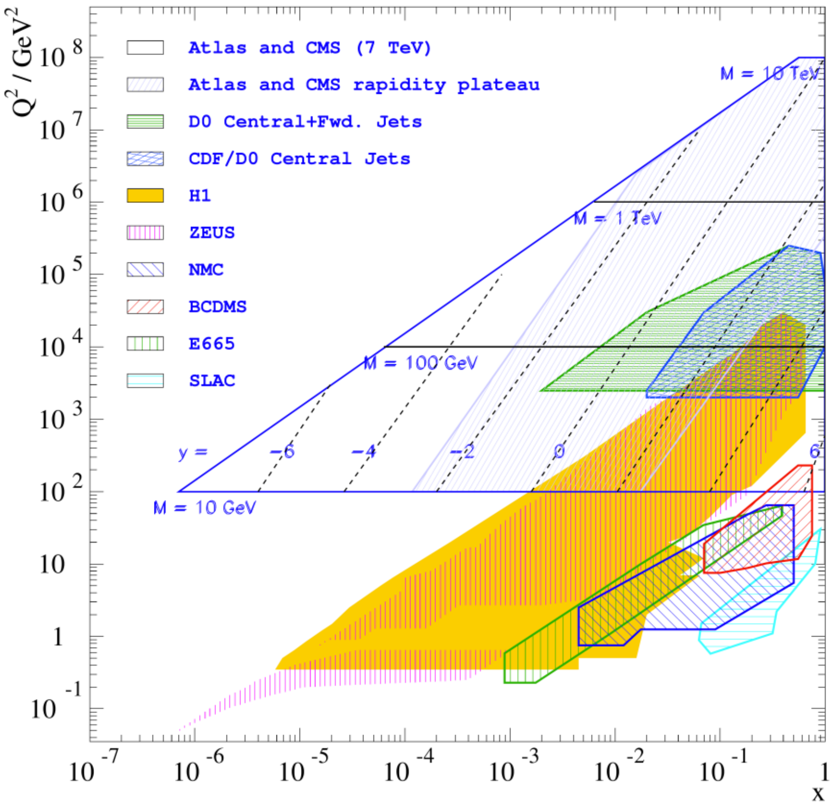
CMS Integrated Luminosity, pp



- **Big thanks to the LHC accelerator department for the excellent performance!**
- **Most of the measurements shown in this talk are from the 7 TeV running period but some new results from 8 TeV are also shown**
- **Public Results twiki of ATLAS and CMS at:**
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

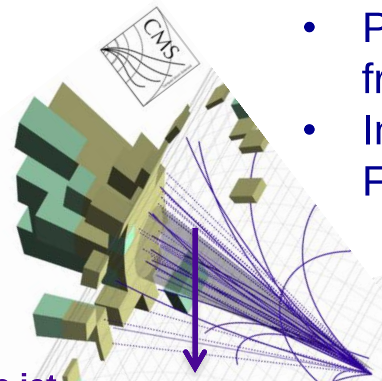
Physics Motivation

- **The jet measurements are important since they can be used to:**
  - Test the pQCD in an unexplored region
  - Constrain parton distribution functions (PDFs), differentiate between PDF sets, measure the strong coupling constant, study parton showering, initial and final state radiation and many other effects
  - Better tune Monte Carlo generators
  - Look for possible deviations from the Standard Model



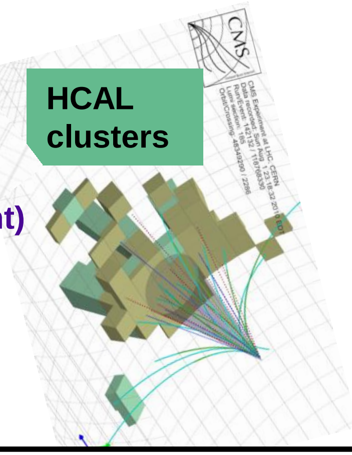
Jet Reconstruction

CMS
- Particle Flow Algorithm combines all information from several sub-detector systems
- Individual particles are reconstructed with Particle Flow Algorithm and then clustered into jets



complete jet
(All the visible particles in the event)

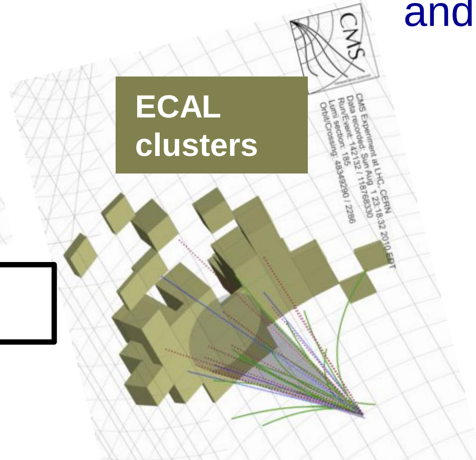
HCAL+ECAL+Tracker info
μ, $e^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, p, K^0, π^0,…



HCAL clusters

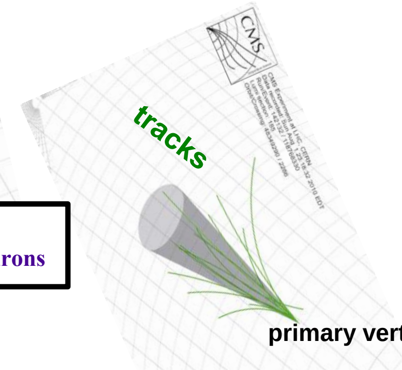
HCAL info
Charged and neutral hadrons

ATLAS
- Clustering of Calorimeter Towers composed of ECAL and HCAL energy deposits

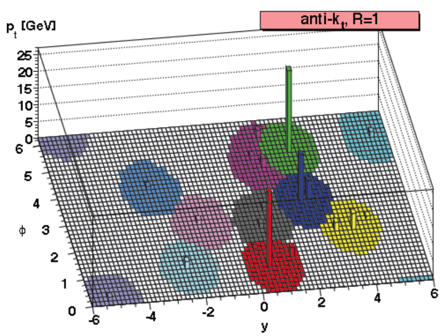


ECAL clusters

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



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



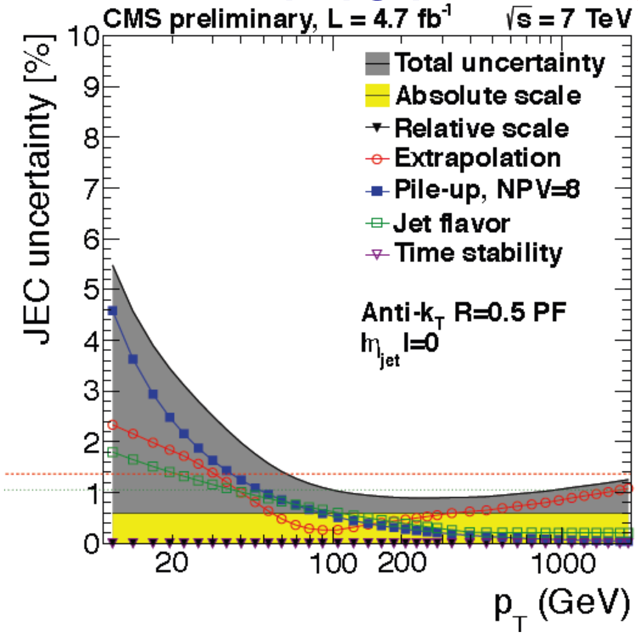
Anti-kt clustering algorithm
with R = 0.5 and 0.7 for CMS; with 0.4 and 0.6 for ATLAS
It is infrared and collinear safe, geometrically well defined, and tends to cluster around the hard energy deposits

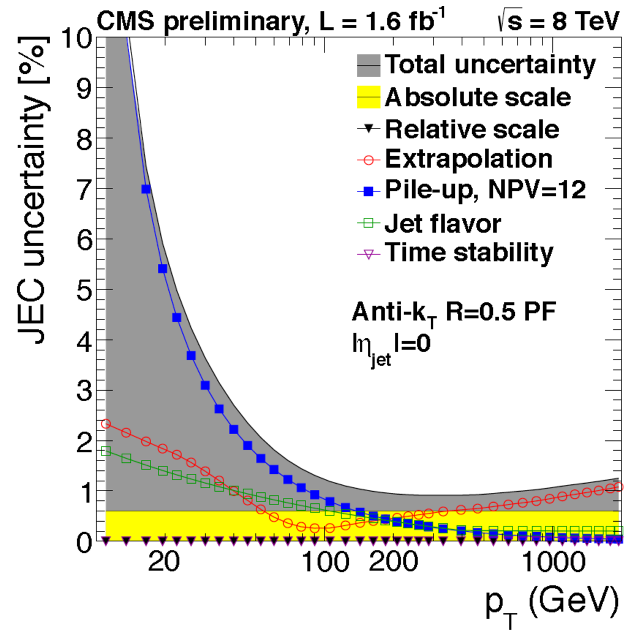
Jet Energy Scale

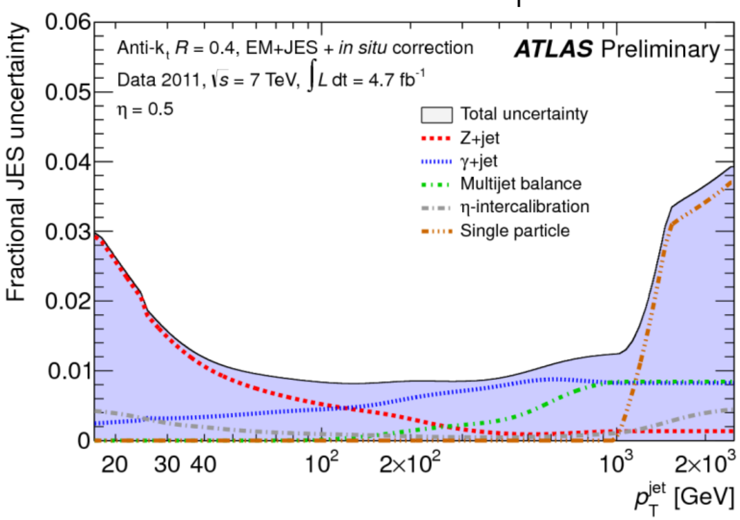
7 TeV

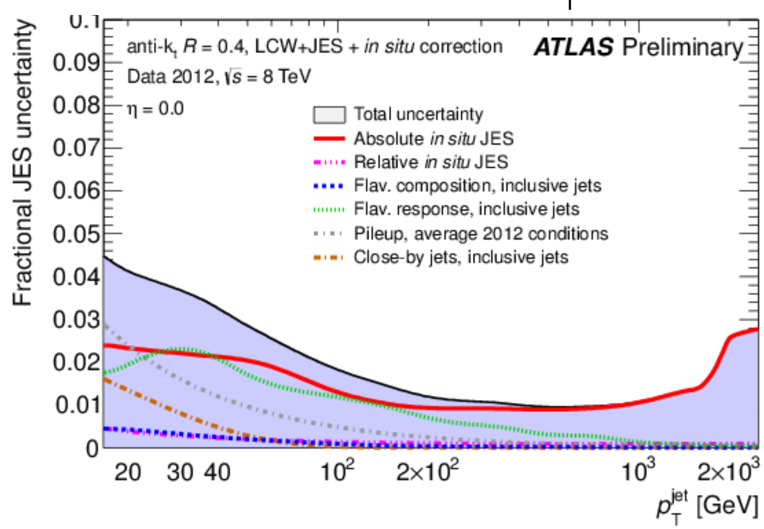
JEC at the 1% level

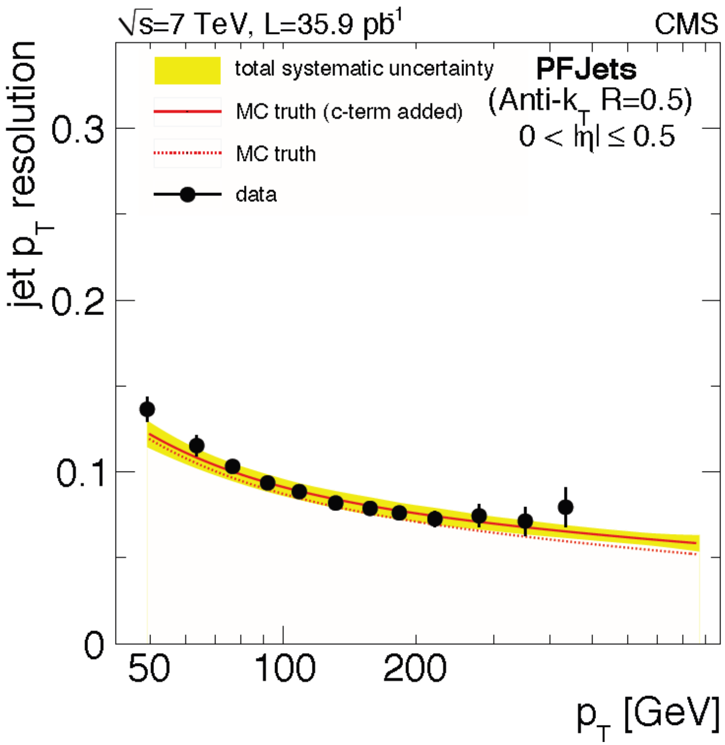
8 TeV



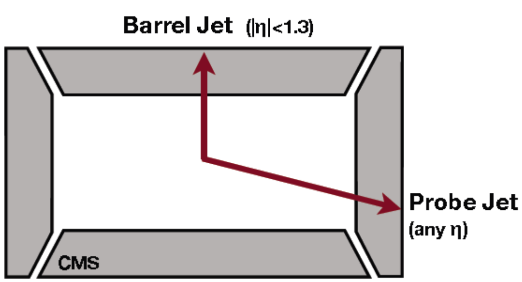


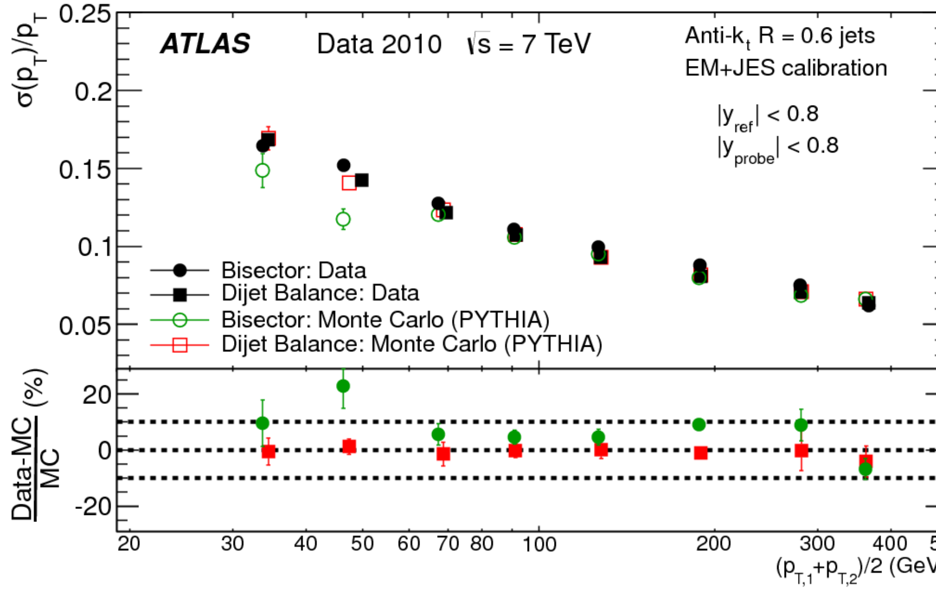




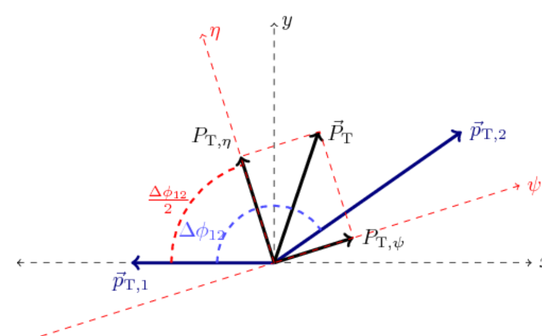


CMS: dijet asymmetry



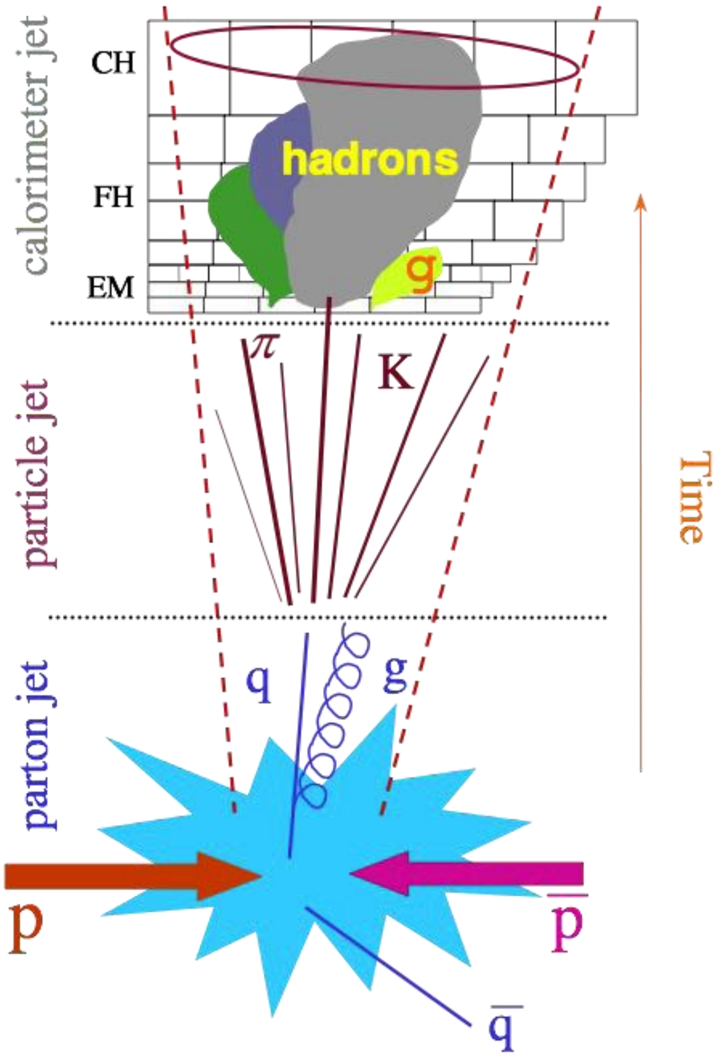


ATLAS: bisector method

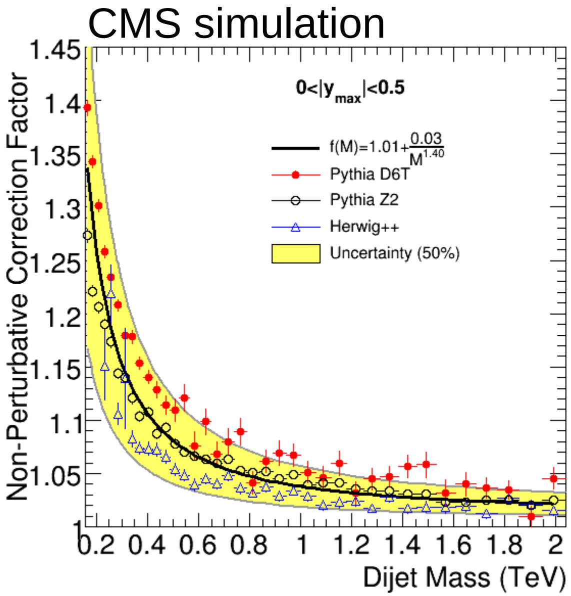


Theoretical Tools

- Perturbative QCD calculations @ NLO
  - NLOJet++/JETPHOX
  - fastNLO
- PDFs
  - CT10
  - MSTW2008
  - NNPDF2.1
  - HERAPDF1.5
  - ABKM09, ABKM11
- Non-perturbative corrections for multi-parton interactions and hadronization effects
- Parton showering effects (NLO Matrix Element MC (POWHEG) with PS matching)
- LO QCD Monte-Carlo generators
  - PYTHIA6, PYTHIA8
  - HERWIG++
  - ALPGEN
  - MADGRAPH-
  - MC@NLO
  - SHERPA



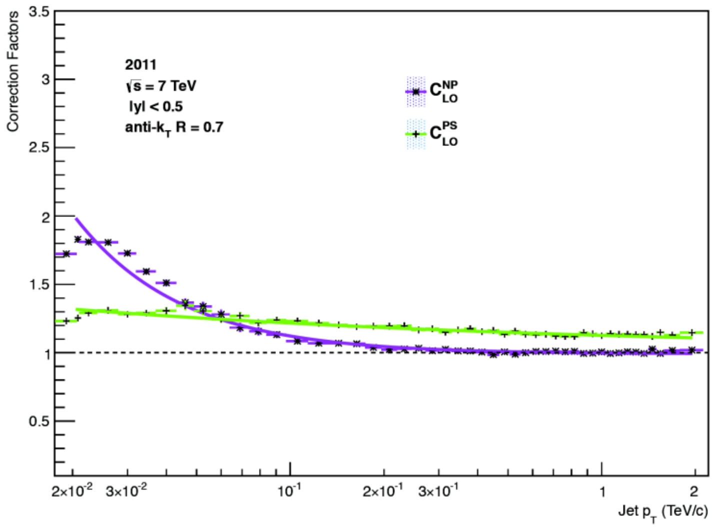
Non-Perturbative Corrections

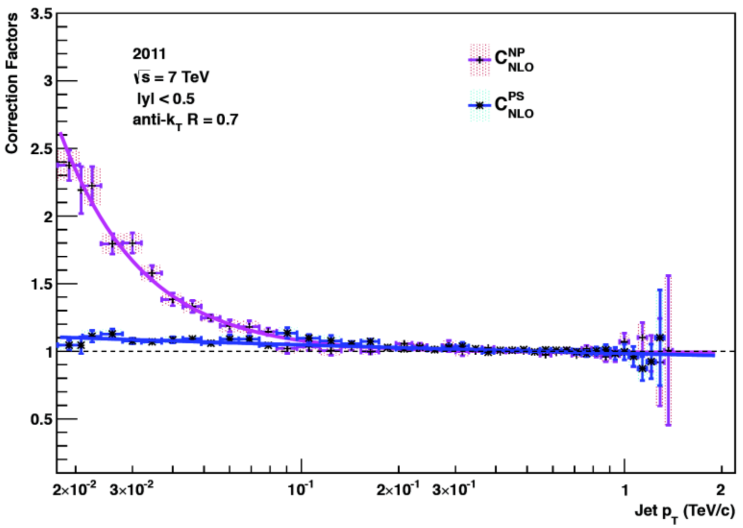


$$\text{NP correction} = \frac{\text{predictions with nominal settings}}{\text{predictions with MPI and Hadronizat ion switched off}}$$

- NP corrections are derived from LO simulation and applied to NLO calculation to account for:
  - Multi-parton interactions (MPI)
  - Hadronization effects
- Assumptions:
  - Effects the same between LO and NLO
  - Parton showering effects small at NLO

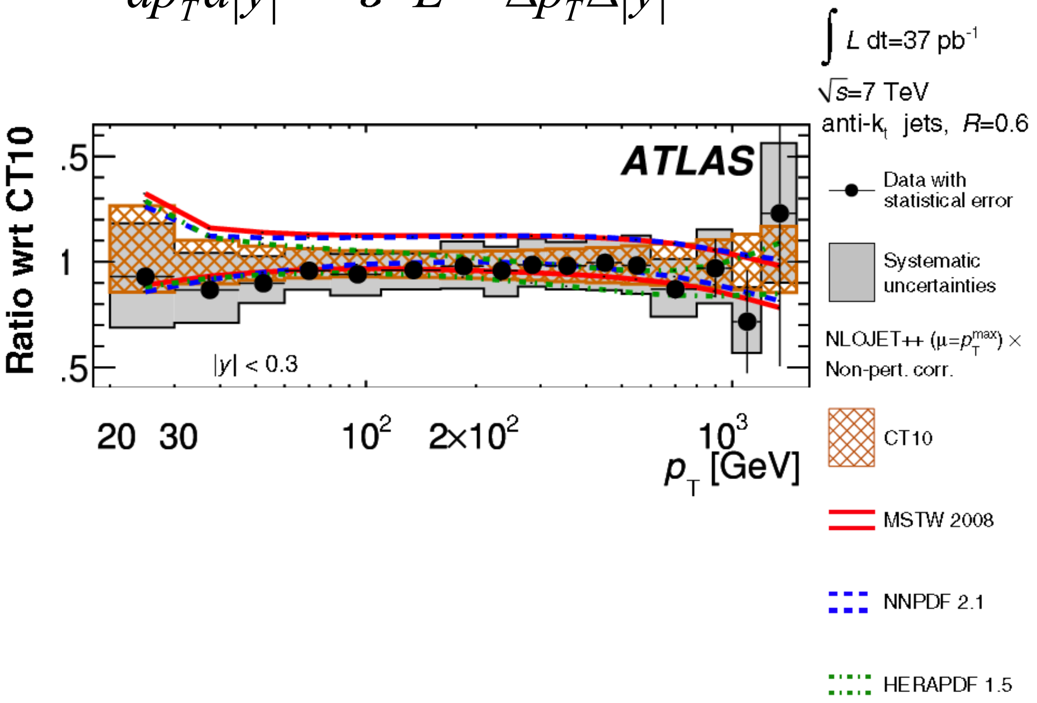
Figures courtesy of S.Dooling *etal.*, arXiv:1212.6164

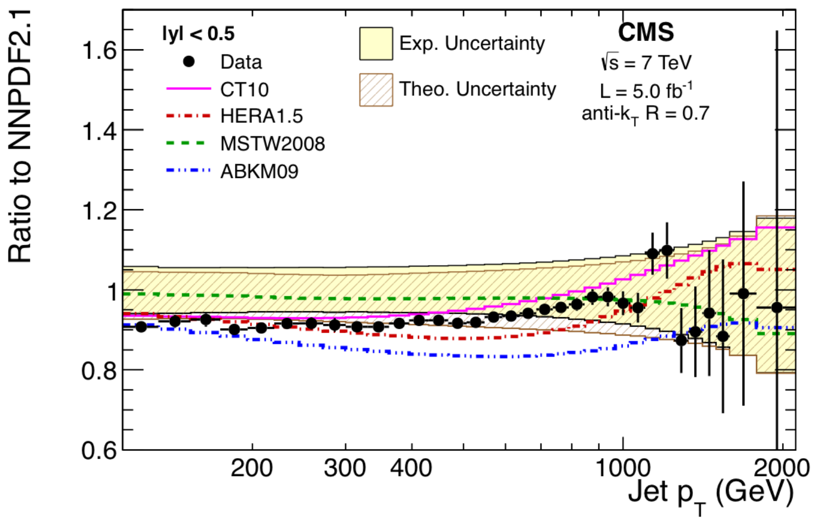




Inclusive Jet Cross Section

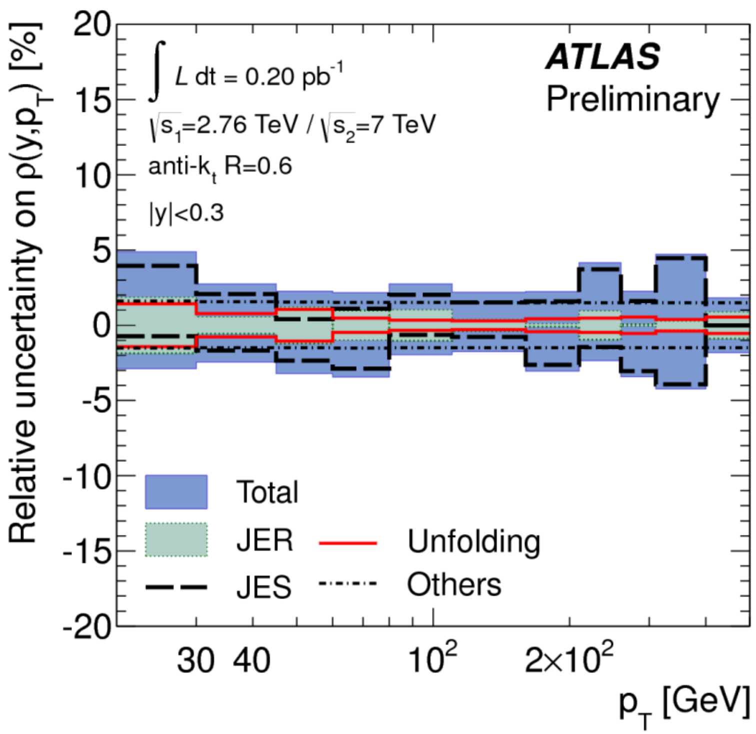
$$\frac{d^2\sigma}{dp_T d|y|} = \frac{C_{unfold}}{\varepsilon \cdot L} \cdot \frac{N_{jets}}{\Delta p_T \Delta |y|}$$

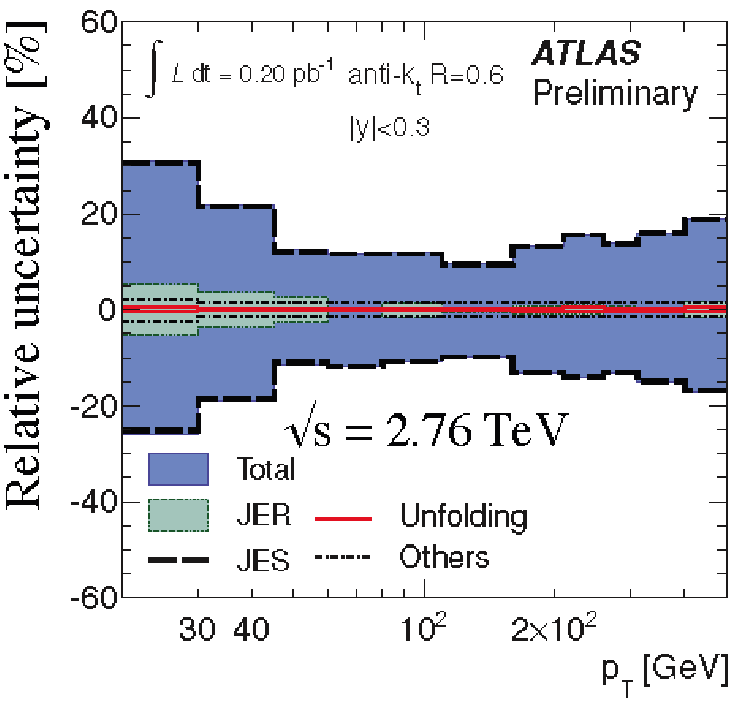




- Agreement between ATLAS and CMS (given the different cone sizes) and agreement between data and theory
- Some PDFs describe the data better than others: these measurements are useful for PDF tuning and for constraining PDFs

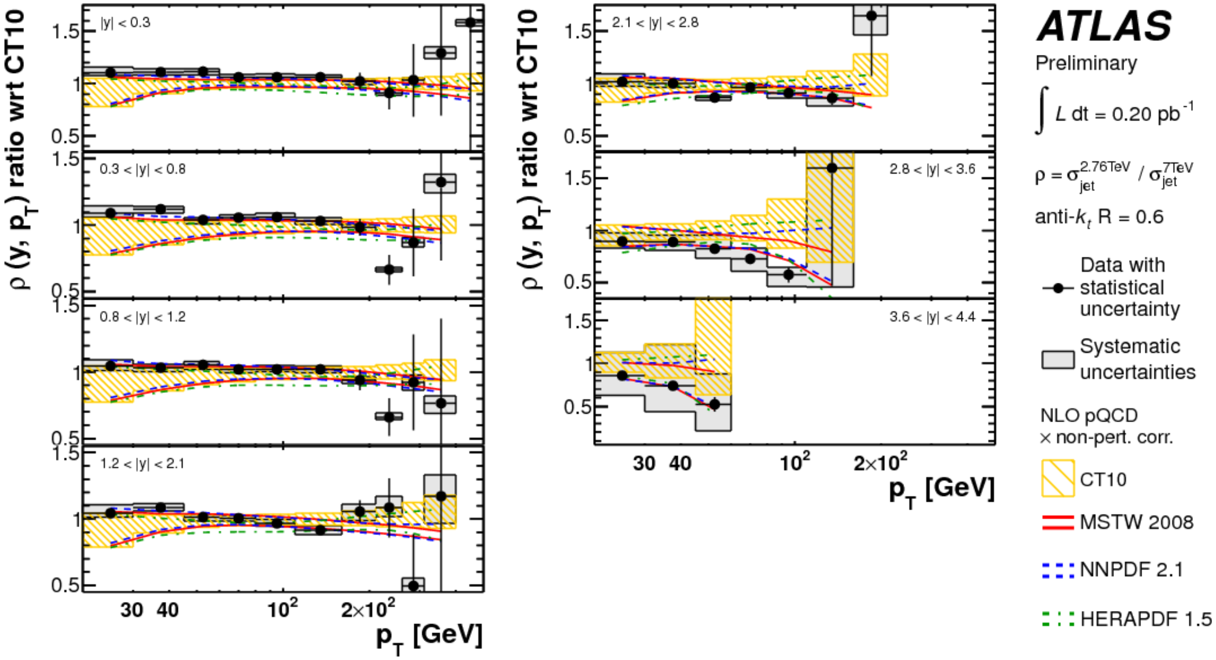
Ratio of Inclusive Cross Sections 2.76 / 7 TeV

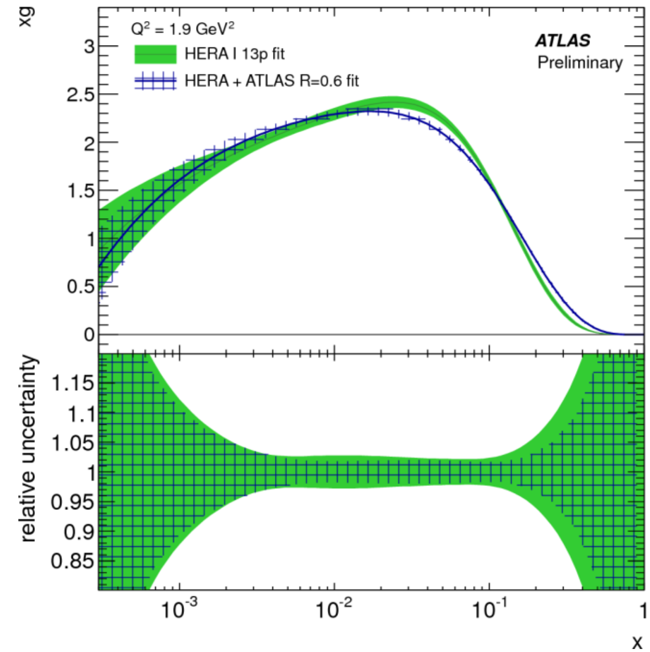




- Most of the experimental uncertainties cancel out in the ratio

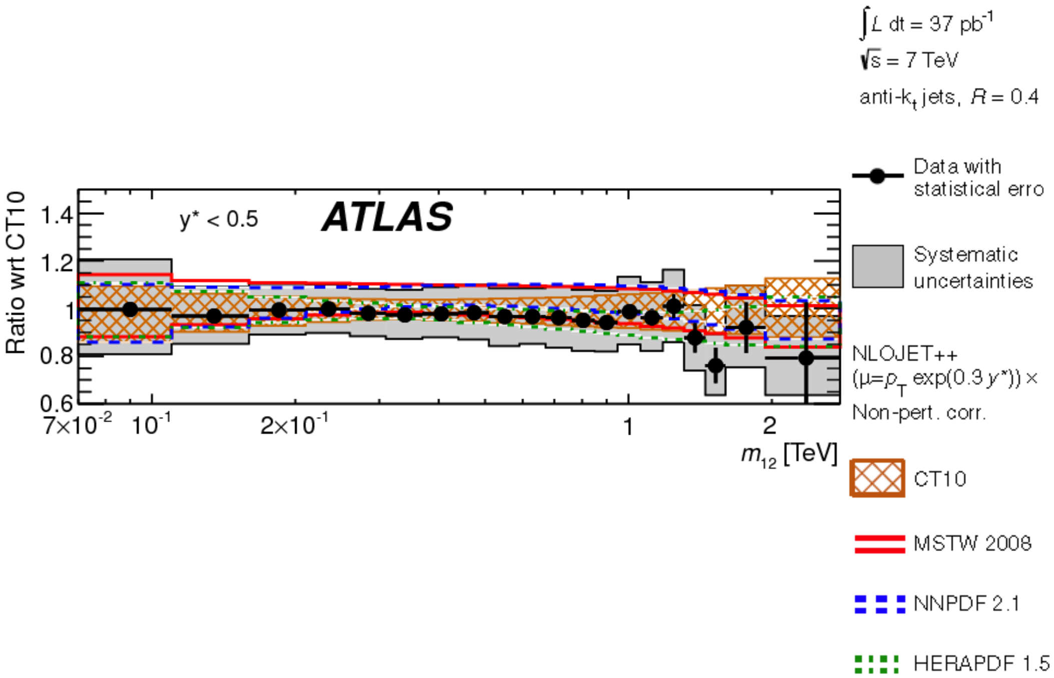
Ratio of Inclusive Cross Sections 2.76 / 7 TeV

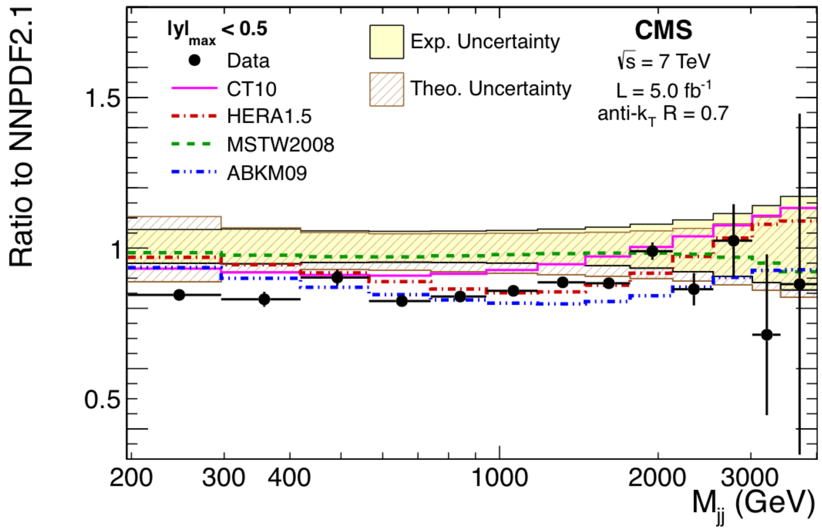




- Ratios of cross sections useful in order to constrain and differentiate between different PDF sets

Dijet Cross Section

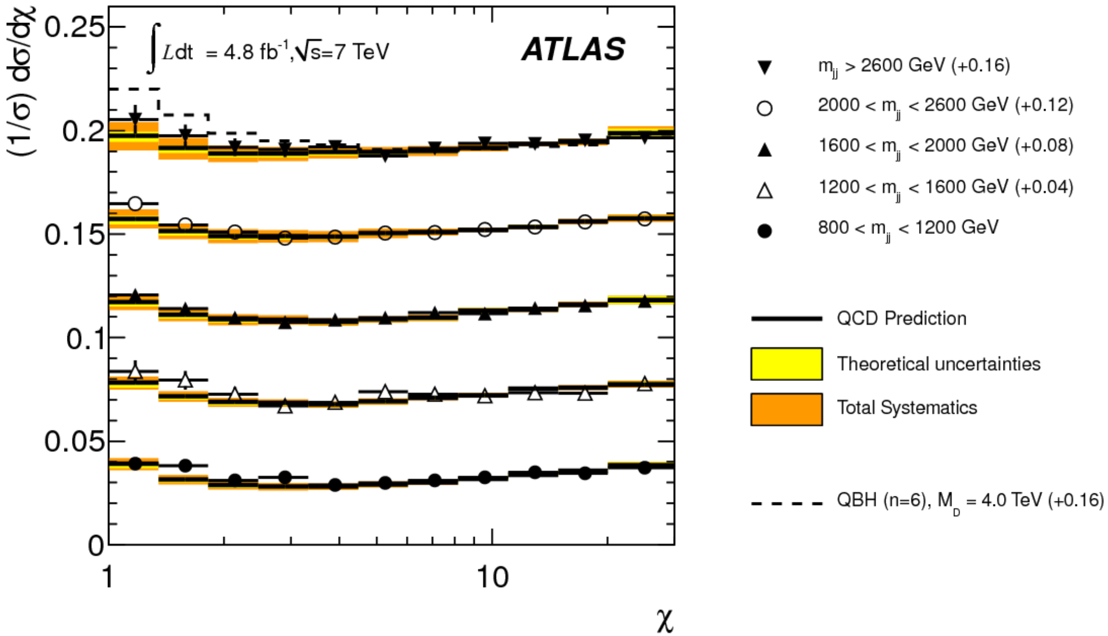


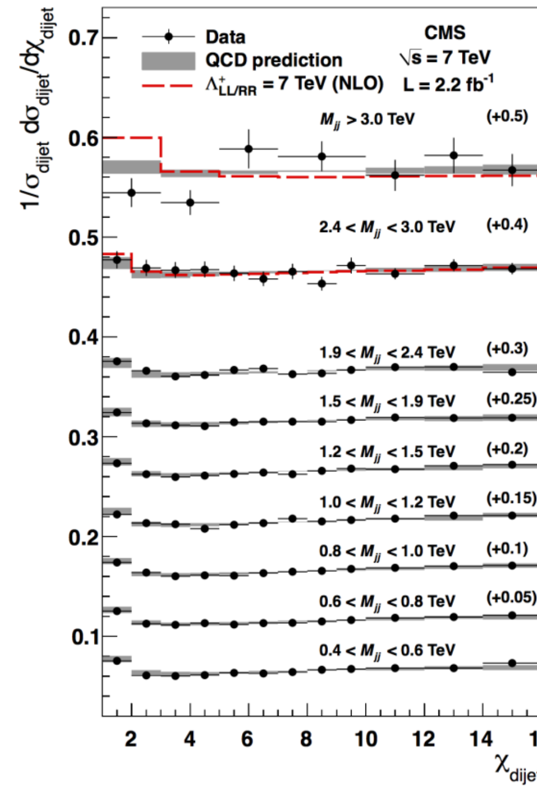


- Results between ATLAS and CMS consistent given different cone sizes and y definitions
- Results in agreement with expectations and similar trends observed as with the inclusive jet data

Dijet Angular Distributions

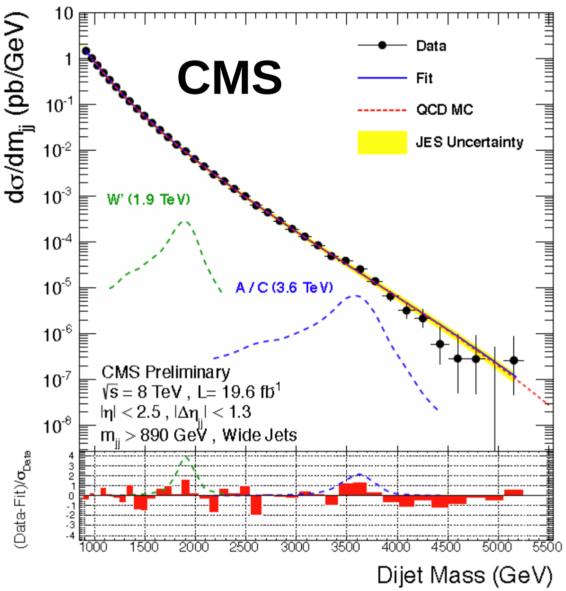
$$\chi = e^{|y_1 - y_2|} \approx \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

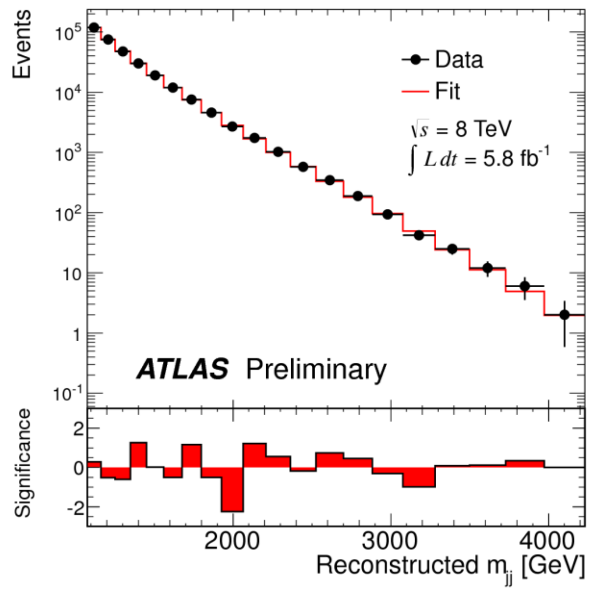


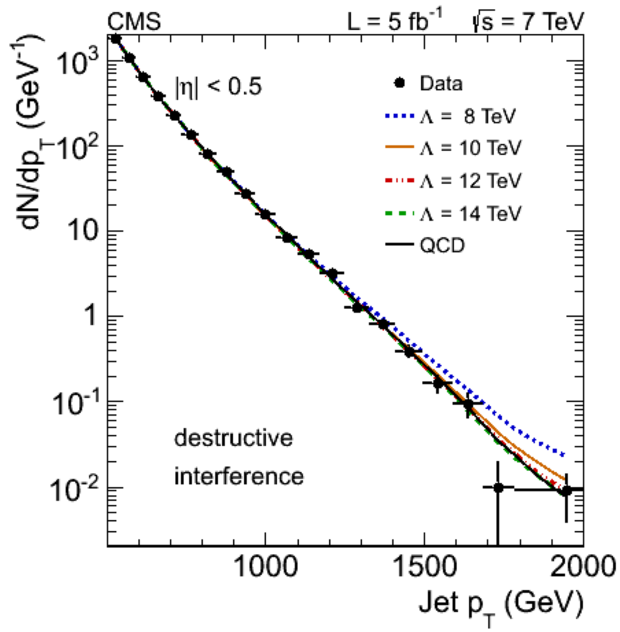


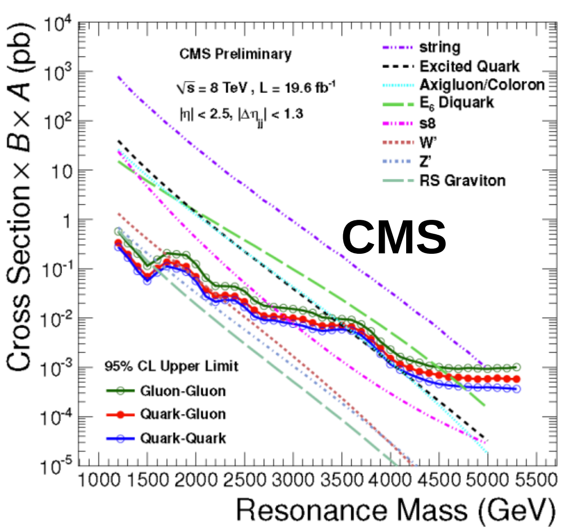
- χ chosen since QCD flat as a function of it
- Experimental uncertainties dominated by jet resolution and relative (vs η) JES (absolute cancels)
- Theoretical uncertainties dominated by non perturbative corrections and renormalization scale
- **Good agreement between data and theory. Highest mass bins sensitive to contact interactions**

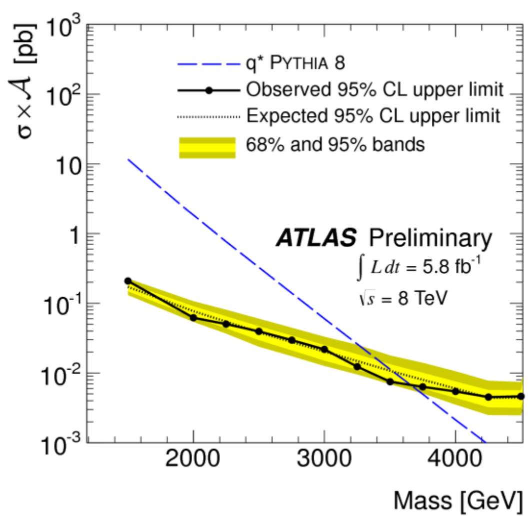
New physics searches with the inclusive and dijet spectra





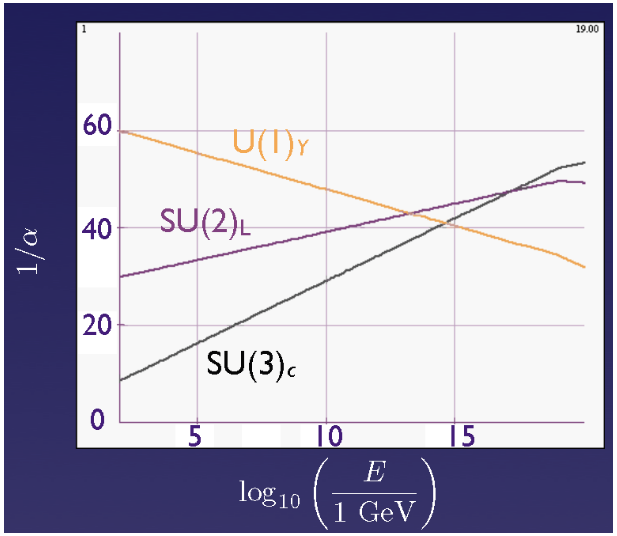


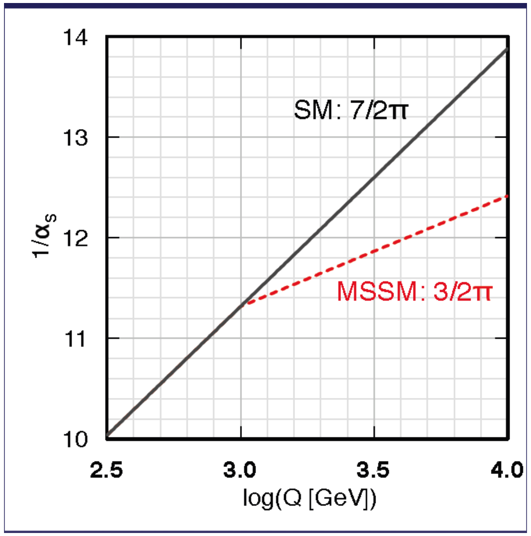




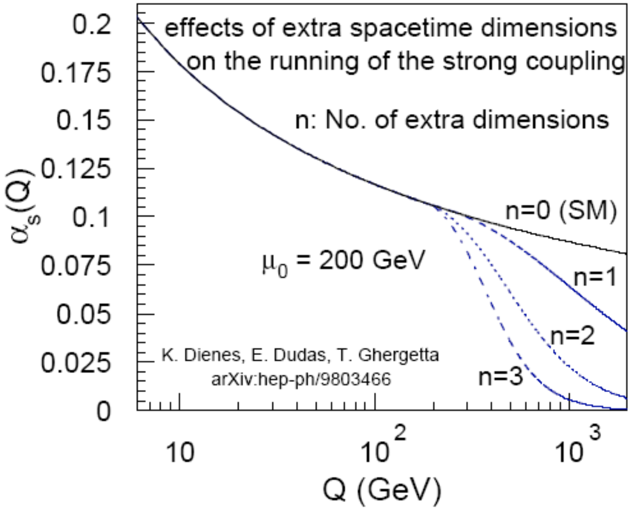
Dijet and Inclusive jet cross sections used also to search for new physics

The strong coupling constant





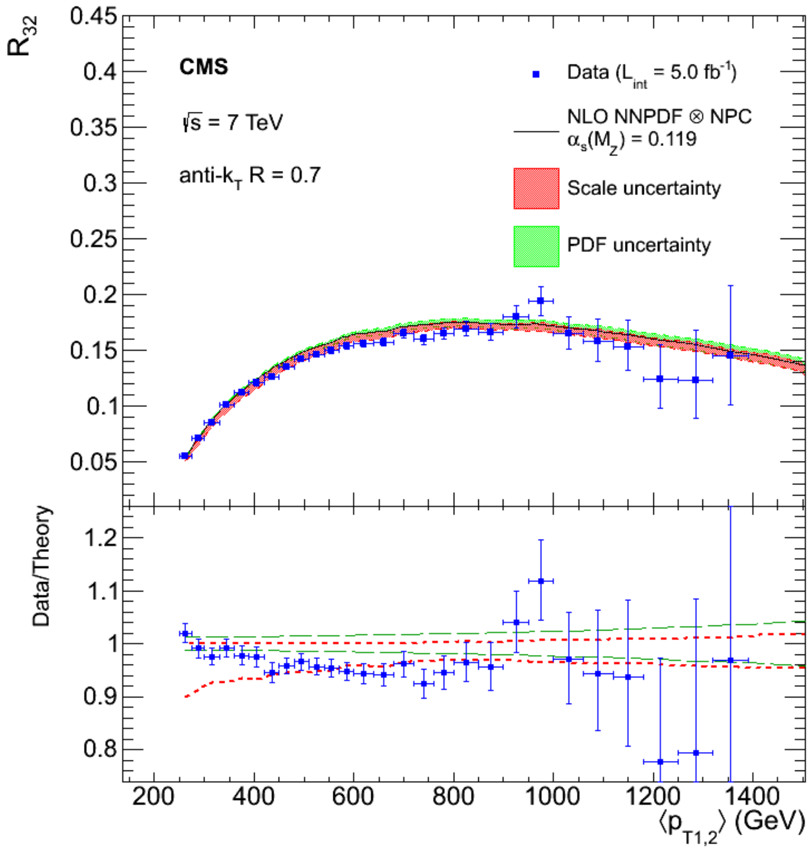
C.Quigg arXiv:1301.4905

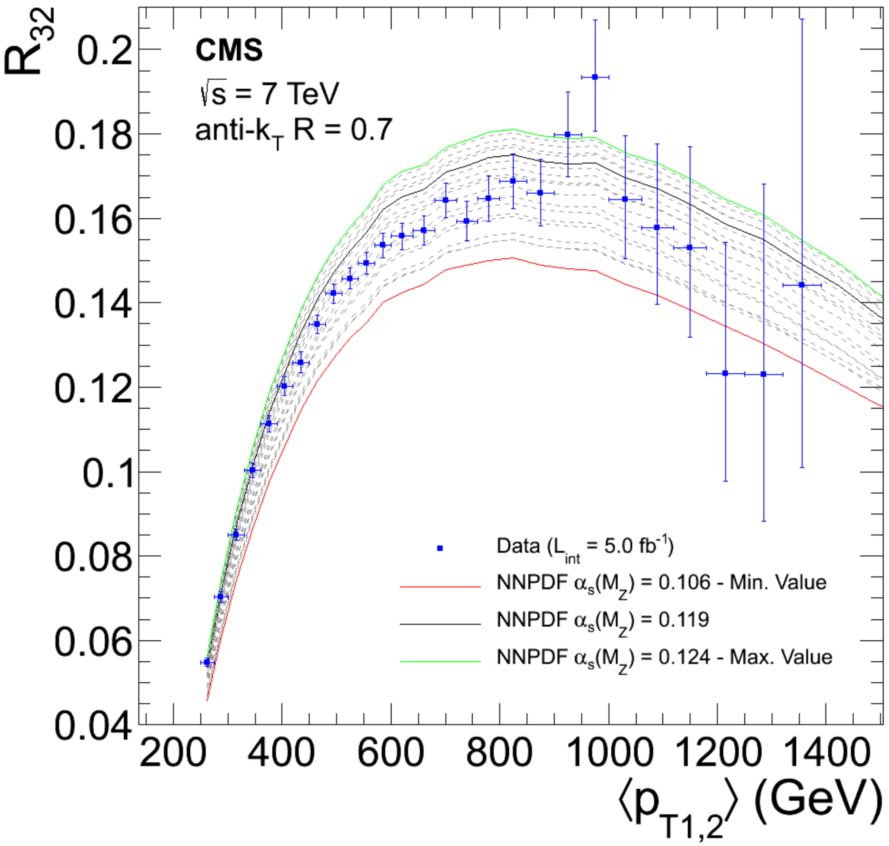


- The strong coupling constant is the fundamental QCD quantity
- Running of α_S sensitive to new physics

Three to two jet ratio and α_S

CMS

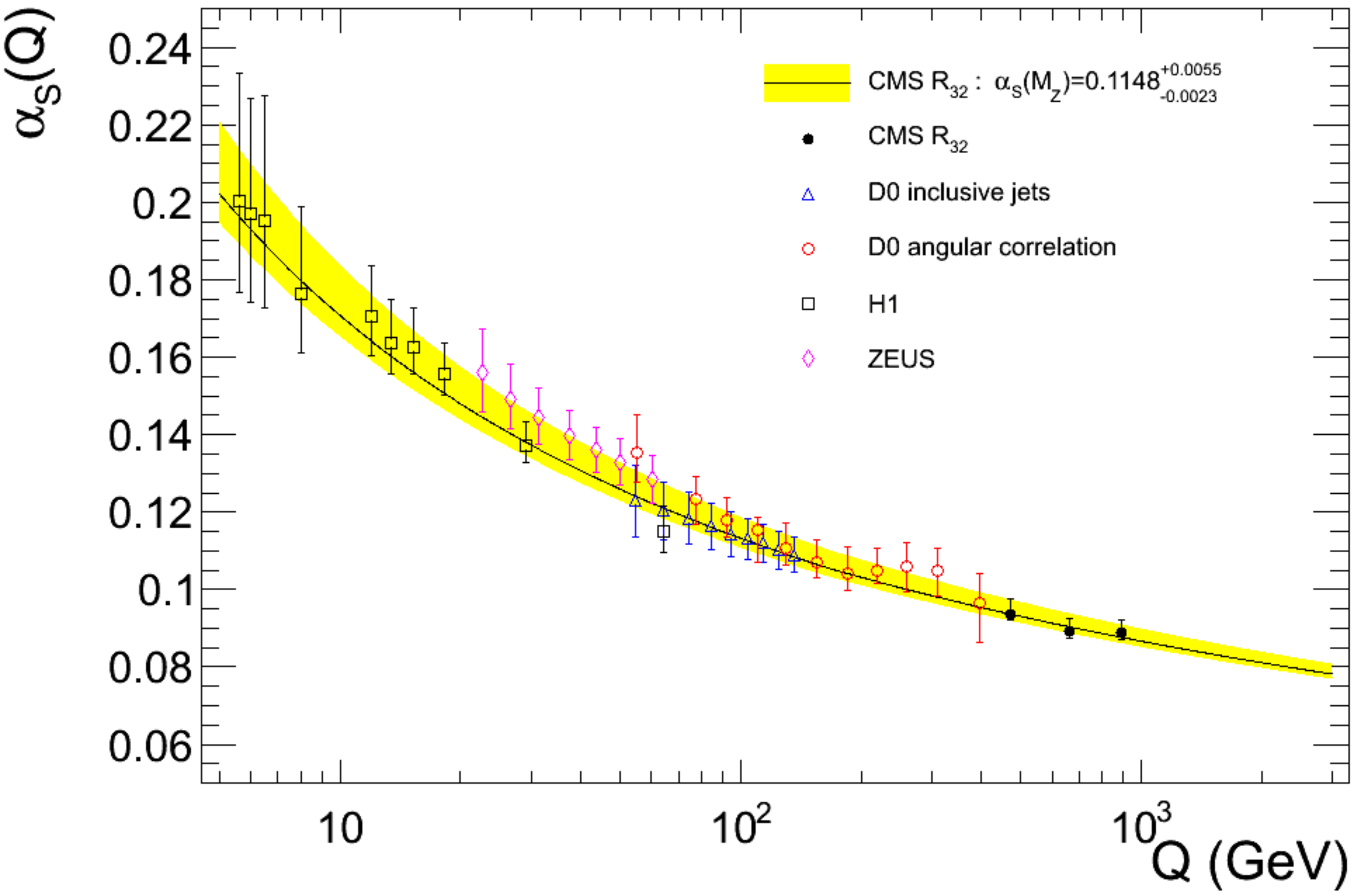




- Many systematic uncertainties cancel out in the ratio
- The ratio is sensitive to the strong coupling constant

Three to two jet ratio and α_S

CMS



First and very precise measurement at the TeV scale

$$\alpha_S(M_Z) = 0.1148^{+0.0055}_{-0.0023}$$

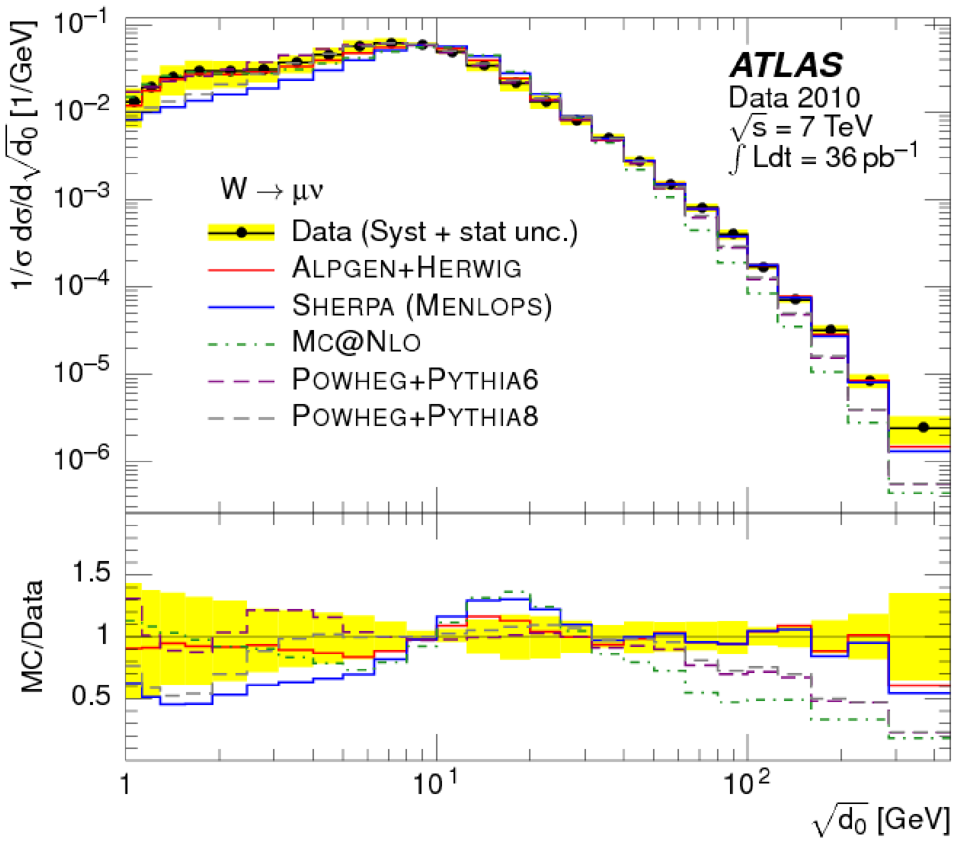
ATLAS

$\sqrt{d_0}$ ~ the transverse momentum of the highest-p_T jet

$$d_{ij} = \min(p_{T_i}^2, p_{Tj}^2)\frac{\Delta R^2_{ij}}{R^2}, \Delta R^2_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = p_{T_i}^2$$

$$\sqrt{d_k} = \min(\sqrt{d_{ij}}, \sqrt{d_{iB}})$$

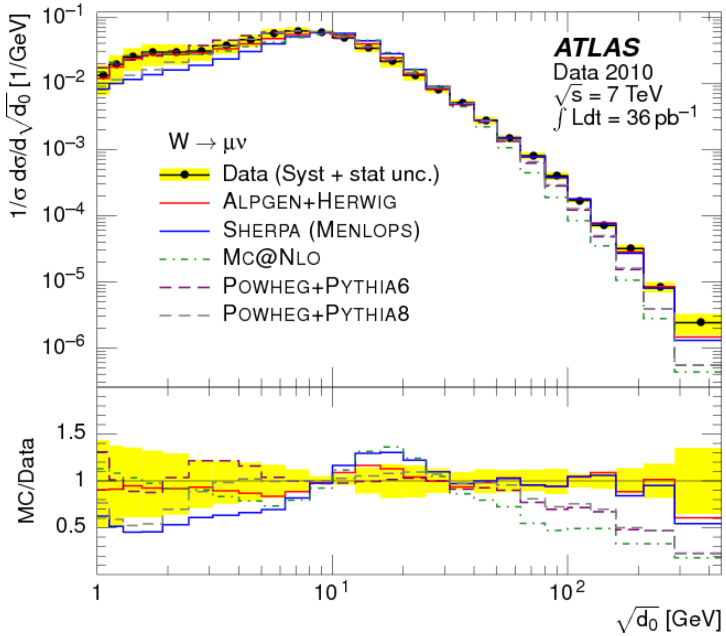


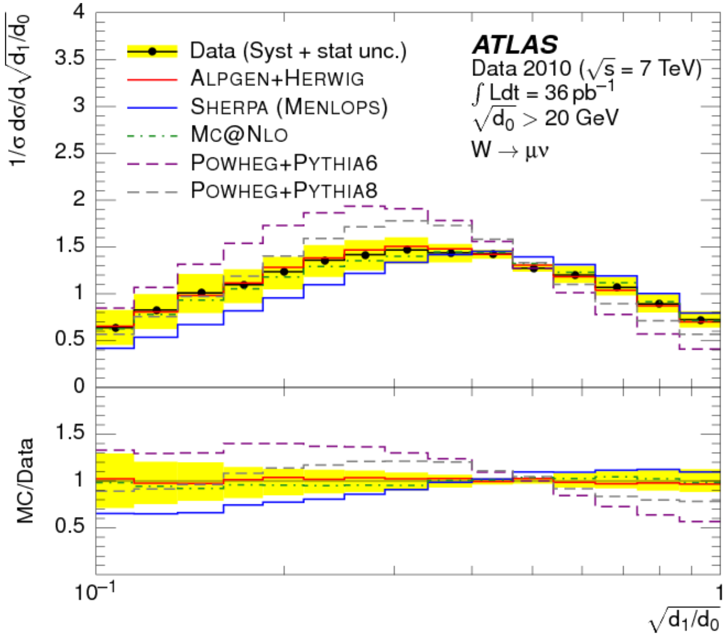
- Each step of the k_T algorithm identifies the parton pair most likely produced by QCD interactions and hence mimics the reversal of QCD evolution

- Aim of measurement is to improve theoretical modeling of QCD effects

- The $\sqrt{d_k}$ contain information about the p_T spectra and substructure of jets

ATLAS

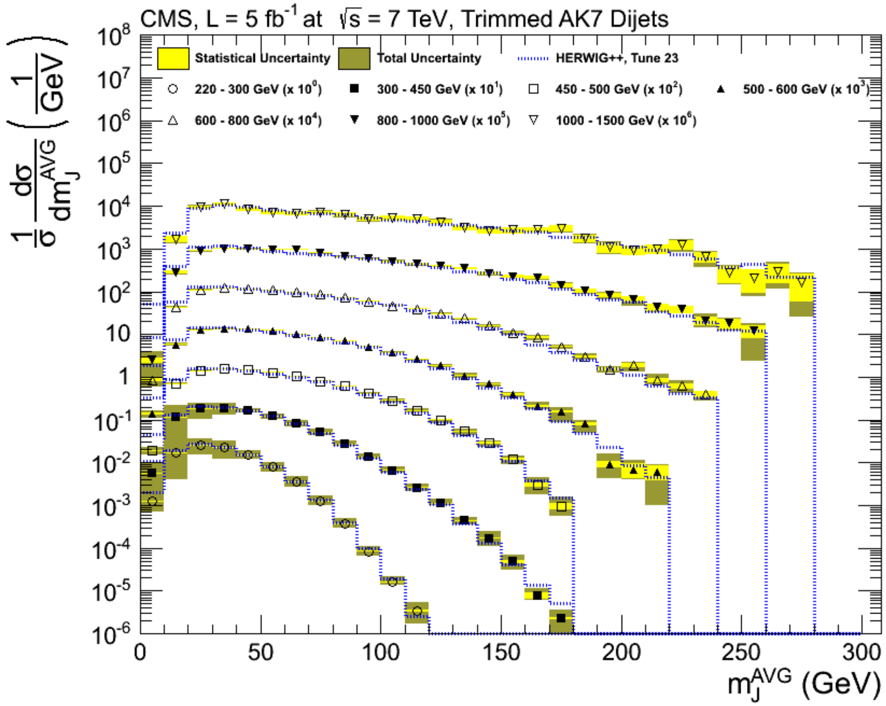


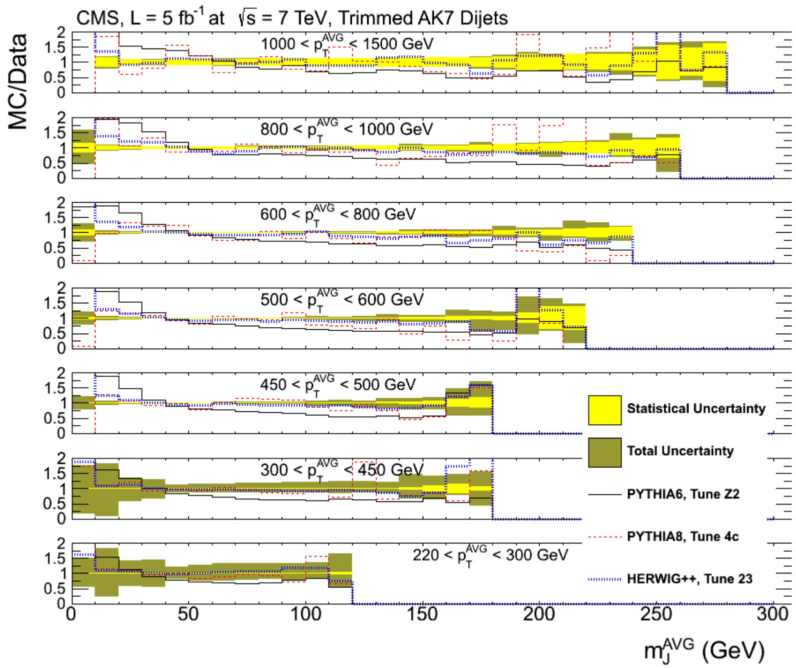


- “Hard” region ($\sqrt{d_k}$ > 20 GeV) dominated by perturbative QCD effects. “Soft” region dominated by MPI and hadronization effects
- Hard tails of distributions better described by the multi-leg generators Alpgen+Herwig, Sherpa
- In the soft regions of the splitting scales, larger variations between all generators become evident

Jet mass and substructure

CMS





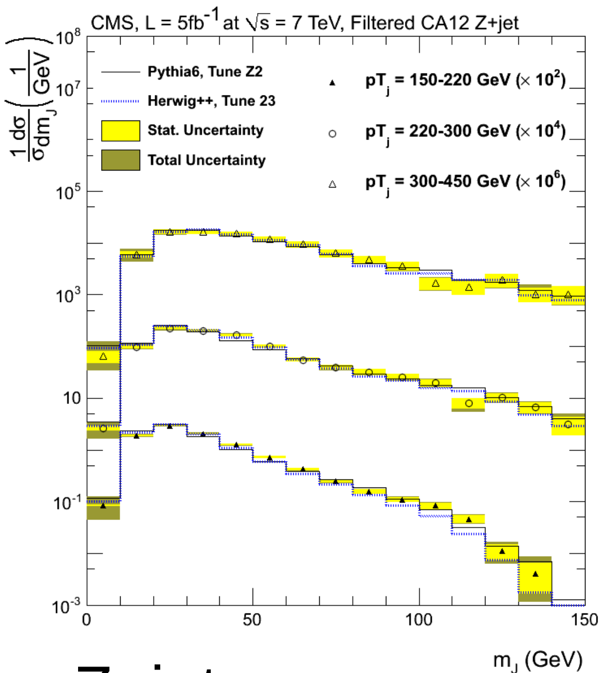
- Jet mass can discriminate between massive particles (SM or new physics) decaying to jets from QCD
- Jet “grooming” techniques are designed to identify jets from the decay of heavy boosted particles as opposed to quark/gluon initiated jets with large mass
- These techniques need to be tested and studied on real data

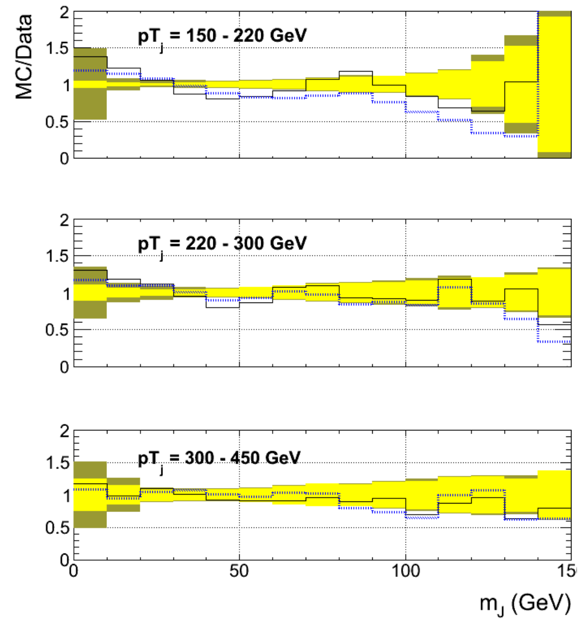
Jet mass and substructure

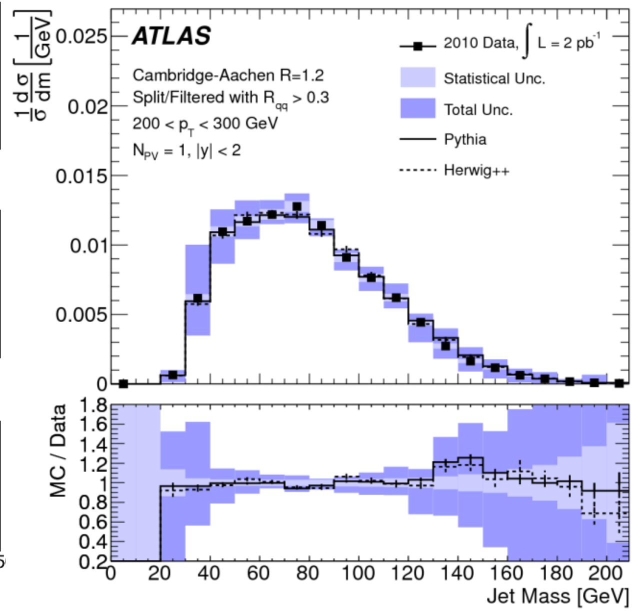
CMS

Cambridge-Aachen Algorithm R=1.2
MCs used: Pythia, Herwig++

ATLAS







Z+jets

Jets

- CMS: Better agreement with MC using V+jets events, pointing to better simulation response for quark-originated jet w.r.t. gluon ones
- ATLAS and CMS: Slight differences perhaps due to different running conditions (for example pileup)

Summary - Outlook

- With excellent understanding of jet reconstruction and calibration we are entering a precision QCD measurement era at LHC

- Measurements with jets are being used to:
  - test new physics models
  - constrain and tune PDFs
  - extract the strong coupling constant and test its running
  - study the effect of various jet algorithms

- The CMS and ATLAS results are in agreement. There is ongoing work on "standardizing" many aspects of the measurements (like cone-sizes, bin-sizes etc) in order to further facilitate comparisons and common usage

- There are many ongoing analyses with the 8 TeV data so stay tuned!