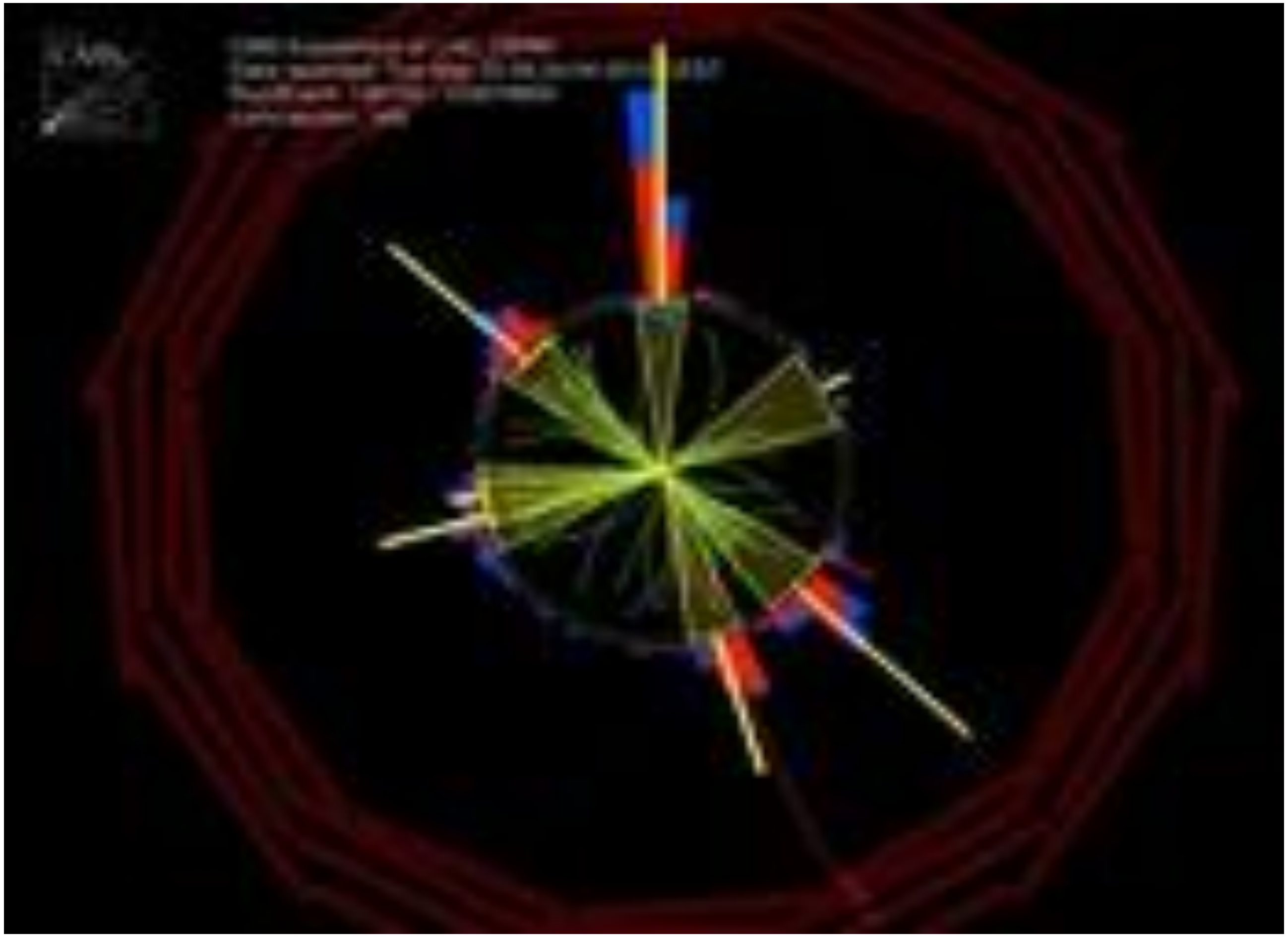
CMS QCD physics results

Olga Kodolova, SINP MSU
on behalf of the CMS Collaboration



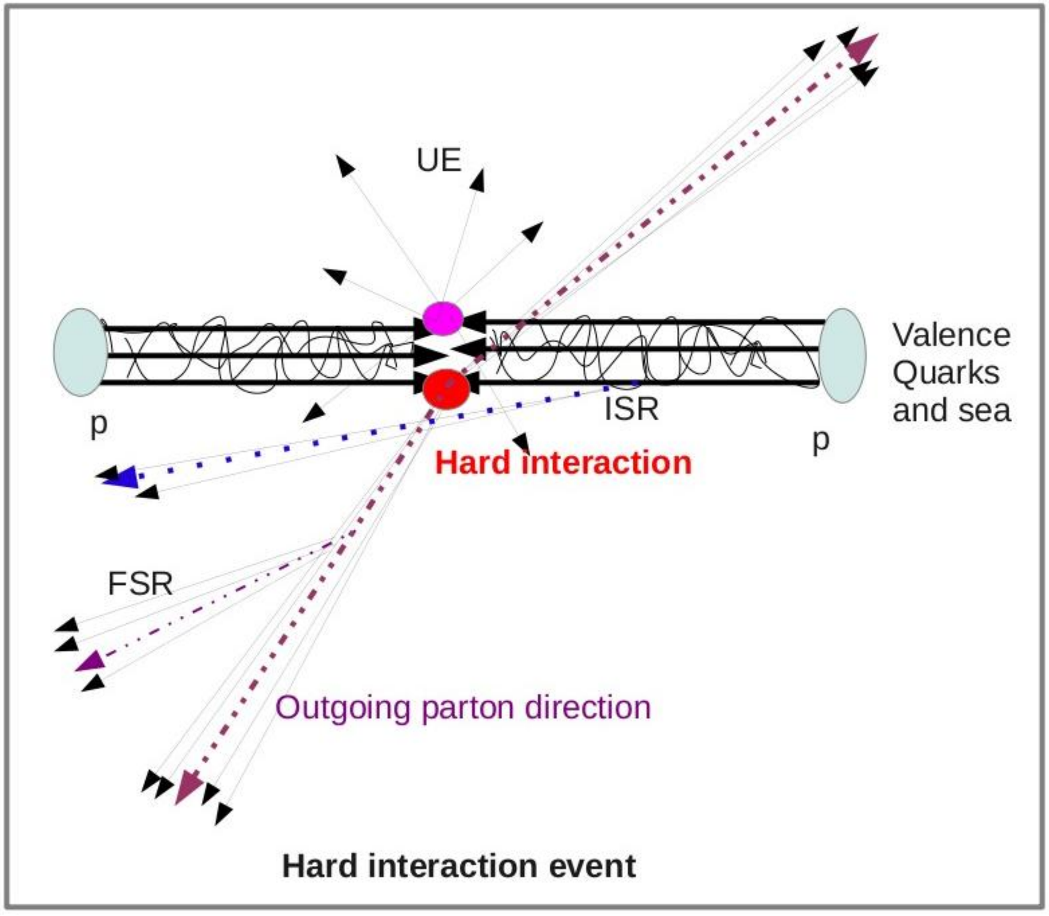
Outline

- Motivation
- Scope of studies
- CMS detector
- Soft physics
- Hard physics
- Summary

Motivation

- QCD is the constituent of the Standard Model which deals with strong interactions
- The verification of the QCD validity is the first step towards the new Physics.
    - QCD processes are background to the Higgs production, SUSY, contact interaction models, rare processes that are scope of the Standard Model itself
    - QCD defines the hadronization process of partons whatelse interaction mediator is in the hard production vertex

Scope of studies



Hard production
- **Inclusive and exclusive cross-section**
- **Transverse momentum**
- **Rapidity**
- **Jet properties**

Soft production
- **Underlying event to hard production**
- **Soft interaction: multiplicity**
  - **Transverse momentum**
  - **Rapidity**
  - **Correlations**

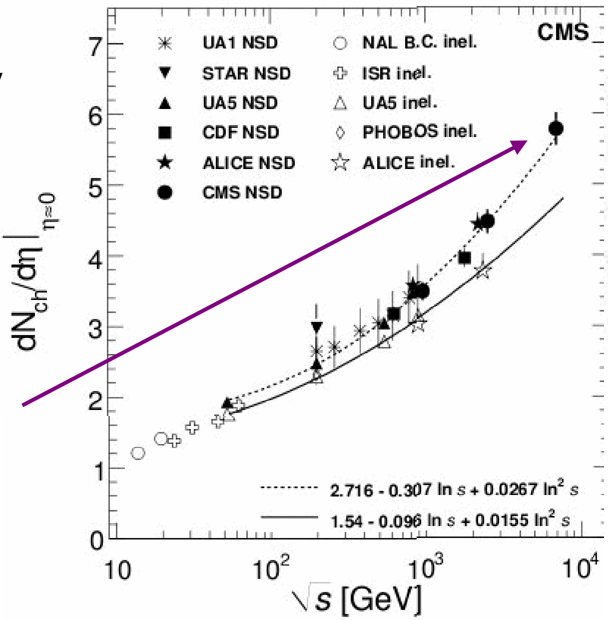
Outcome:
- **Cross-sections**
- **Parton Distribution Functions**
- **Parton showering details**
- **Details of fragmentation process**

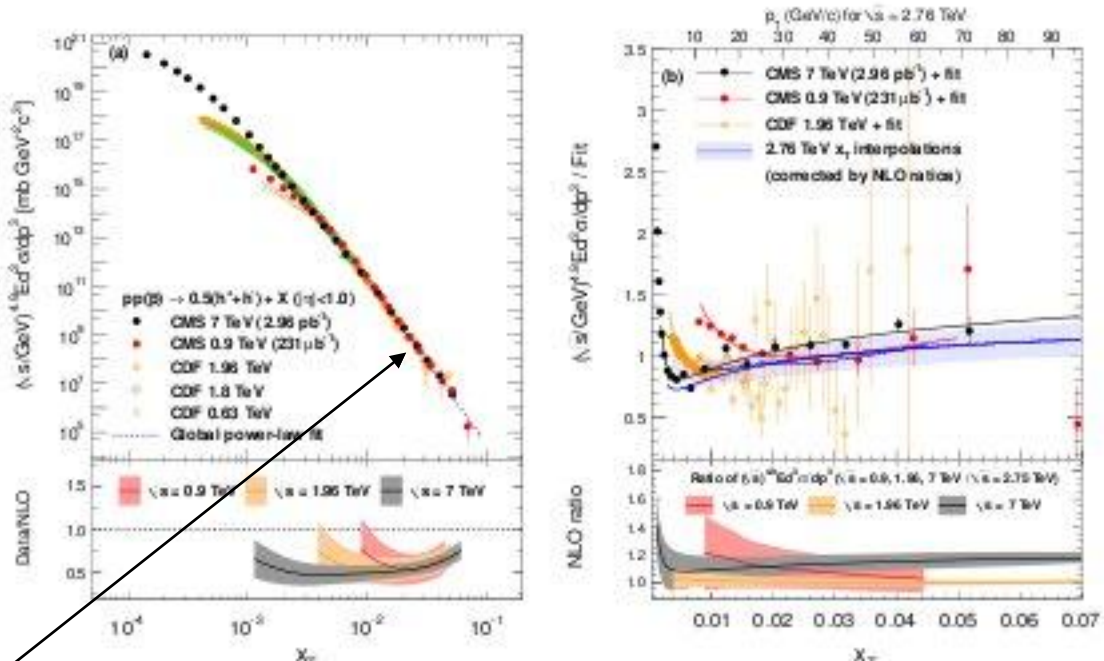
Approximation approaches:
- **Perturbative QCD (pQCD) – LO, NLO, NNLO calculations, ME + parton showering, threshold ressumation**
- **Non-perturbative QCD (Multi-parton interactions (MPI), String/Clustering fragmentation models)**

Charged particles multiplicity and spectra at 0.9 TeV-7 TeV

Measured NSD multiplicity is higher then most of the predicted:

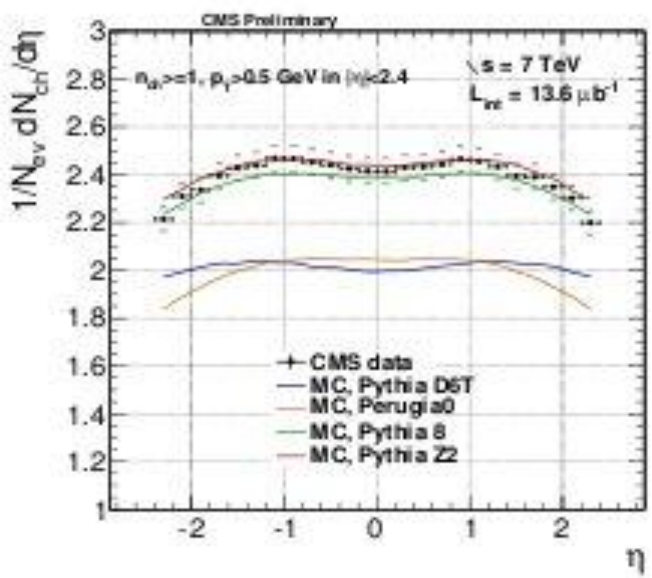
new input to the dynamics of soft hadronic interactions





The CMS results are consistent with $x_T=2p_T/\sqrt{s}$ scaling (pQCD prediction) with exponent N=4.9 +- 0.1

NLO calculations overestimates cross-section twice at all energies for high p_T hadrons

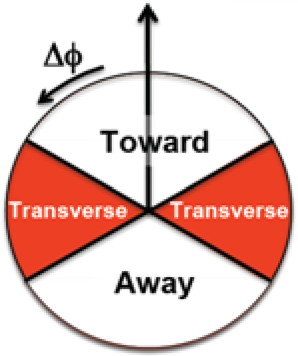


PYTHIA 8 and Z2 describes η-distribution for low-p_T charged hadrons at 7 TeV

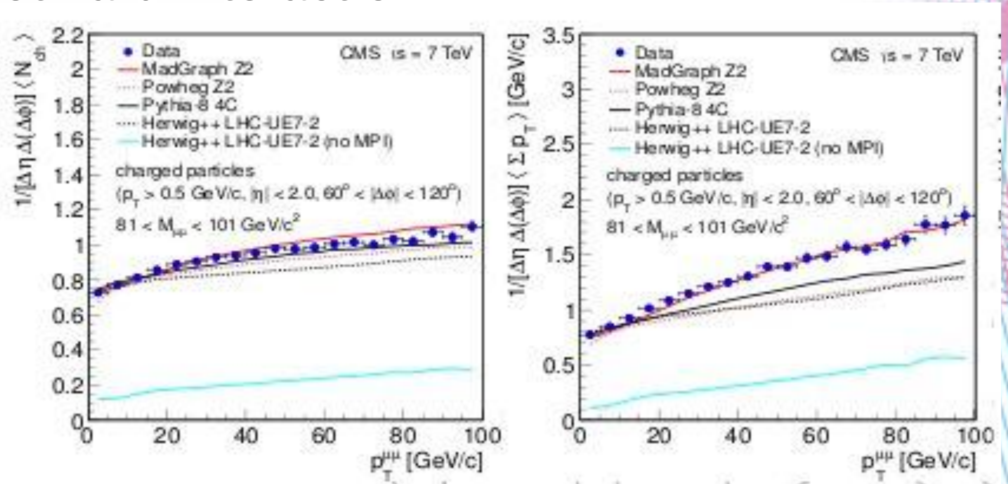
PRL 105(2010) 022002
JHEP08(2011)086
CMS-PAS-QCD-10-024

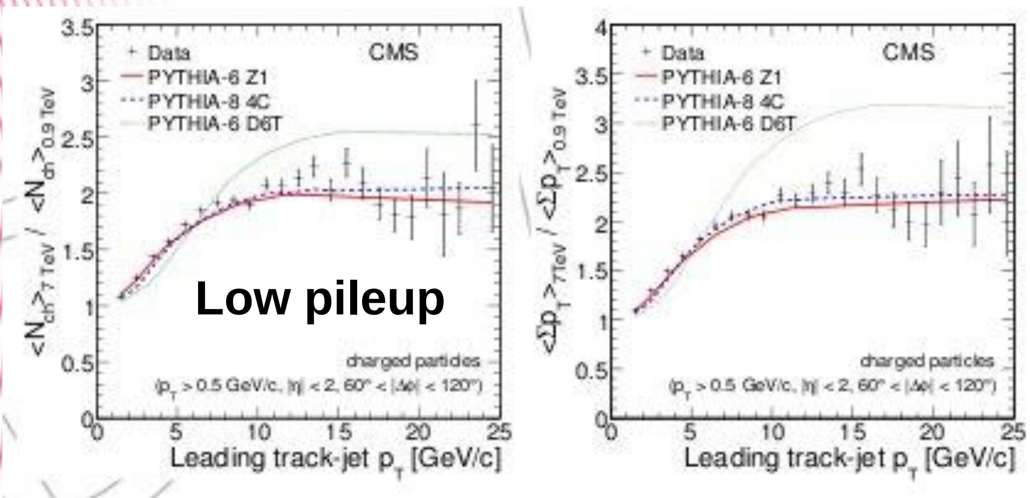
Underlying event

UE- Everything in event that is not hard interaction

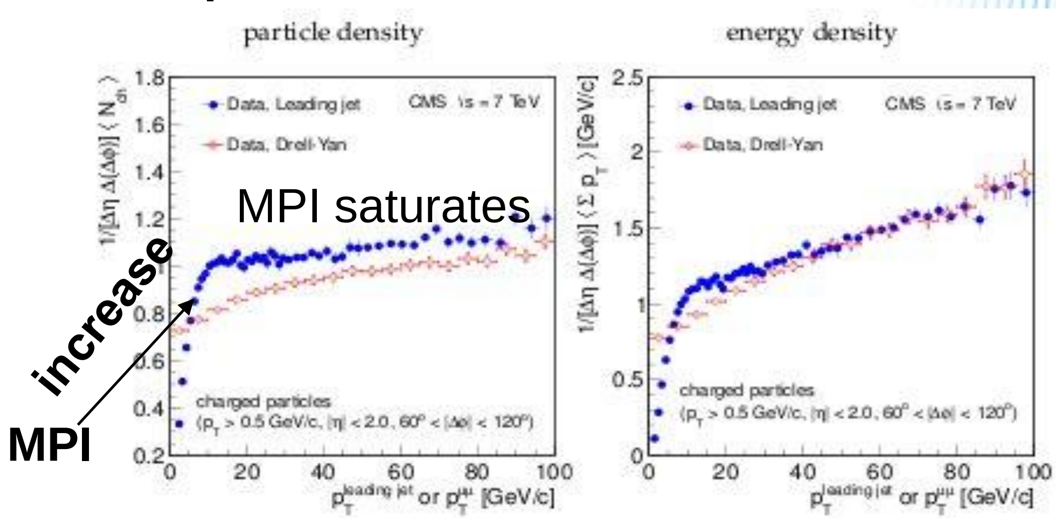


UE in DY events
Relative to $p_T^{\mu\mu}$ with $M_{\mu\mu}$ in the vicinity of Z:
Sensitive to ISR and MPI





Comparison of UE in DY w.r.t. Hadronic:

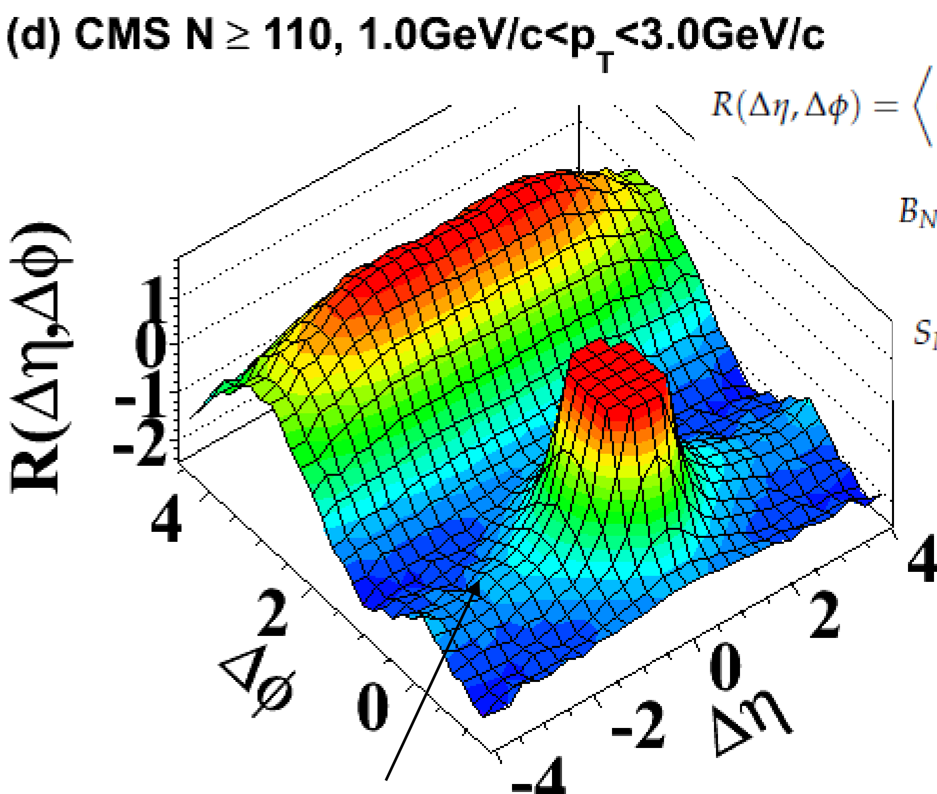


UE in hadronic events
Leading cluster or track jet (jet reconstructed from tracks only; can go down to low-p_T) is expected to reflect the direction of the parton.
Sensitive to ISR,FSR,MPI

Valuable information for further tuning MC models.

JHEP09(2011)109
CERN-PH-EP-2012-085

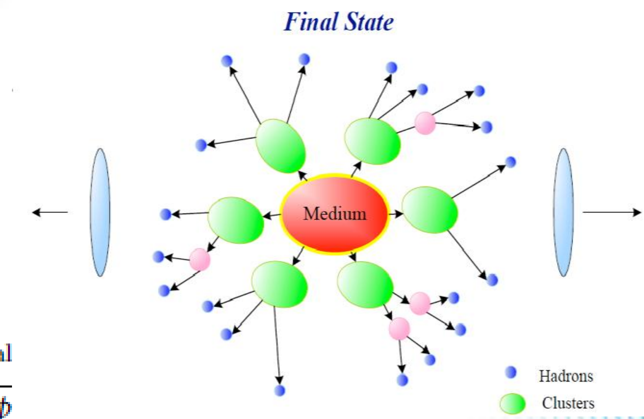
Long range correlations

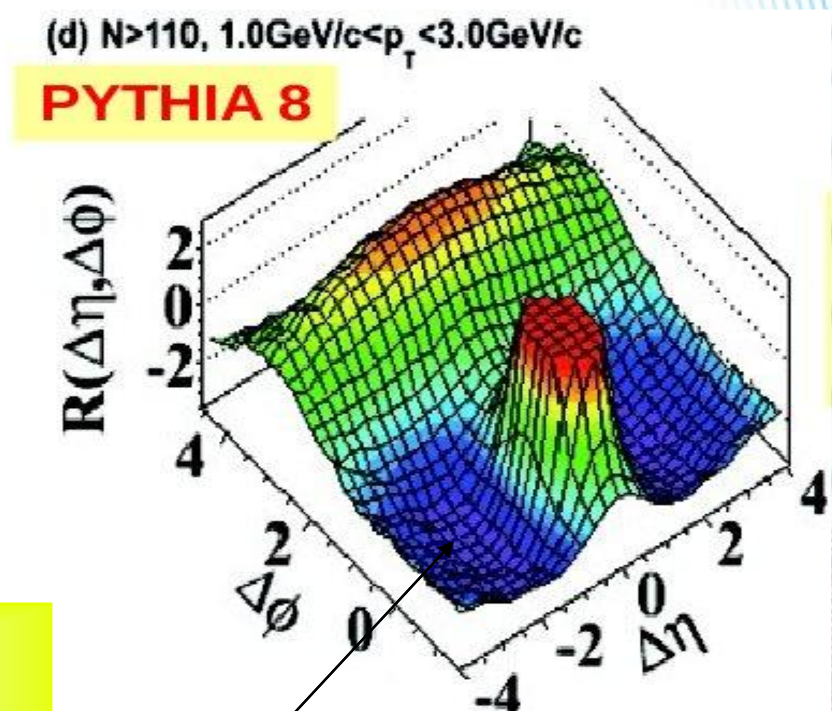


$$R(\Delta\eta,\Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

$$B_N(\Delta\eta,\Delta\phi) = \frac{1}{N^2}\frac{d^2N^{\mathrm{mixed}}}{d\Delta\eta d\Delta\phi}$$

$$S_N(\Delta\eta,\Delta\phi) = \frac{1}{N(N-1)}\frac{d^2N^{\mathrm{signal}}}{d\Delta\eta d\Delta\phi}$$





Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at $\Delta\varphi \sim 0$)

Theoretical hypothesis:
- **initial state correlated gluon flow**
- **collective parton flow effect at the final state**

Ridge is not reproduced neither of PYTHIA versions nor MADGRAPH

JHEP 1009 (2010) 091

Jets reconstruction

Calorimeter jets (CaloJets):
Jet clustered from Calorimeter Towers
Subdetectors: ECAL, HCAL

CaloMET

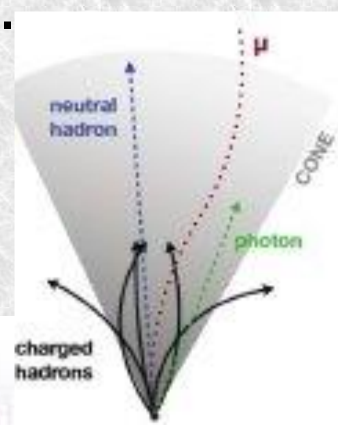
Selected subdetectors participate in reconstruction

Tracker jets:
Jet clustered from Tracks

Subdetectors: Tracker

ParticleFlow jets (PFJets):
Jet clustered from Particle Flow objects (a la generator level particles) which are reconstructed basing on cluster separation.
Subdetectors: ECAL,HCAL, Tracker, Muon

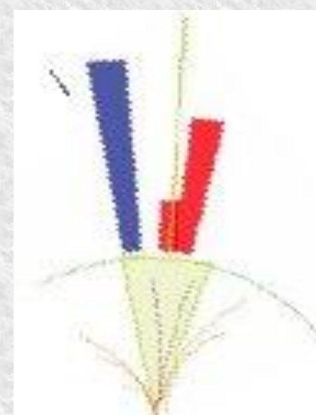
PFMET



All subdetectors Participate in reconstruction

The residual jet energy corrections is applied on top for all algorithms

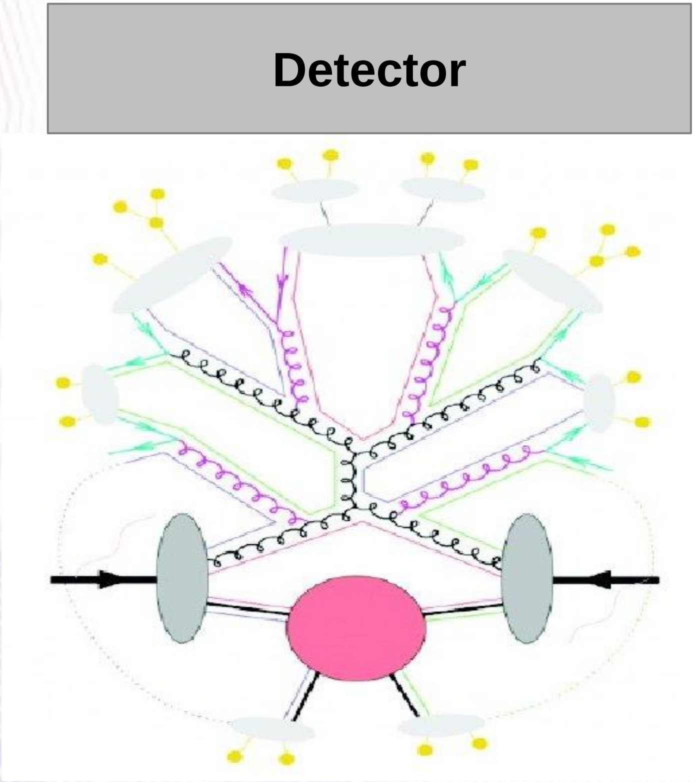
JetPlusTrack jets (JPTJets):
Starting from calorimeter jets tracking information is added via subtracting average response and replacing with tracker measurements.
Subdetectors: ECAL,HCAL, Tracker, Muon
TcMET

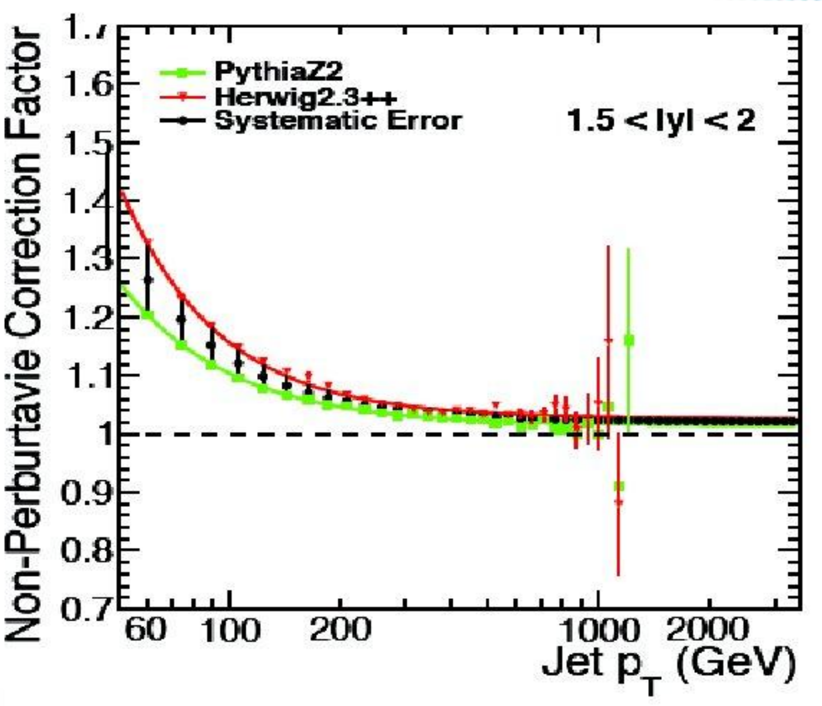


Two notes towards jet production measurement

Measurements are corrected to particle level via either unfolding procedure or bin-to-bin corrections

NLO calculations are corrected to particle level for fragmentation and MPI effect with and without Including parton showering using LO+PS generators

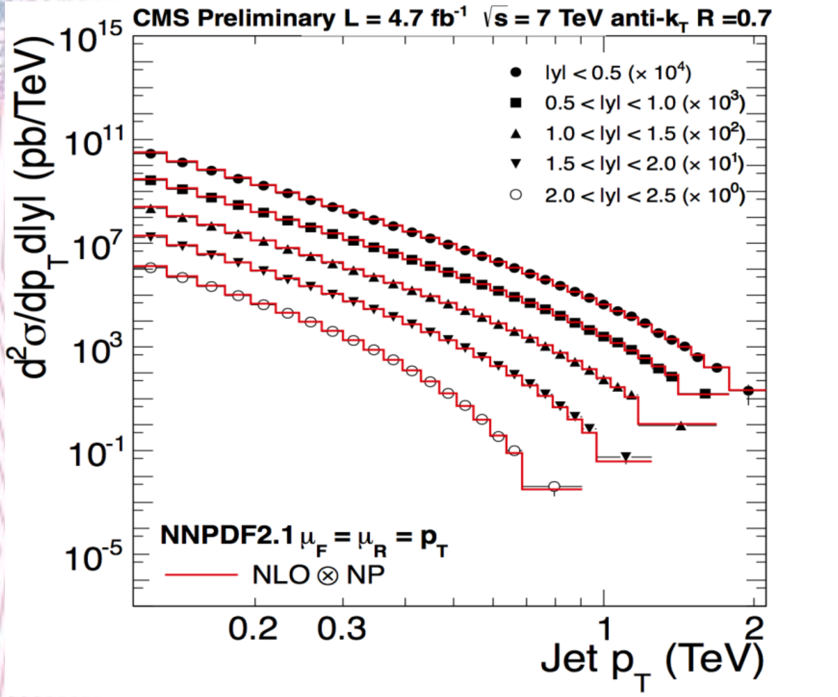


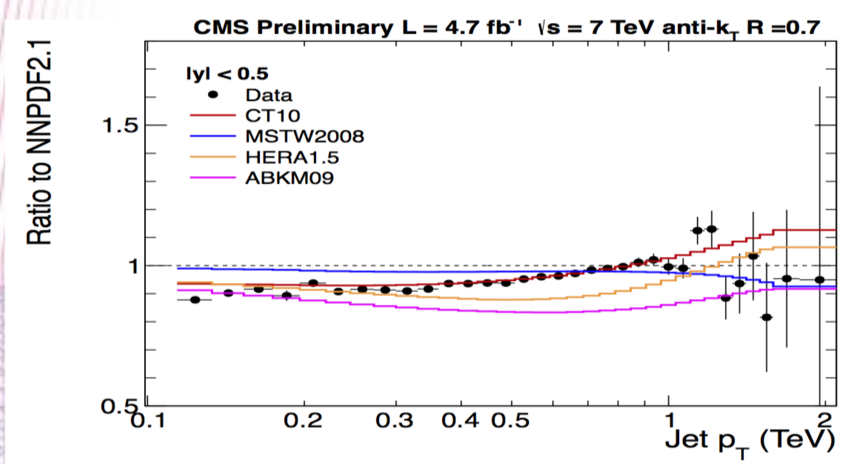


Inclusive central jets production

Jets: $|\eta|<2.5$

Motivation: constrain PDFs, differentiate between the different PDF sets





Measured jet p_T spectra in 5 rapidity bins were unfolded to particle level jet spectra using dAgositini Multidimensional unfolding method.

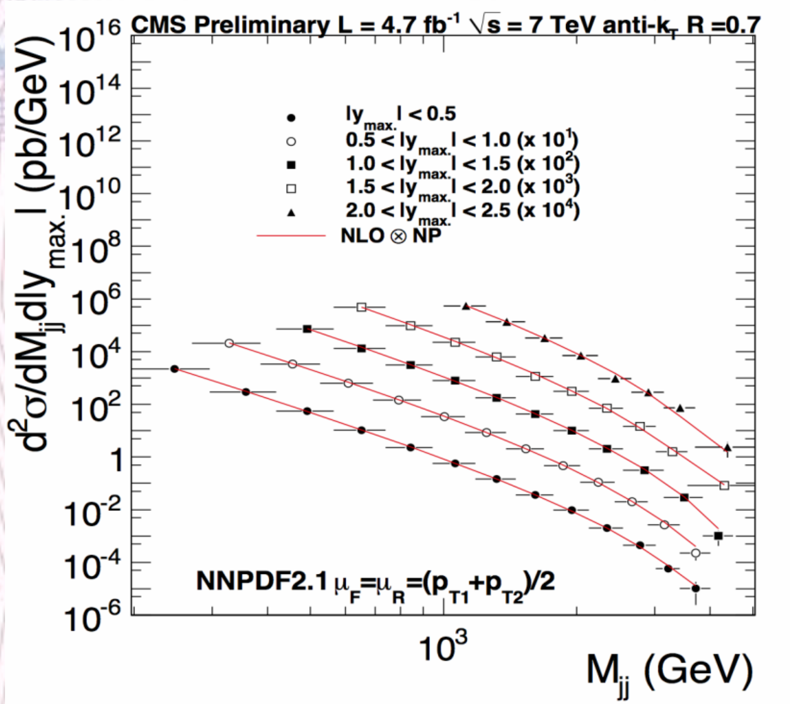
NLO calculations with non-perturbative corrections (NP) are used for comparison with data. NP corrections are got as averaged value between NPC got with PYTHIA and HERWIG.

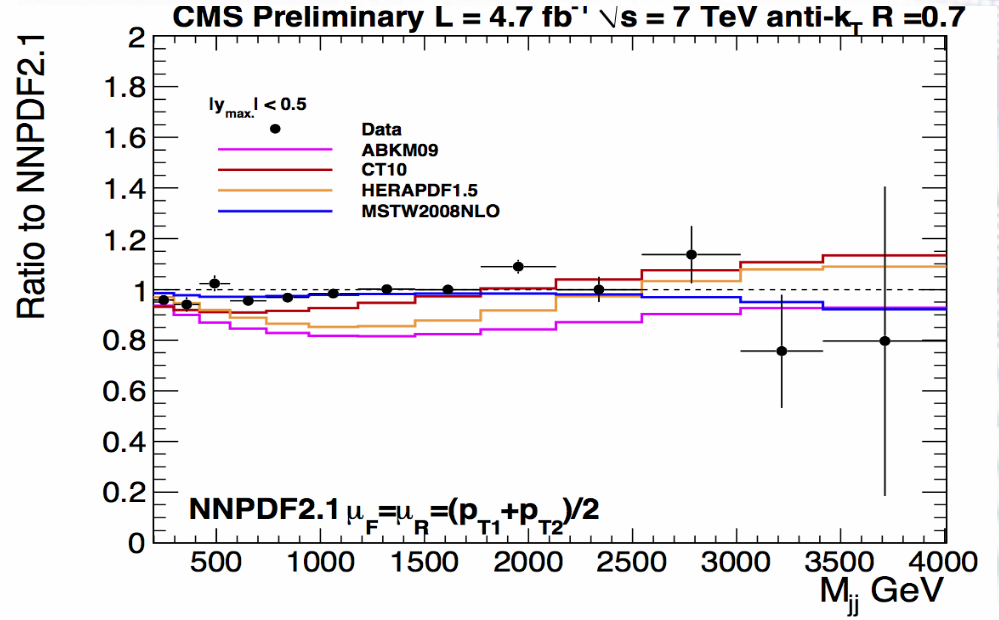
A set of the different NLO PDFs is used to account for PDF uncertainty.

Data are in agreement with NLO calculations withing systematic uncertainties although NLO calculations are systematically overestimate cross-section in all rapidity bins.

CMS-PAS-QCD-11-004
CERN-PH-EP/2011-053

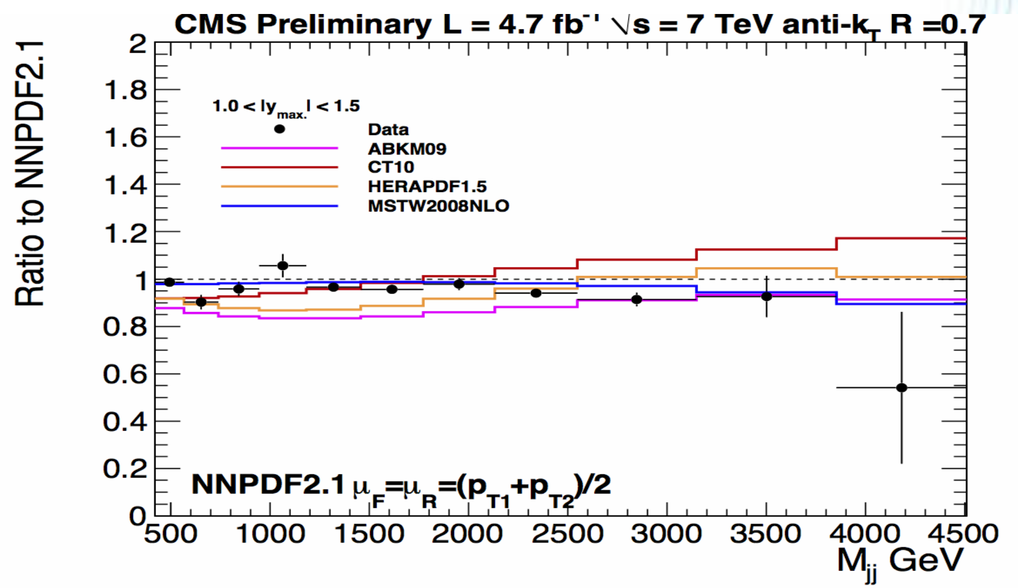
Dijet production





NLO QCD (NLOJet++) + NP corrections

Comparison with dats is done for the different PDFs in the different rapidity Bins.



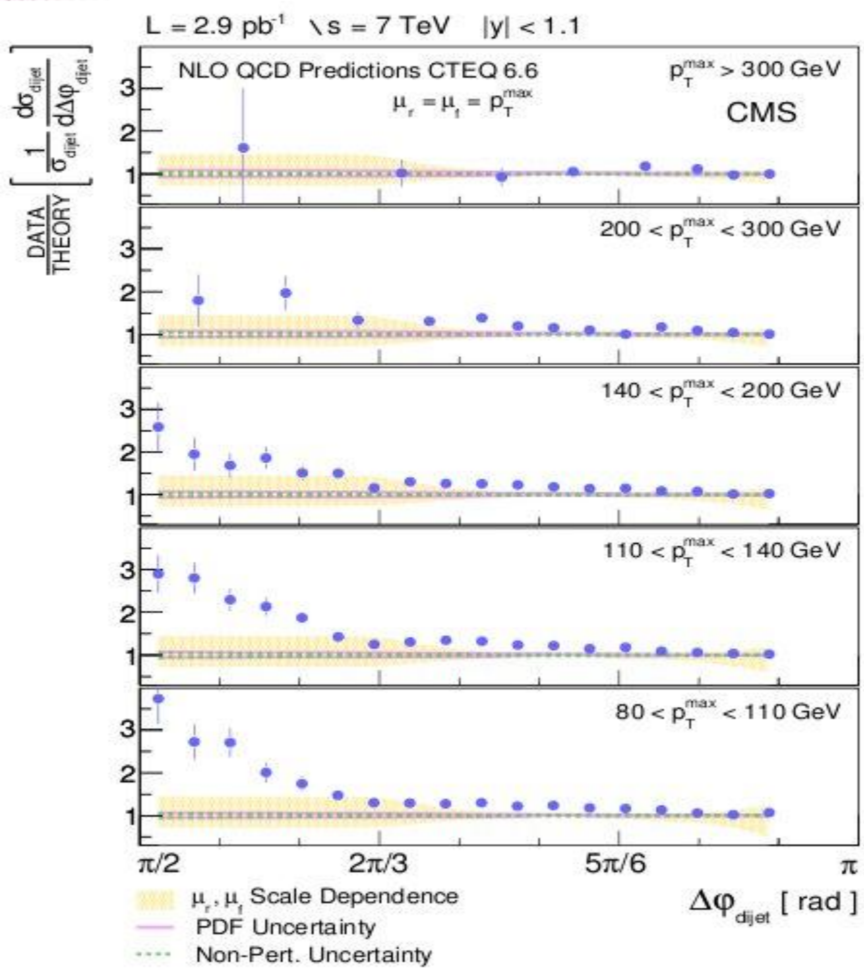
Consistent with NLO calculations within Uncertainties, gives the constraint to PDFs.

CERN-PH-EP-2012-088, submitted to EPJC

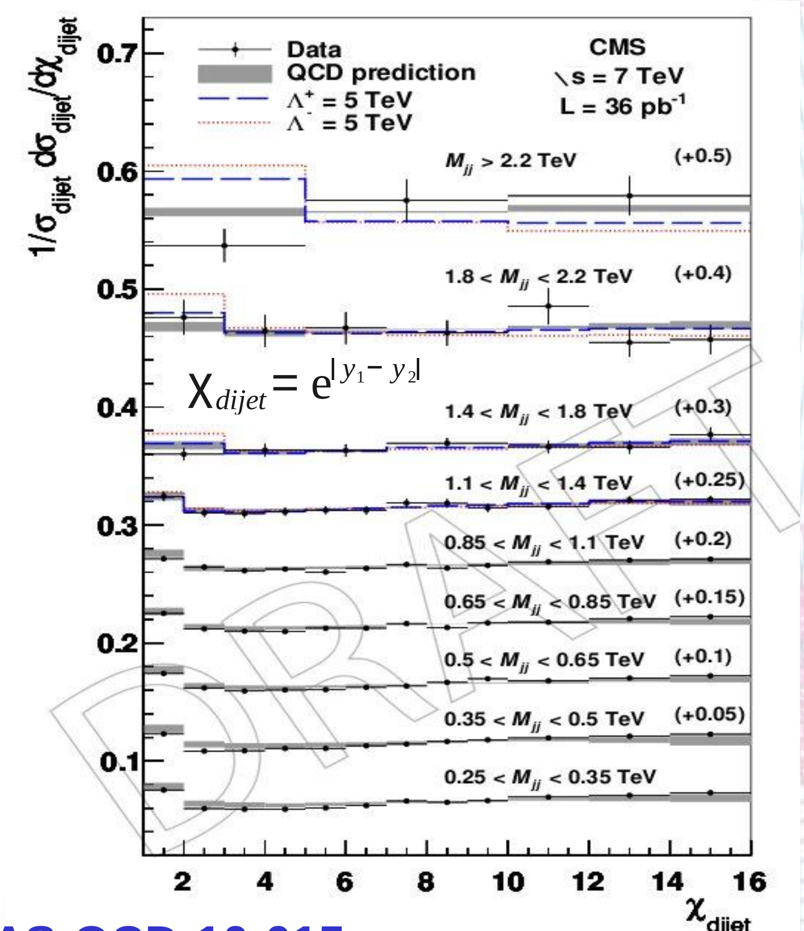
Dijet production: Δφ,Δη

Sensitivity to the initial and final state radiation.

NLO QCD (NLOJet++) + NP corrections
Disagree with data at small Δφ dijets
Where multiparton radiation effect dominates.



Good agreement of the dijet angular distribution with NLO QCD + NP corrections. A lower limit on the contact interaction scale 5.6 TeV(+), 6.7 TeV(-) is obtained.

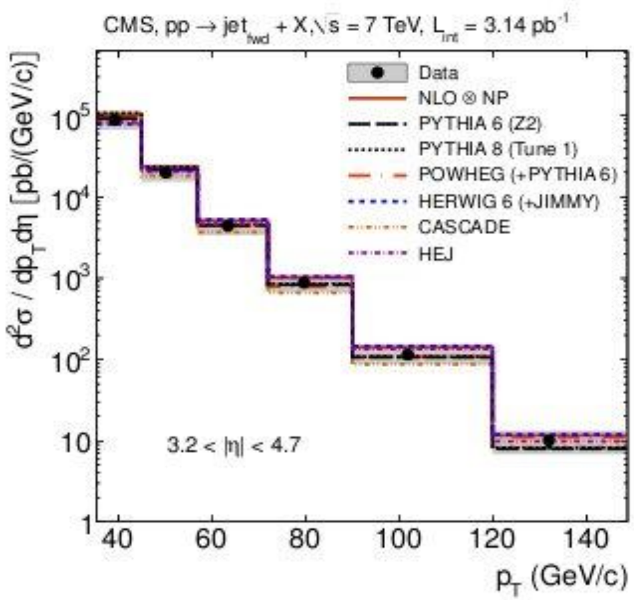


$$\chi_{dijet} = e^{|y_1 - y_2|}$$

CMS-PAS-QCD-10-015
PRL 106(2011)122003

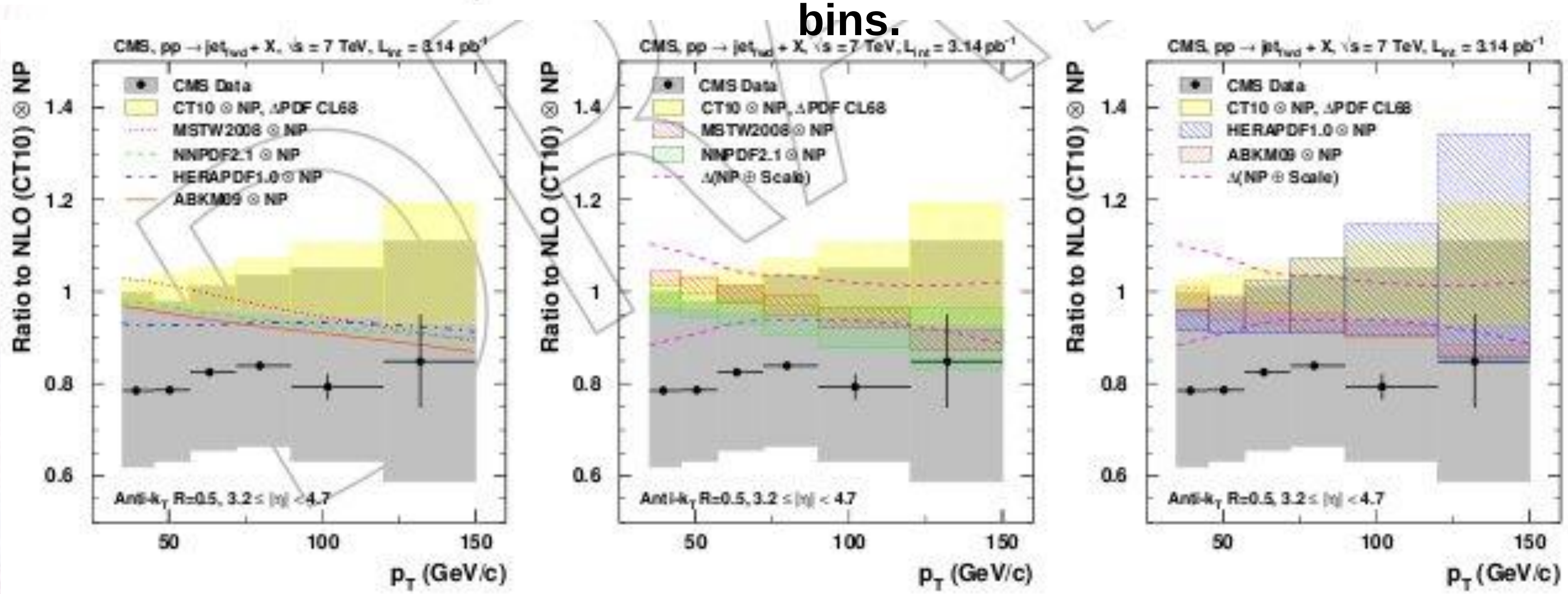
Inclusive forward jets production

Jet 3<|η|<5



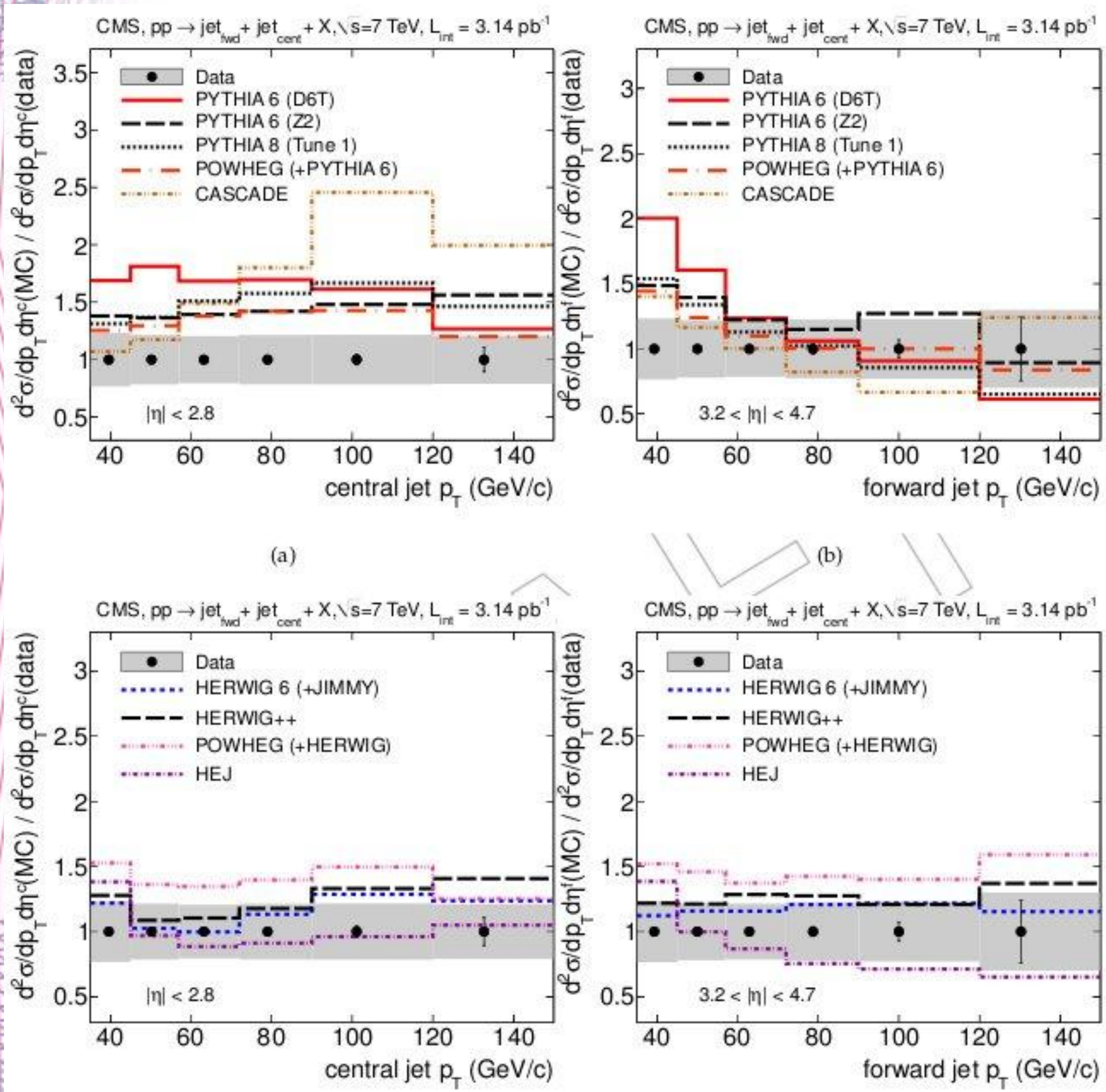
1. **DGLAP evolution + parton showering (PYTHIA6/8, HERWIG 6) with the different UE tunes DGLAP with angular ordered shower (HERWIG++ 2.3)**
2. **NLO (POWHEG)+PYTHIA6 or HERWIG 6**
3. **NLO (NLOJET++, HEJ)+NP corrections**
4. **CCFM evolution (CASCADE) + uPDF**

Data are in agreement with NLO calculations withing systematic uncertainties although NLO calculations are systematically overestimate cross-section in all rapidity bins.



JHEP06(2012)036

Central-forward dijets



One jet |η|<2.8
Second jet 3<|η|<5

HERWIG6, HERWIG++ agrees both with central and forward jets flow

HEJ shows the reasonable agreement with dijet data

All PYTHIA tunes and NLO contributions from POWHEG overestimate data

Valuable test of pQCD; possibility to constraint models

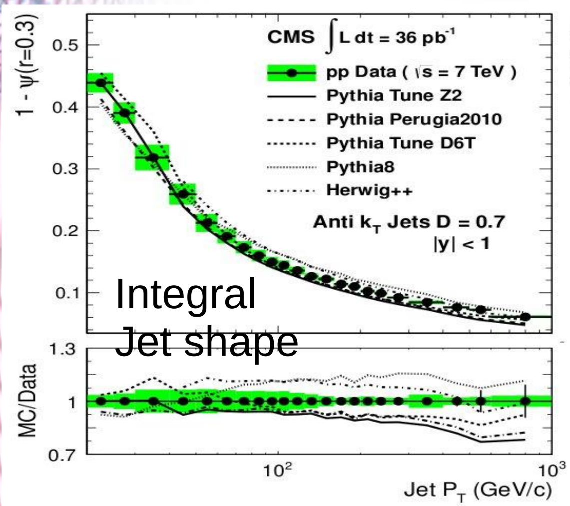
JHEP06(2012)036

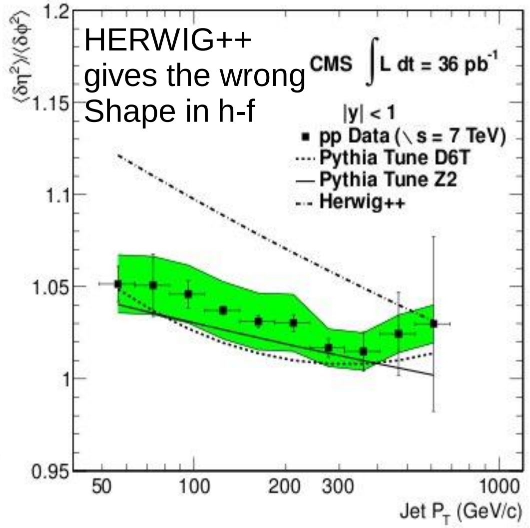
Jets properties: charged particles multiplicity, shape

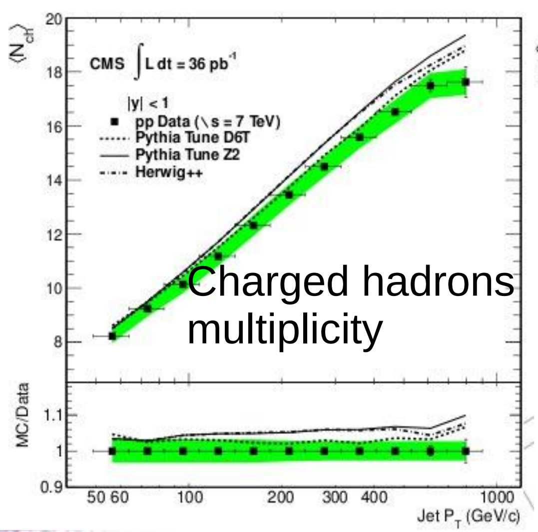
$$\langle \delta R^2 \rangle (p_T) = \langle \delta\varphi^2 \rangle (p_T) + \langle \delta\eta^2 \rangle (p_T)$$

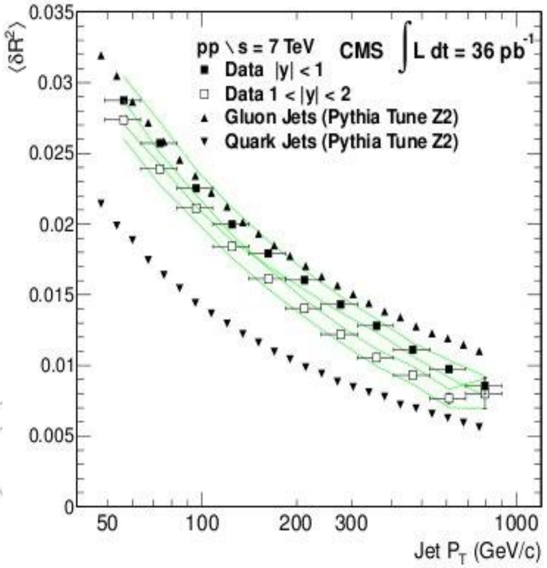
$$\langle \delta X^2_{jet} \rangle (p_T) = \frac{\sum_{i\in jet} (X_i - \langle X \rangle)^2 \cdot p_{T i}}{\sum_{i \in jet} p_{T i}}$$

X=η or ϕ









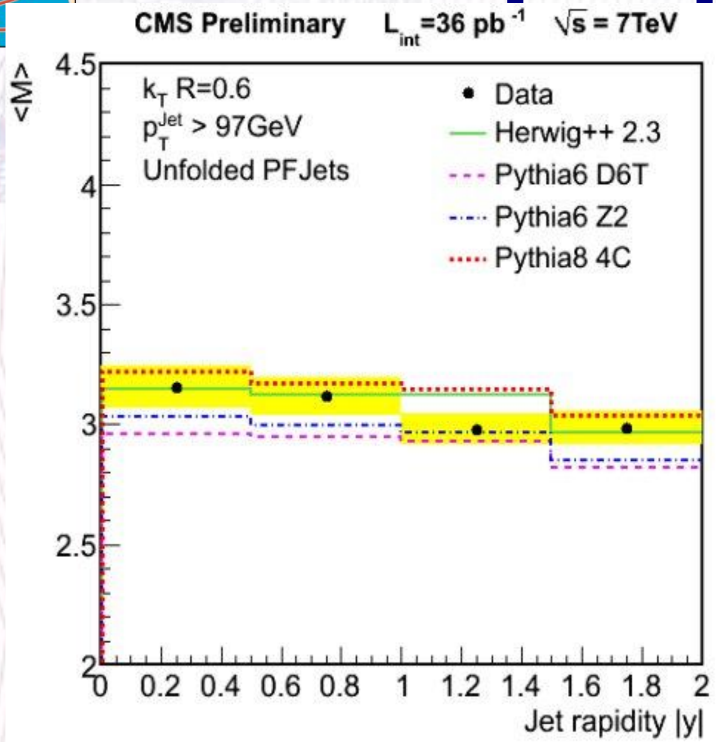
Unfolding to particle jets is done with bin-to-bin and Tikhonov regularization method with the quasi-optimal solution.

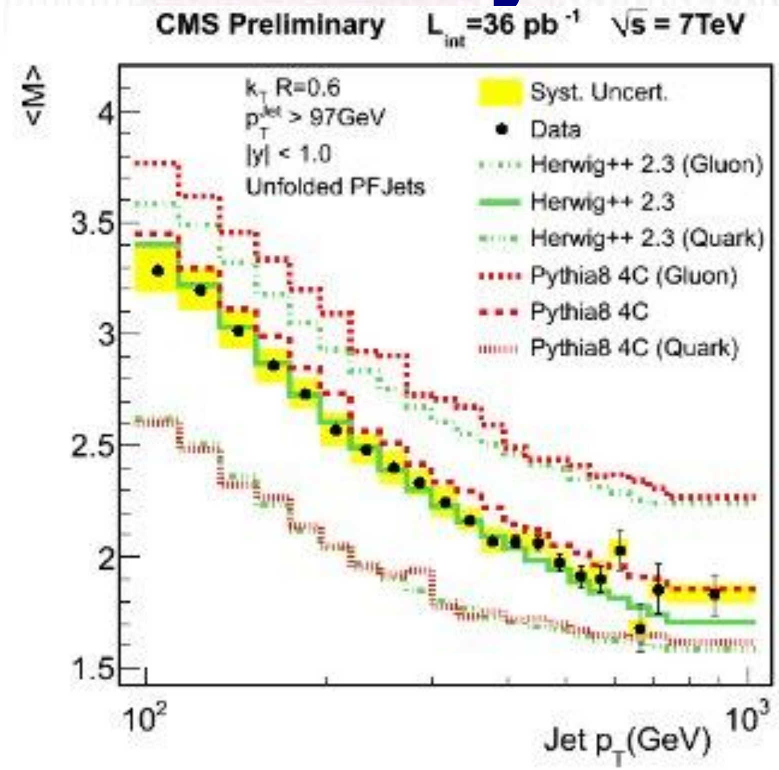
Jets become narrower with increasing p_T and |y|

Agreement with predicted increase in the fraction of quark-induced jets at higher jet p_T and |y|

Results gives impact to modeling PDFs, parton showering, fragmentation function

Jet properties: subjets



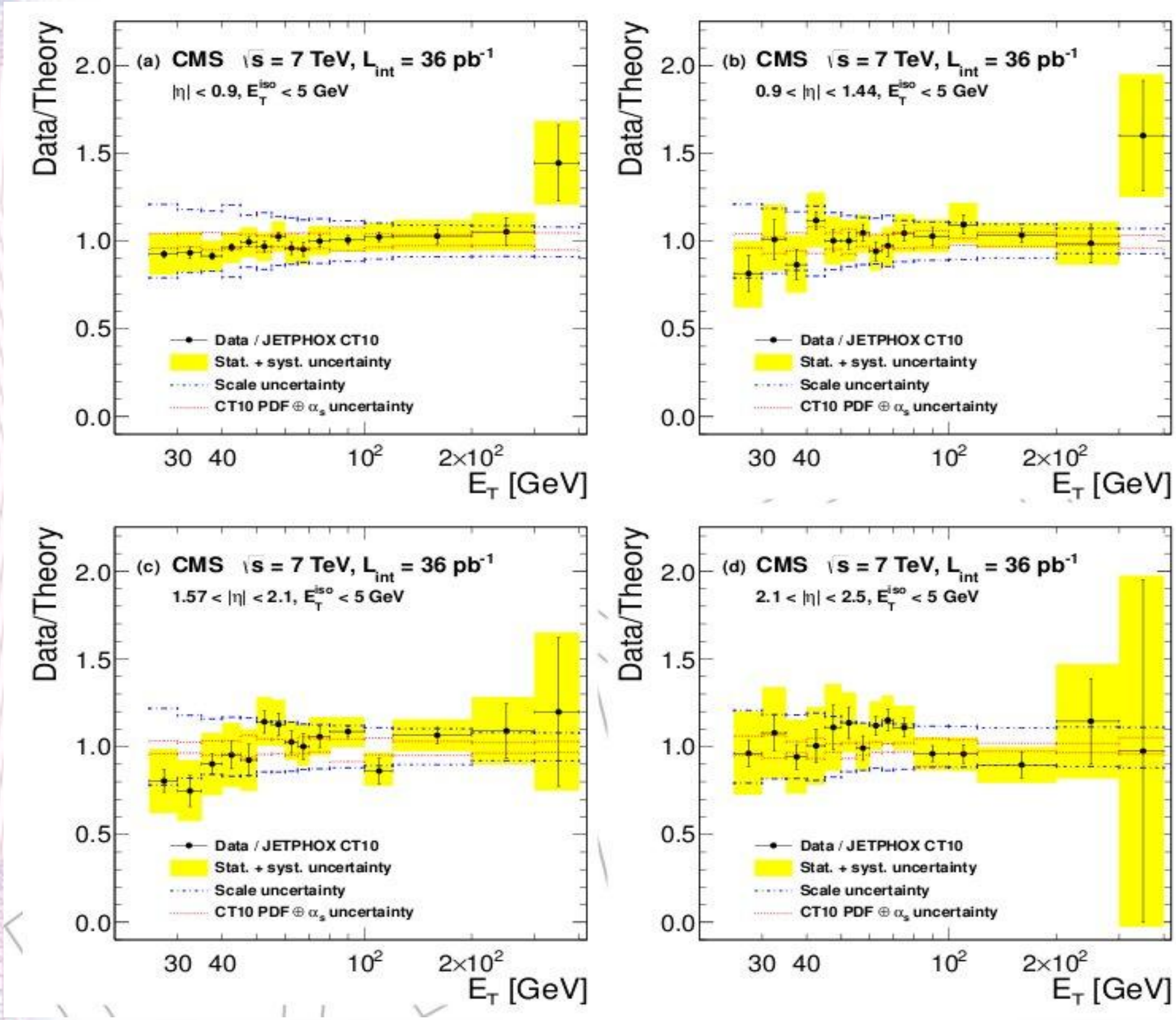


KT algorithm with parameter R=0.6 and a subjet resolution cutoff of r=10^{-3} was used for subjet reconstruction

dAgositini Multidimensional unfolding method was used to unfold distributions to the particle level jets.

The average subjet multiplicity decreases with increasing jet p_T
Fraction of the quark-induced jets increases with jet p_T and |y|
The best agreement is achieved with HERWIG++ (but see previous slide – HERWIG++ gives the wrong shape in $\eta-\phi$ plane)

High-pT photon production

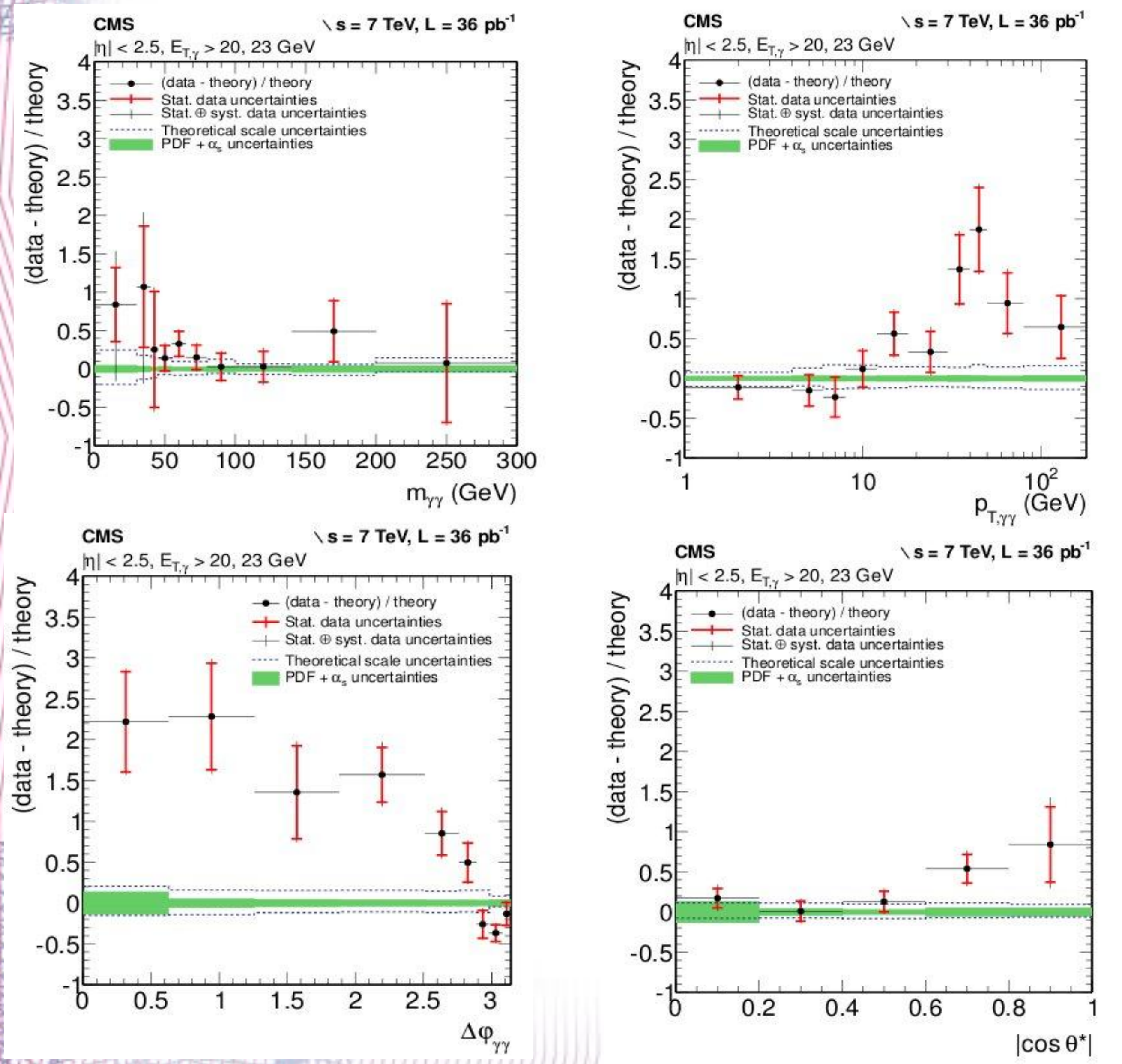


Bin-to-bin unfolding is performed

Predictions from the NLO pQCD (JETPHOX)) agrees with Data except low p_T photons where NLO predictions tends to overestimated data.

PRD 84 052011 (2011)

Di-photon production



Unfolding to the particle level is done via Inverted matrix.

Annihilation: qq → γγ
Fusion: gg →γγ
Fragmentation: qg → γγq

Calculation is done at NLO with DIPHOX,GAMMA2MC

The overall agreement in diphoton mass spectrum

The theoretical predictions underestimate the measured cross section for $\Delta\varphi_{\gamma\gamma} < 2.8$

JHEP01(2012)133

Summary

- CMS measures both hard and soft QCD processes in the different phase space regions comparing with the wide range of LO and NLO calculations
- The data are, in general, in broad agreement with the perturbative predictions, but enough discrepancies are observed to keep us busy for a while.

Bonus material