The Latest QCD Results from pp Collisions at CMS

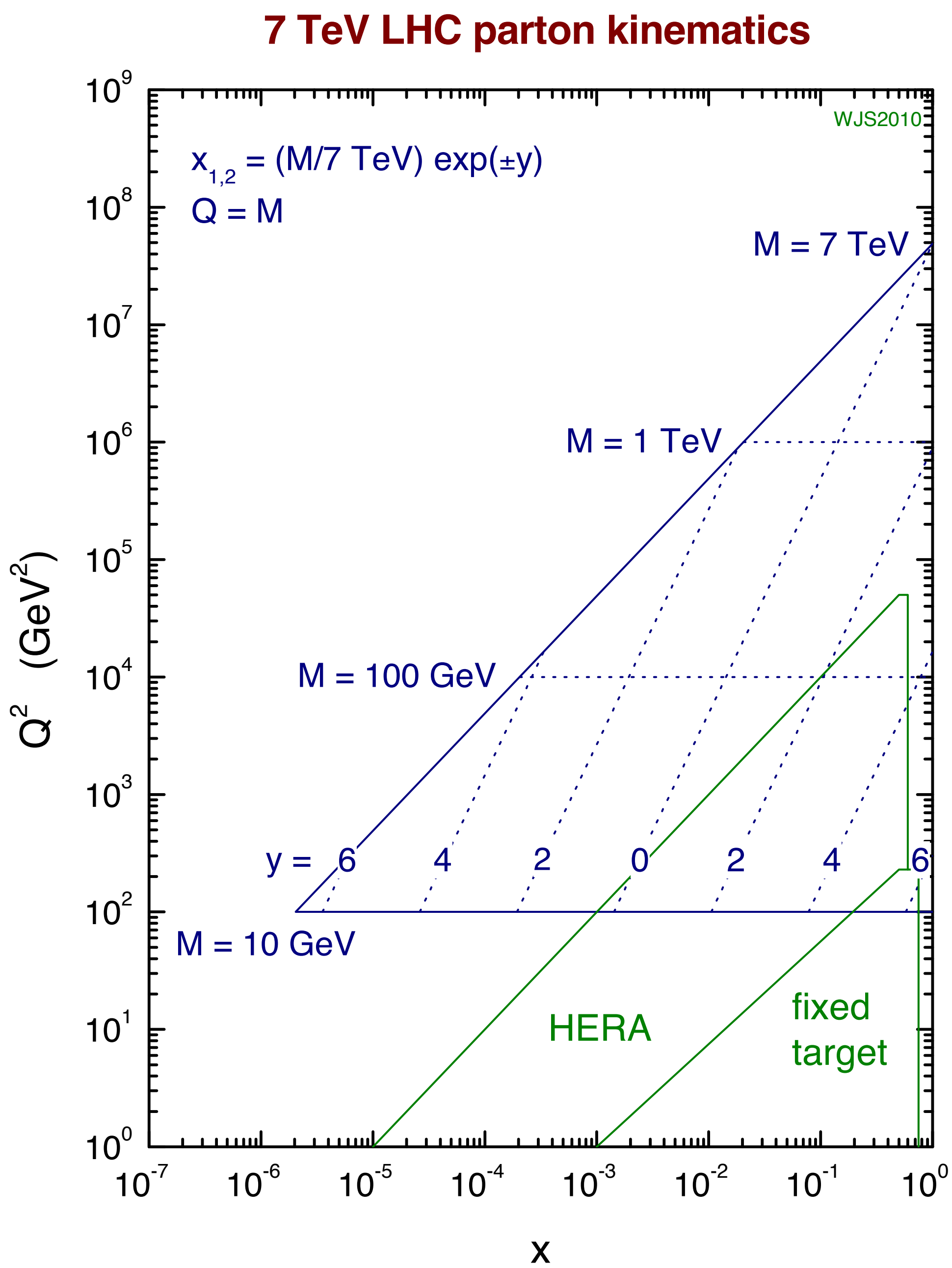
Bora Isildak
Ozyegin University ISTANBUL

Will try...

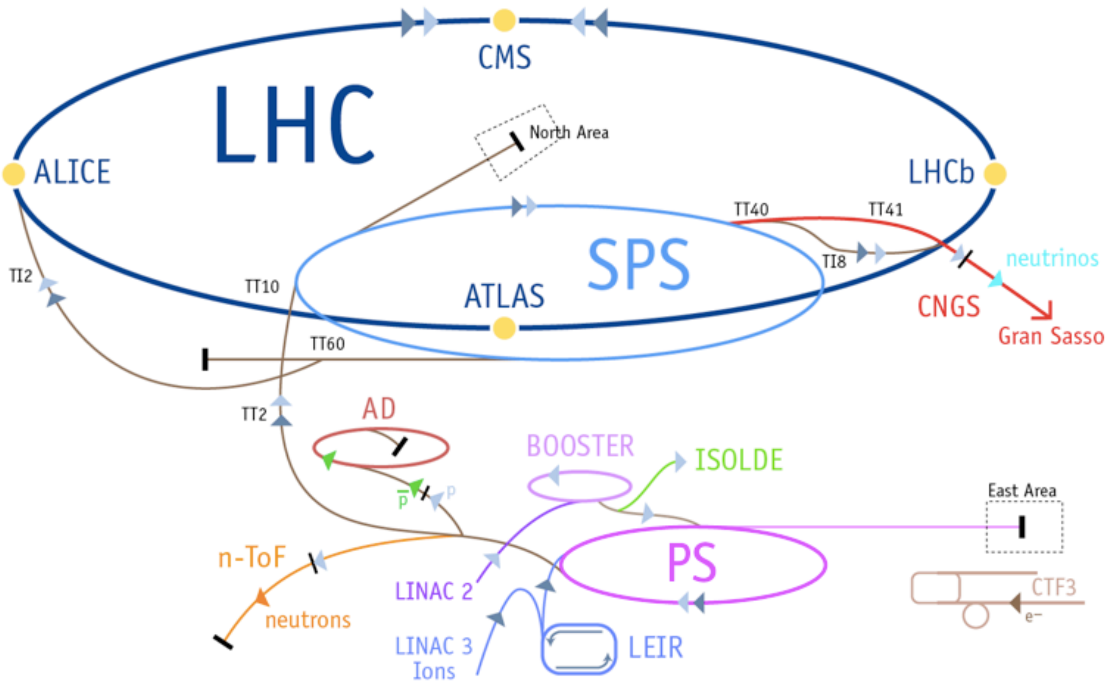
- Introduction
- CMS Experiment (Quick)
- Tools For Theory Predictions
- Non-Perturbative Corrections
- Jet Reconstruction and Calibration
- Inclusive Jet Cross Section
- Dijet Production
- 3-Jet to 2-Jet Ratio
    - Determination of Strong Coupling Constant
- Conclusions
- References

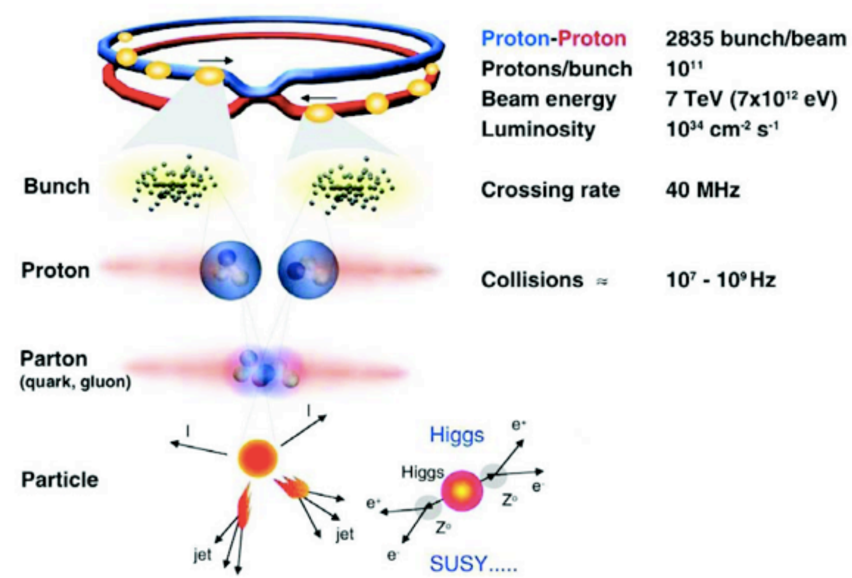
Introduction

- QCD processes are dominant in pp collisions at LHC
  - they affect all measurements;as signal or as background
  - must be understood in detail
- LHC *pp* collisions covers an extensive and unexplored kinematic region
- A more precise knowledge of QCD is important for new-physics searches
  - multijet production is important for SUSY searches



LHC

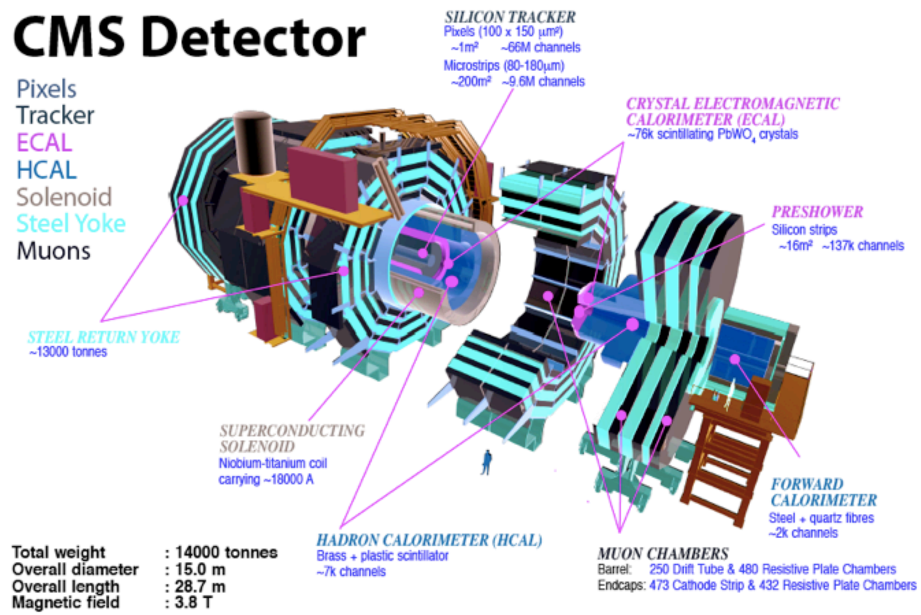


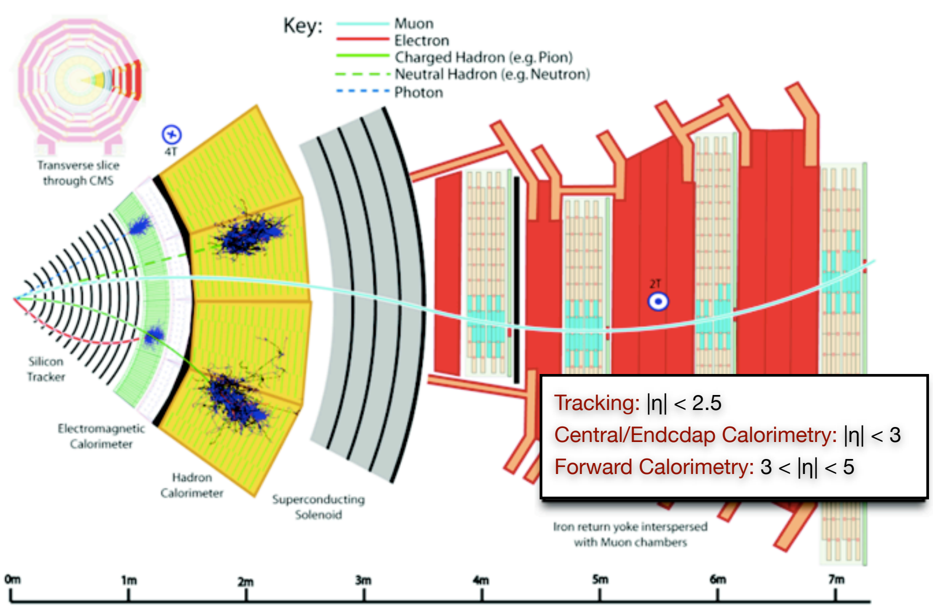


- The LHC is the world's largest and the most powerful collider, located in the existing LEP tunnel between 50 and 175 m underground with 26.7 km circumference long.
- The LHC hosts four main detectors (ALICE, ATLAS, CMS, LHCb).
- The first *pp* collision in March 2010, the first *Pb-Pb* collision in November 2010, and the first p-Pb collisions in September 2012

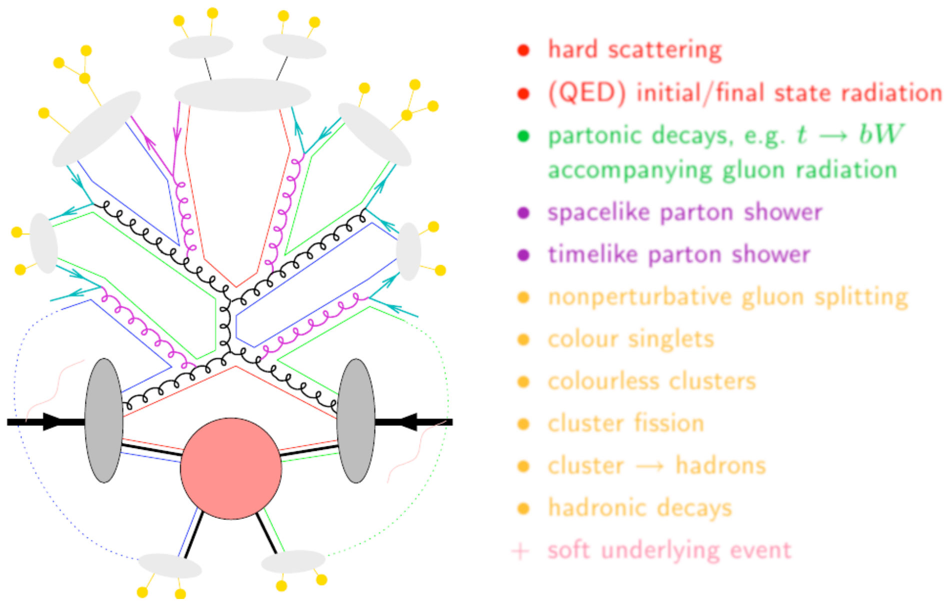
CMS Detector

- The Compact Muon Solenoid (CMS) is a multi purpose detector at the LHC.
- The CMS detector design is similar to the structure of an onion.
- She consists of several layers of each one which is specialized to measure and identify different classes of particles.
- The detector requirements for CMS
  - Good muon identification and momentum resolution,
  - Good charged particle momentum resolution and reconstruction efficiency in the inner tracker,
  - Good electromagnetic energy resolution, good diphoton and dielectron mass resolution,
  - Good MET and dijet mass resolution.





Tools for Theory Predictions



A naïve illlustration of pp scatter

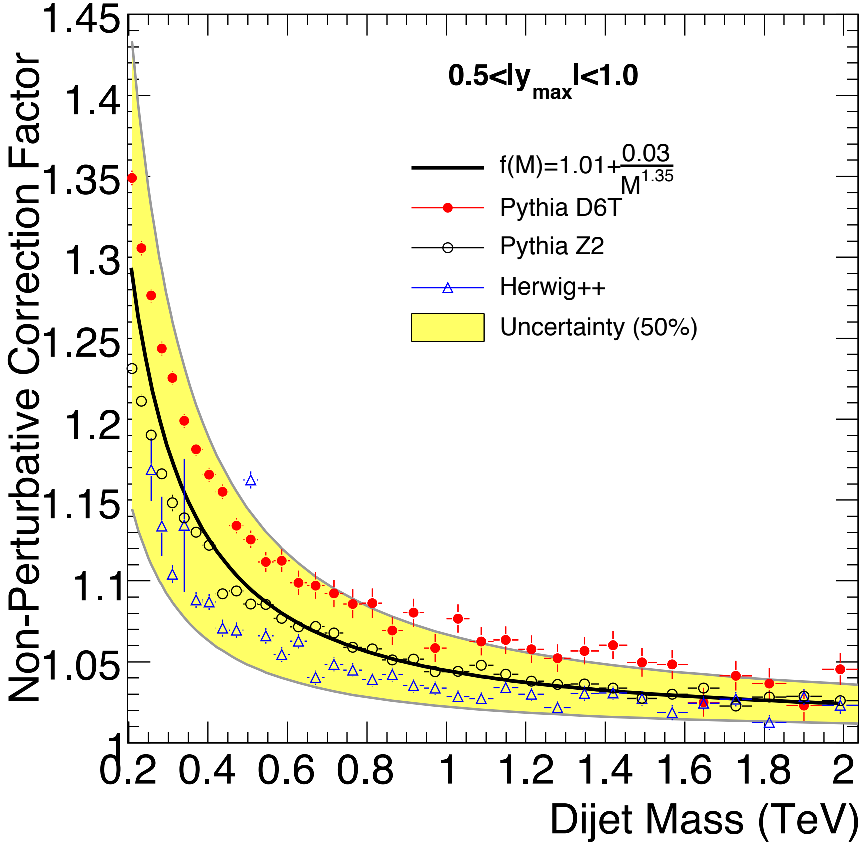
- Perturbative QCD calculations @ NLO are performed by
  - using NLOJet++/JETPHOX
  - use of fastNLO package
- Parton distribution functions (PDF) used are:
  - CT10
  - MSTW2008
  - NNPDF2.1
  - HERAPDF1.5
  - ABKM09, ABKM11
  - ABM11
- Non-perturbative corrections counts for:
  - multi-parton interaction (MPI)
  - hadronization
- QCD Monte-Carlo generators:
  - PYTHIA6, PYTHIA8
  - HERWIG++
  - ALPGEN
  - MADGRAPH

Non-Perturbative Correcitons

- A correction to pQCD is needed to "translate" the parton-level observables to the particle level, if there is no MC @ NLO event generator available

- Account for effects that cannot be calculated with pQCD
  - multi-parton interactions
  - hadronization

- The non-perturbative correction is estimated by using different MC generators
  - turn "on" and "off" the MPI and hadronization
  - most measurements use the average between PYTHIA6 and Herwig++

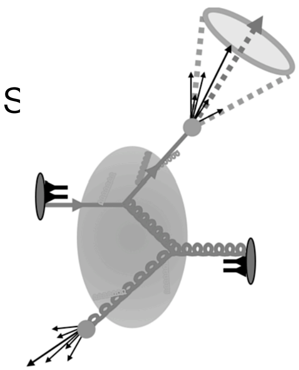


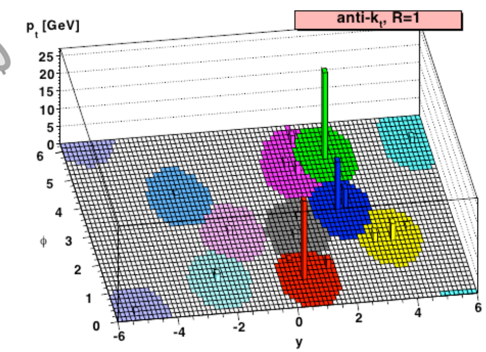
Jet Reconstruction and Calibration

Jet Reconstruction

- Jets are the experimental signatures of quarks and gluons
- It is an object that is clustered out of collimated spray of particles by using a set of mathematical rules

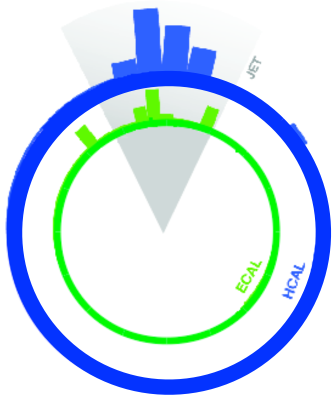
$$d_{ij} = p_{T,i}^{2p} \qquad d_{ij} = min(p_{T,i}^{2p}, p_{T,j}^{2p})\frac{\Delta R_{ij}^2}{D^2}$$



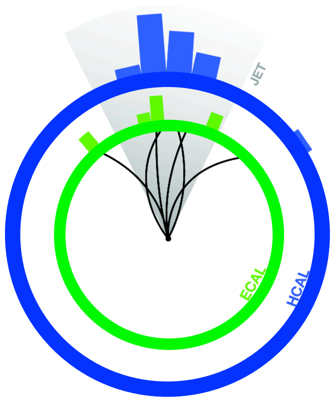


- CMS' default jet reconstruction algorithm is “anti-k_T jet” algorithm with p=-1 in the expression above
  - successive recombination (belongs to the k_T family)
  - infrared and collinear safe
  - geometrically cone-like (some round shape in the y-ϕ plane)
  - tends to cluster around the hard energy depositions

Calorimeter Jets



Particle Flow Jets



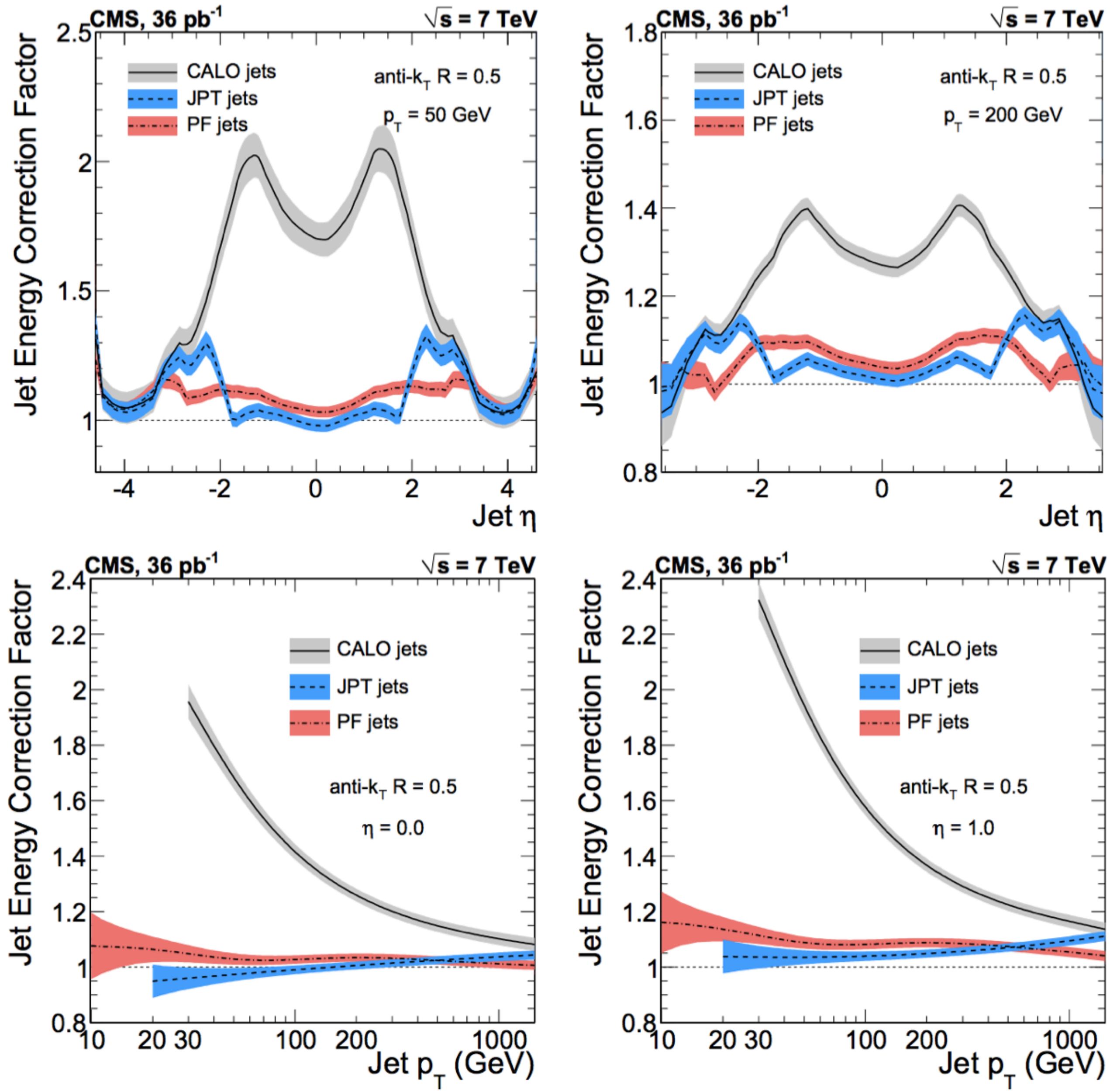
- The jet reconstruction in CMS follows the “E-Scheme”
  - addition of Lorentz vectors
  - massless particles → massive jets

calorimeter towers or particle-flow candidates → Jet clustering algorithm → CaloJets or PF Jets

Jet Reconstruction and Calibration

J. Instrum. 6 (2011) P11002

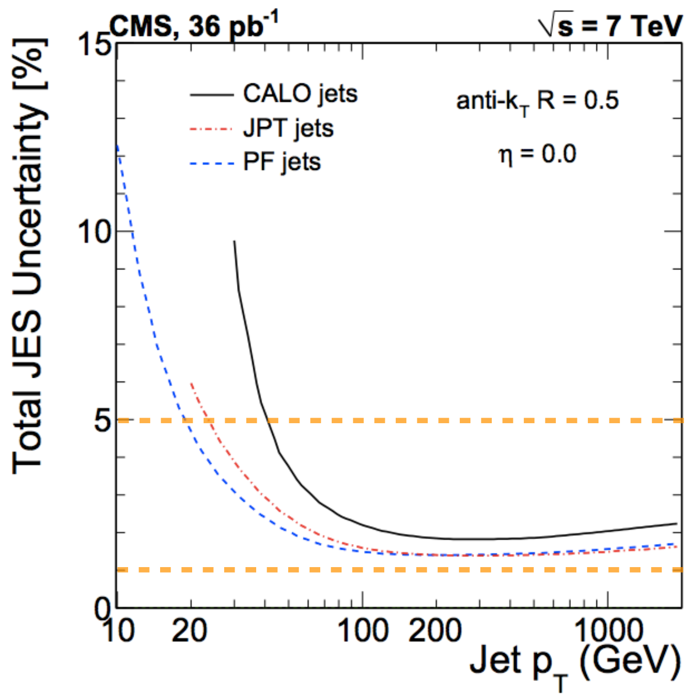
- Jet Energy Calibration
- Factorized approach is used like in Tevatron
- offset correction
- relative correction
- absolute JEC scale determined with $Z \to \mu^+\mu^-$+jet, $Z \to e^+e^-$+jet/γ +jet
- pile-up corrections becomes important
- dijet p_T balance
- MPF method adopted from DØ

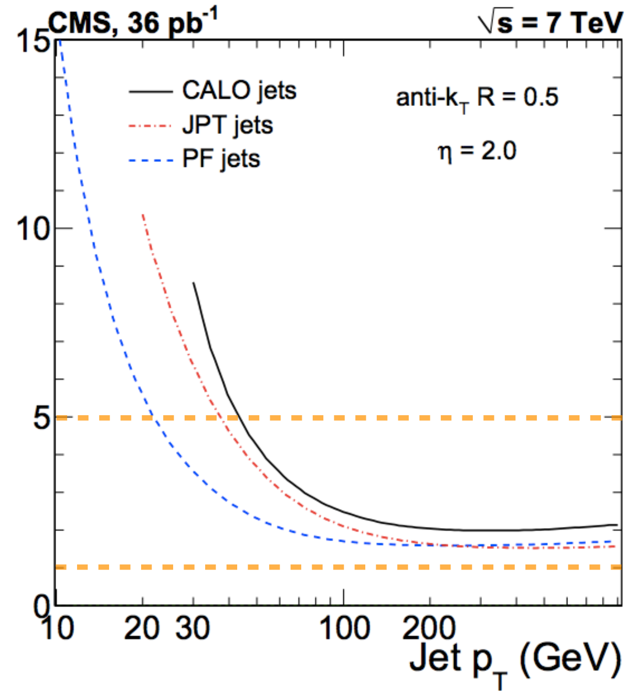


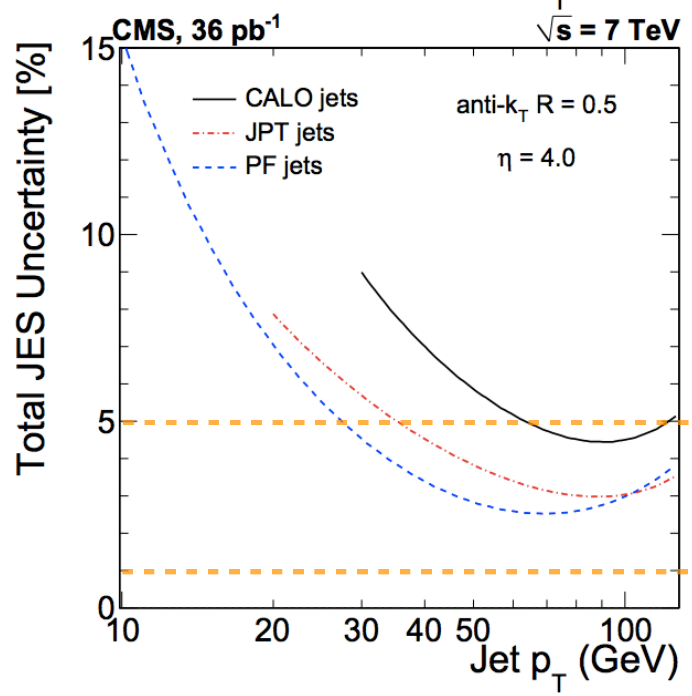
- Jet Calibration vs. η is better than 0.5% in $|\eta_{jet}|<2$ region

Jet Reconstruction and Calibration

J. Instrum. 6 (2011) P11002





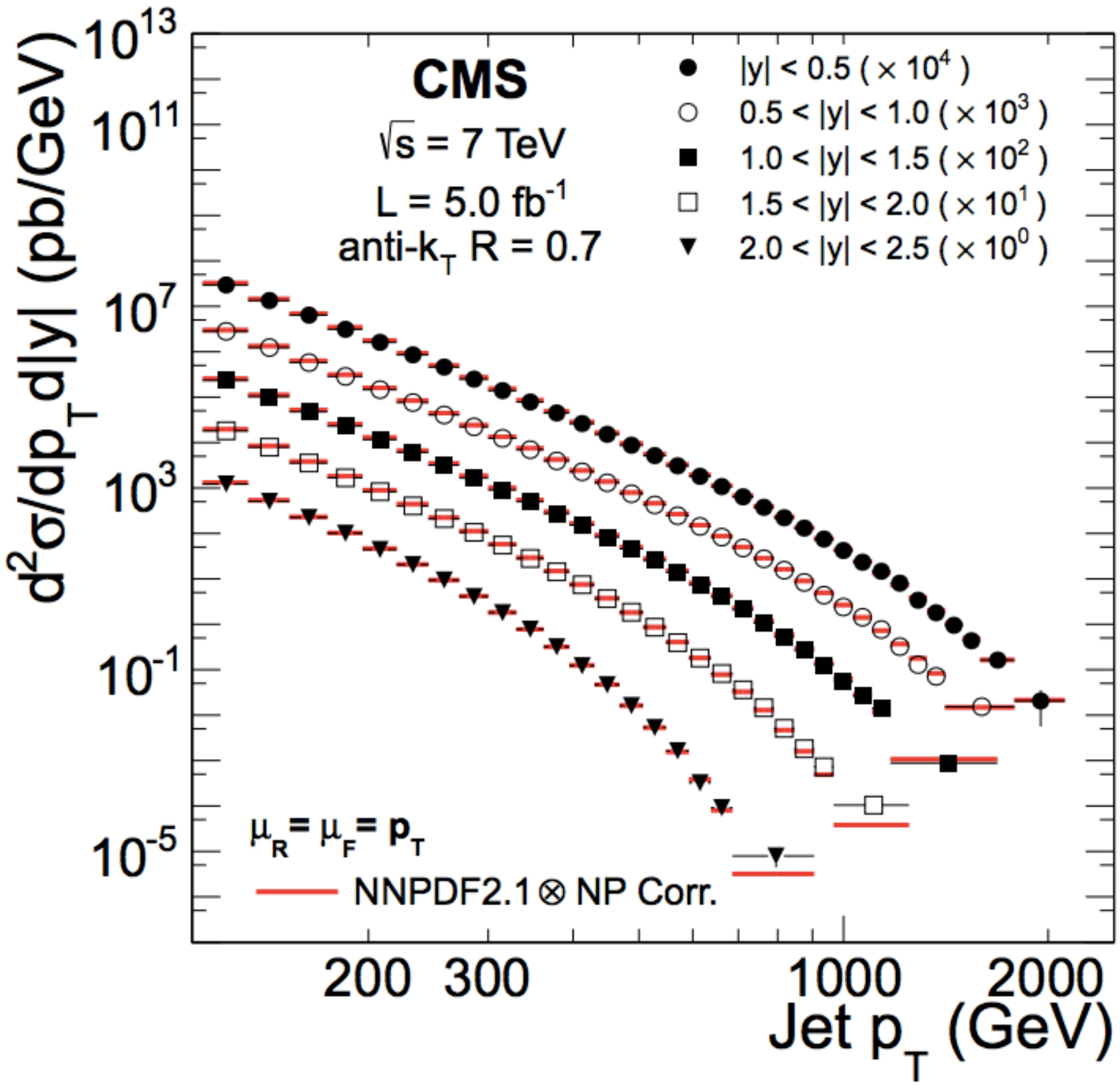


Total jet-energy-scale uncertainty, as a function of jet p_T for various η values.

Inclusive Jet Cross Section

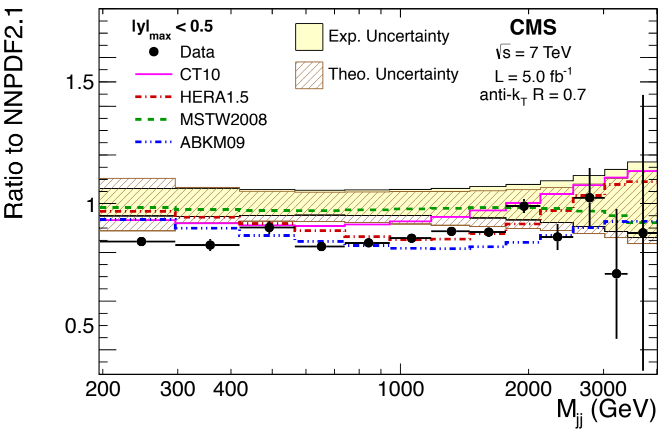
arXiv:1212.6660v1 *(submitted to Physical Review D)*

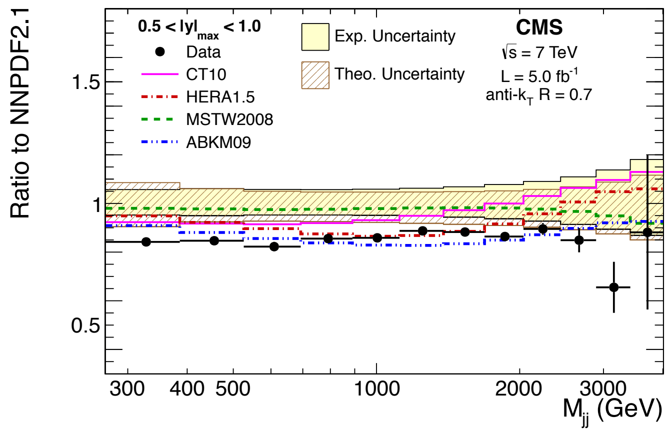
- Measured jet p_T spectra in 5 rapidity bins
- Unfolded to particle level jet spectra using D'Agositini Multidimensional unfolding method.
- NLO calculations with non-perturbative corrections (NPC) are used for comparison with data. NPC are got as averaged value between NPC got with PYTHIA and HERWIG.
- A set of the different NLO PDFs is used to account for PDF uncertainty.
- Data are in agreement with NLO calculations within systematic uncertainties although NLO calculations are systematically overestimate cross-section in all rapidity bins.

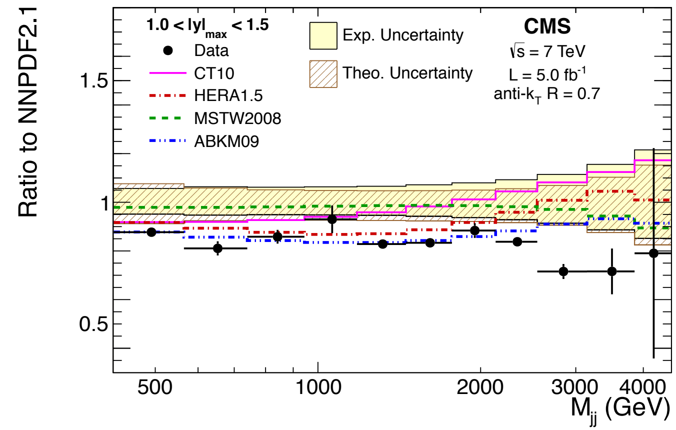


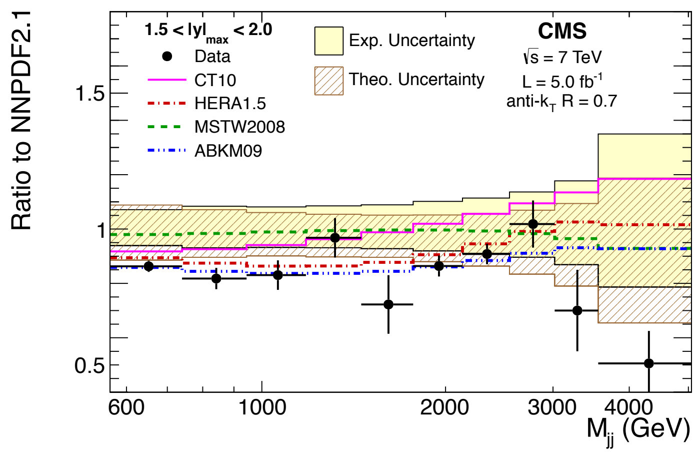
Inclusive Jet Cross Section

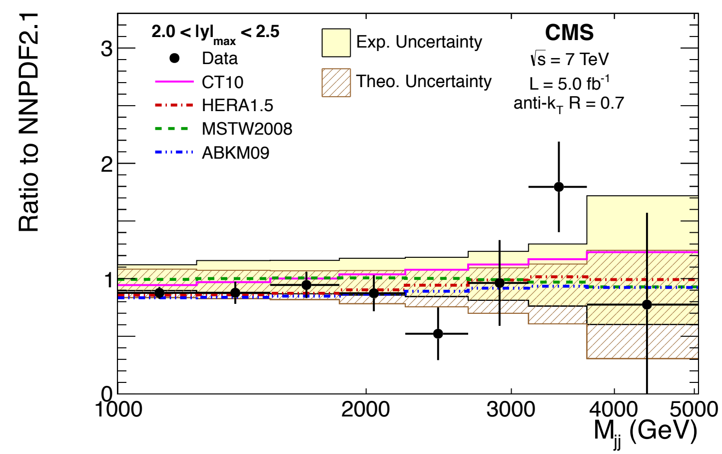
DATA VS NLO COMPARISON WITH NNPDF2.1 FOR ALL RAPIDITY BINS







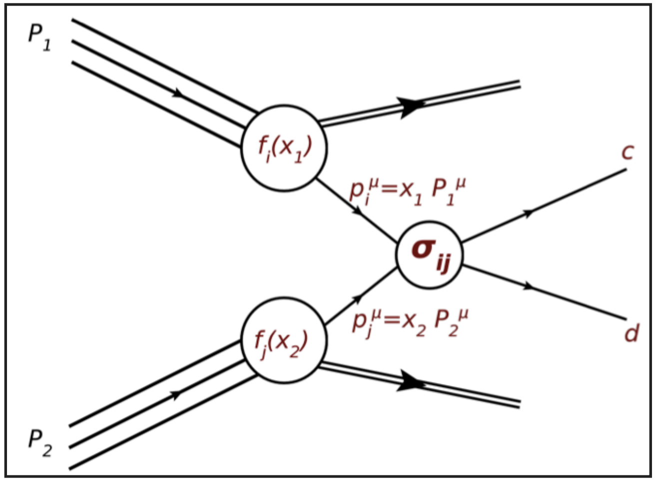




Ratio of inclusive jet cross sections to the theoretical prediction using the central value of the NNPDF2.1 PDF set for the first three $|y|$ and $|y|_{max}$ bins respectively. The solid histograms show the ratio of the cross sections calculated with the other PDF sets to that calculated with NNPDF2.1. The experimental and theoretical systematic uncertainties are represented by the continuous and hatched bands, respectively.

Dijet Production

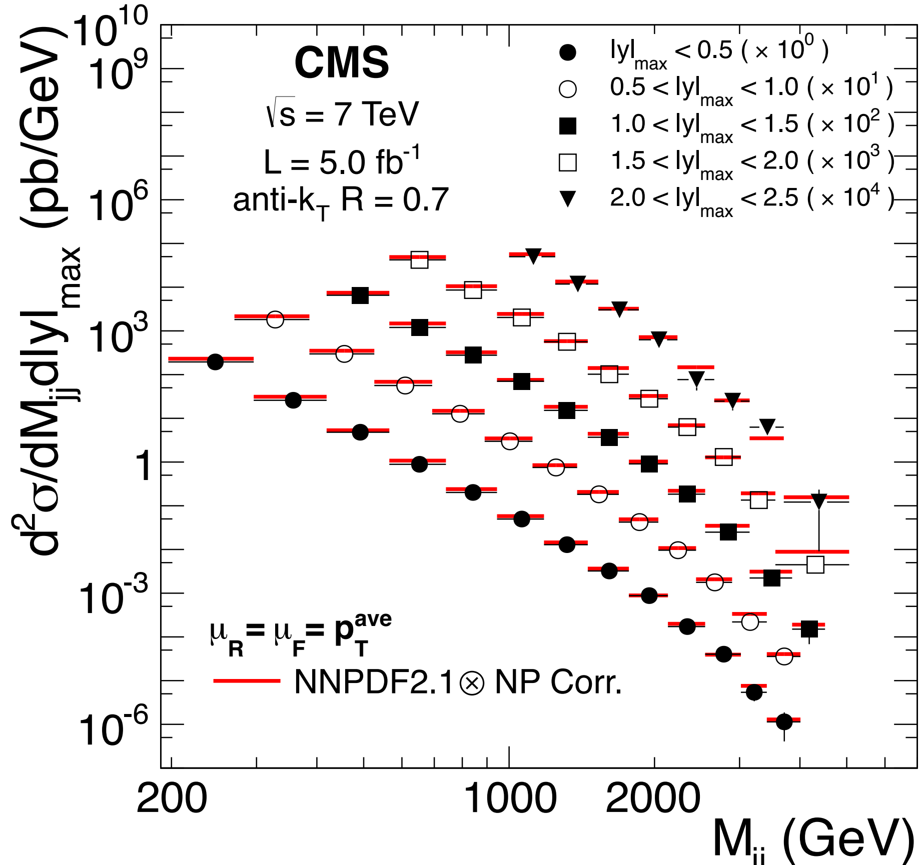
arXiv:1212.6660v1 *(submitted to Physical Review D)*



- Events with two energetic partons (quarks or gluons) arise in proton-proton collisions from parton-parton scattering.
- We observe this outgoing parton pair as two hadronic jets (dijets) in the detector.
- The dijet mass spectrum predicted by Quantum Chromodynamics (QCD) falls smoothly and steeply with increasing dijet mass.

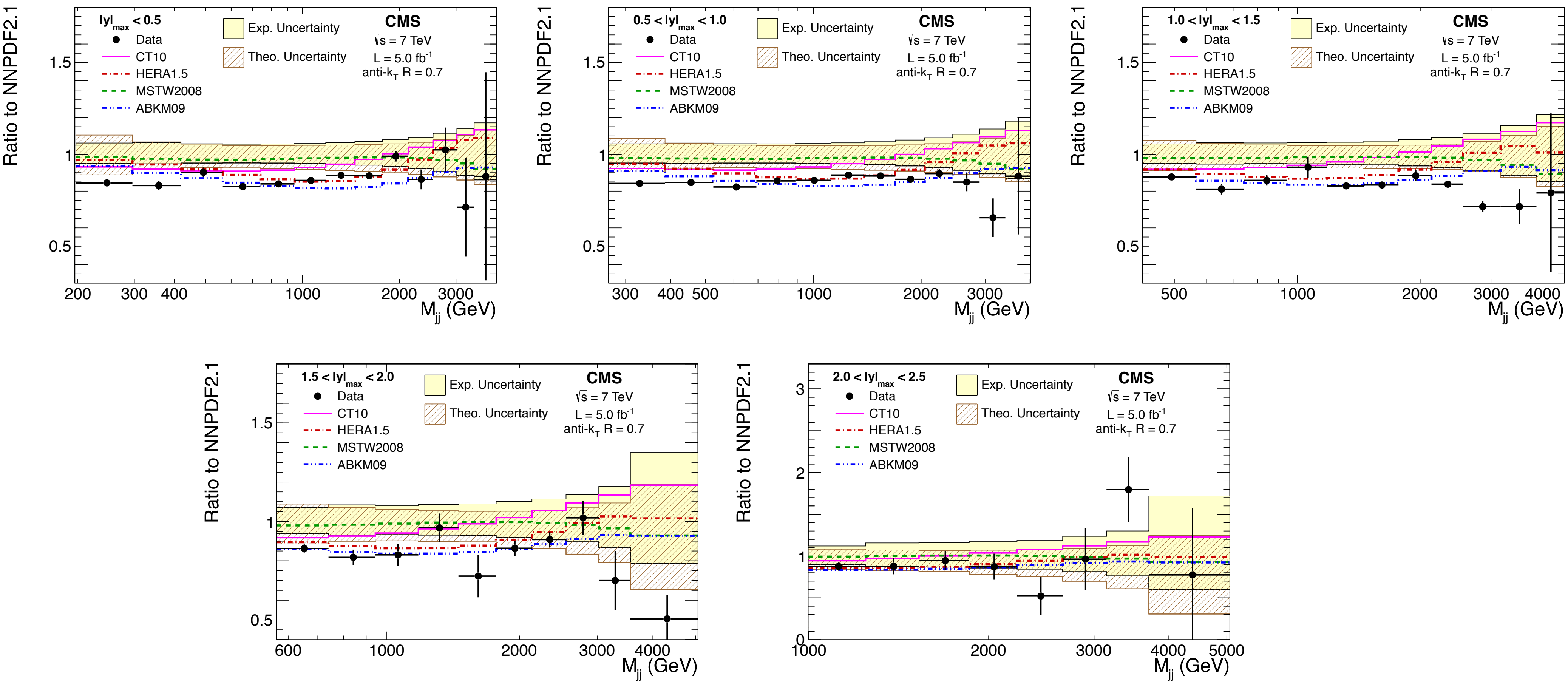
$$d\sigma(P_1P_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{q_i,q_j} f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2) d\hat{\sigma}_{q_iq_j\to cd}(\alpha_s(\mu_F^2), Q^2/\mu_F^2)$$

- $\sqrt{s}$ = 7 TeV
- *L*= 5.0 fb^{-1}of integrated luminosity
- Jets are reconstructed up to rapidity 2.5
- anti-kT clustering algorithm with distance parameter R = 0.7.
- The measured cross sections are corrected for detector effects
- Compared to pQCD predictions at NLO, using five sets of PDF



Dijet Production

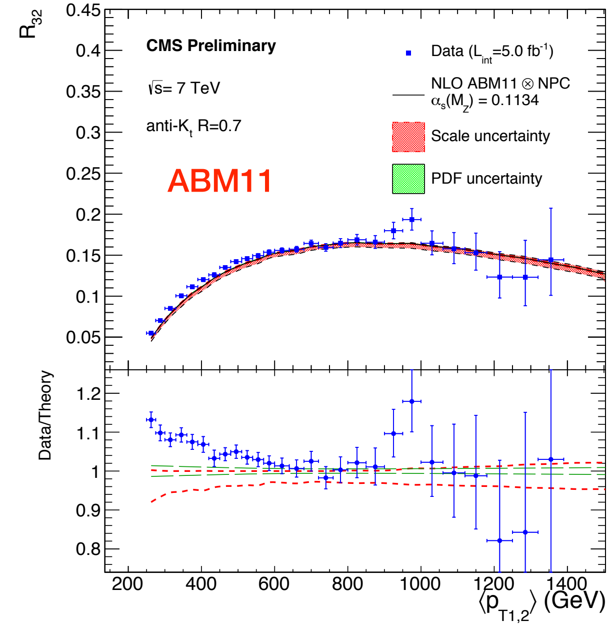
DATA VS NLO COMPARISON WITH NNPDF2.1 FOR ALL RAPIDITY BINS



Ratio of dijet cross sections to the theoretical prediction using the central value of the NNPDF2.1 PDF set for the first three $|y|$ and $|y|_{max}$ bins respectively. The solid histograms show the ratio of the cross sections calculated with the other PDF sets to that calculated with NNPDF2.1. The experimental and theoretical systematic uncertainties are represented by the continuous and hatched bands, respectively.

First determination of the strong coupling at transverse momenta in the TeV range

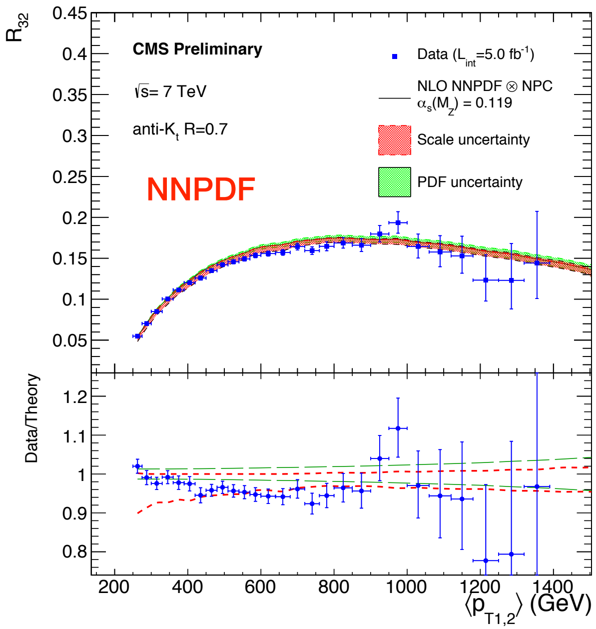
- The plateau of the ratio is sensitive to QCD coupling constant α(s)
- Less sensitive to the dominant Jet Energy Scale (JES) uncertainty than inclusive measurements.

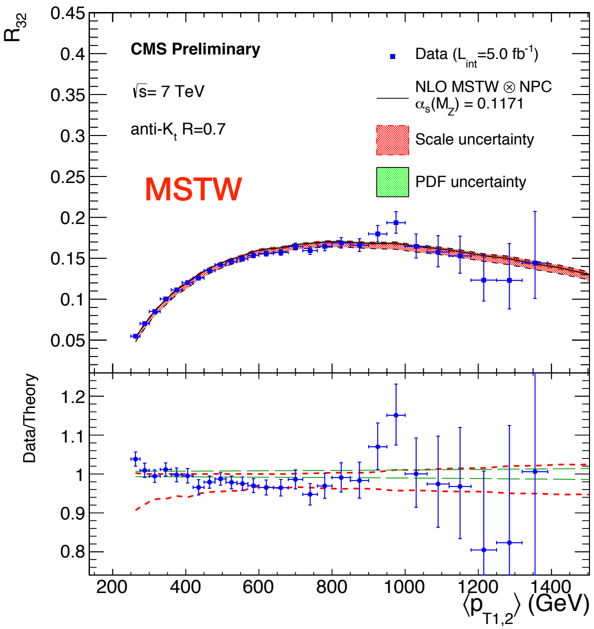


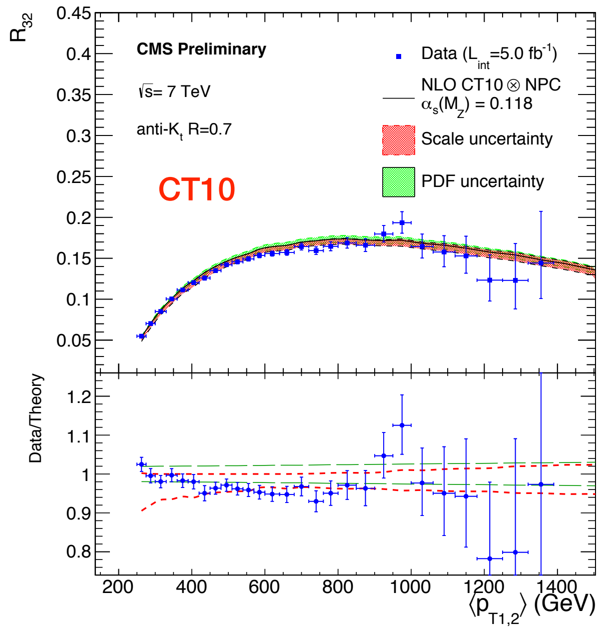
3-jet to 2-jet Ratio is defined as:

$$R_{32} = \frac{d\sigma_3/dH_T}{d\sigma_2/dH_T}$$

H_T is defined as the scalar transverse momentum sum of all jets







3-jet to 2-jet cross-sections

Determination of the strong coupling constant $\alpha_s(M_Z)$

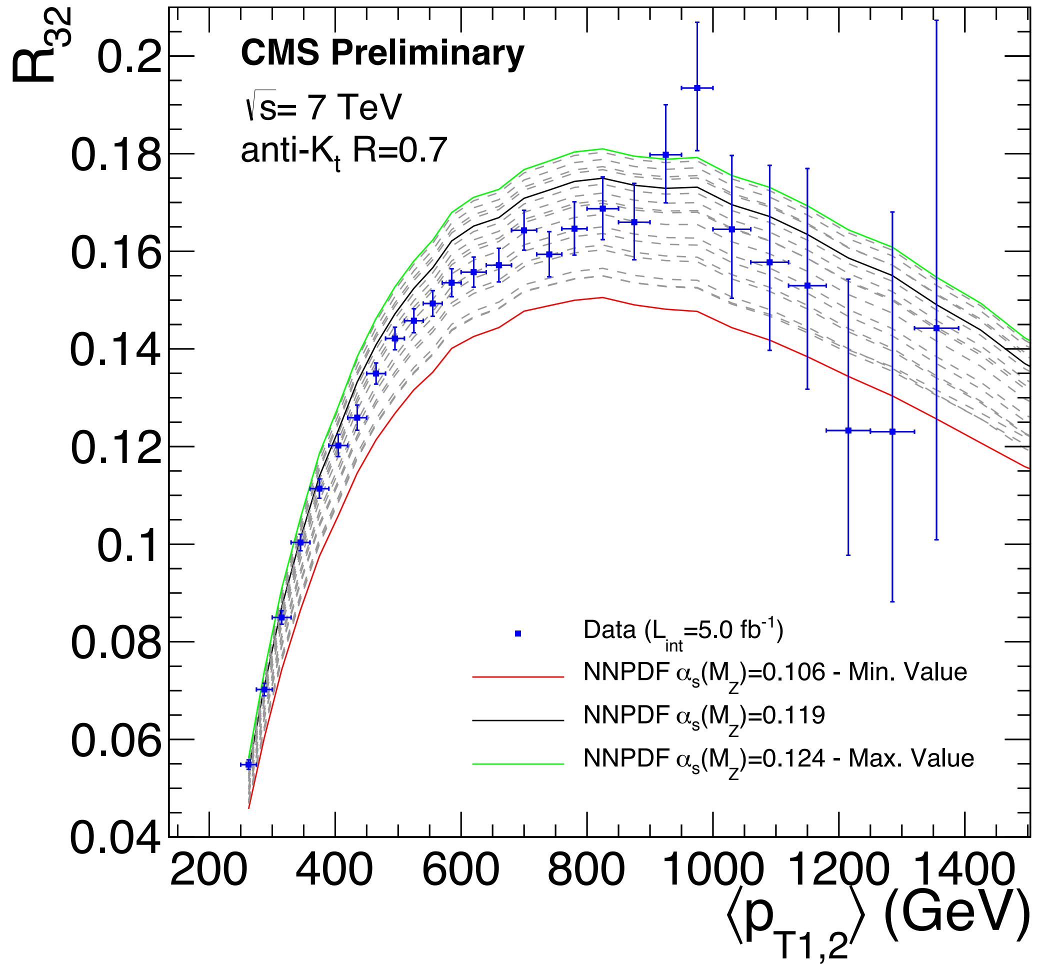
a test of the validity of the RGE

The $\alpha_s(M_Z)$ has been varied in the range:

0.106-0.124	for	NNPDF2.1
0.104-0.120		ABM11
0.107-0.127		MSTW2008
0.110-0.130		CT10

in steps of 0.001

The value of $\alpha_s(M_Z)$ is by minimizing the χ^2 between the experimental measurement and the theoretical predictions



using the NNPDF2.1 PDF sets is

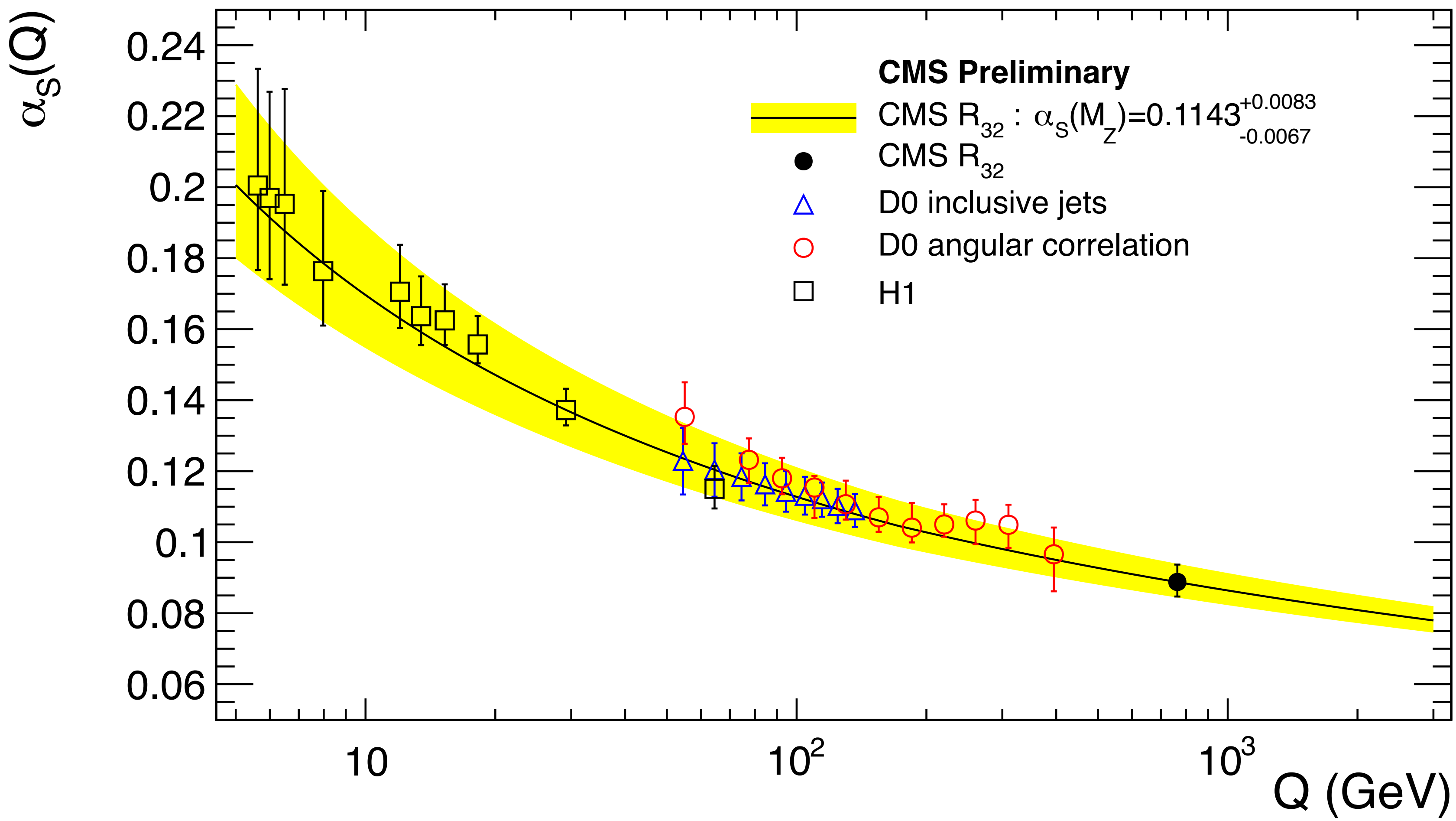
$\alpha_s(M_Z)$ = 0.1143±0.0064(exp.)

world average:
0.1184 ± 0.0007

The NLO predictions using the NNPDF2.1 NNLO PDF set for a series of $\alpha_s(M_Z)$ values of together with the measured R32. $\alpha_s(M_Z)$ has been varied in the range 0.106-0.124, 0.104-120, 0.107-0.127 and 0.110-0.130 in steps of 0.001 for NNPDF2.1, ABM11, MSTW2008 and CT10 respectively.

3-jet to 2-jet cross-sections

Determination of the strong coupling constans $\alpha_s(M_Z)$



The strong coupling α_s (yellow band) as a function of the momentum transfer, Q, where the value at $Q = M_Z$ has been evolved using the three-loop RGE.

Last to say ...

- CMS has completed a very large number of analyses with *pp* collisions at 7 TeV
- Excellent understanding of the detector has been achieved, even at high pile-up conditions!
- The level of the precision of Standard Model measurements are quite high
  - important constraints on theory ingredients (e.g. PDFs) and backgrounds to searches
- Many results have been published and lots of is going to be published soon

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Backup