CMS QCD physics results

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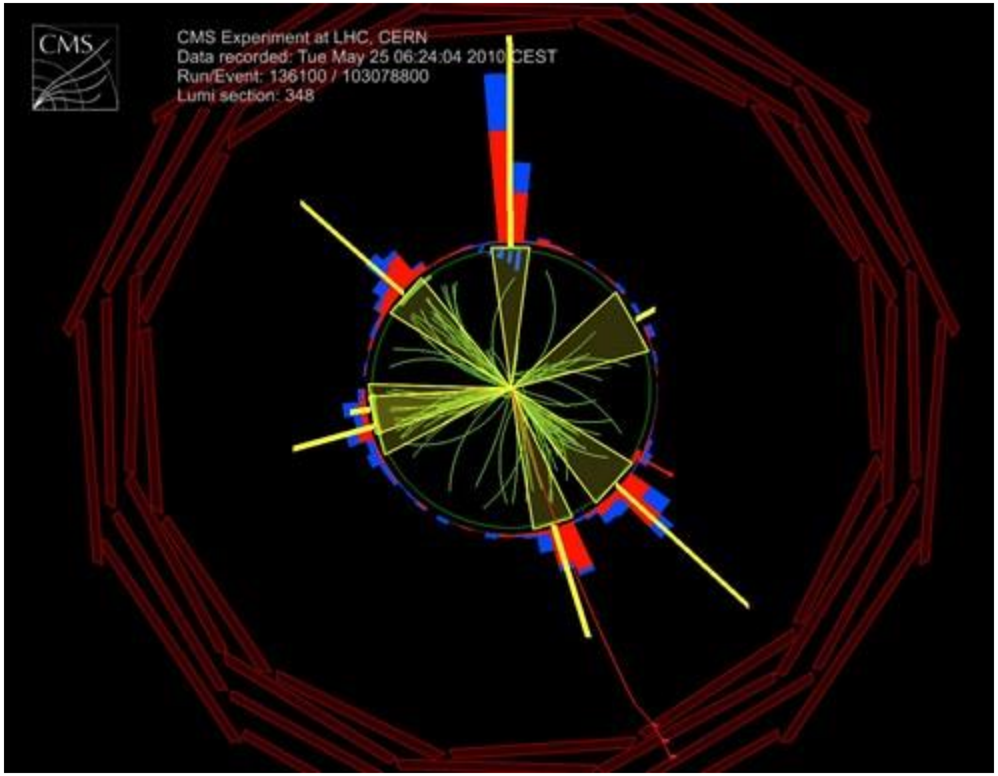
on behalf of the CMS Collaboration



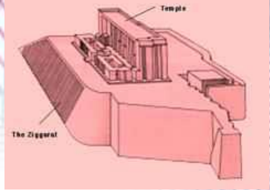
Outline

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

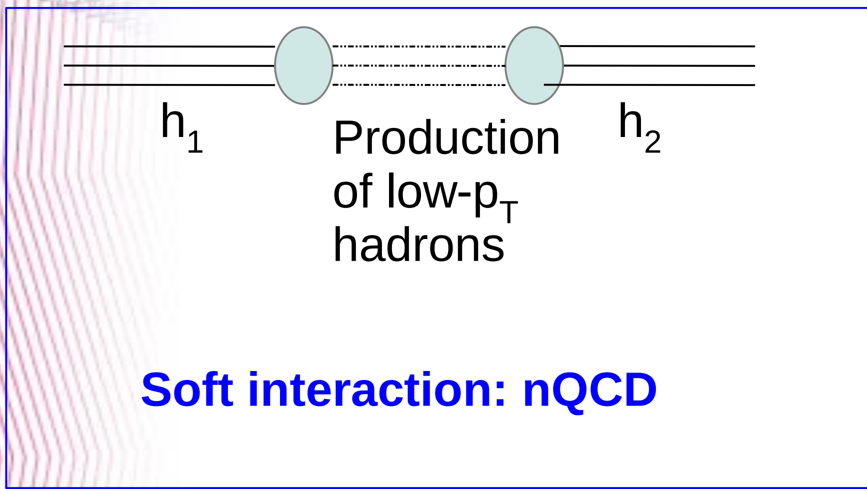
Motivation

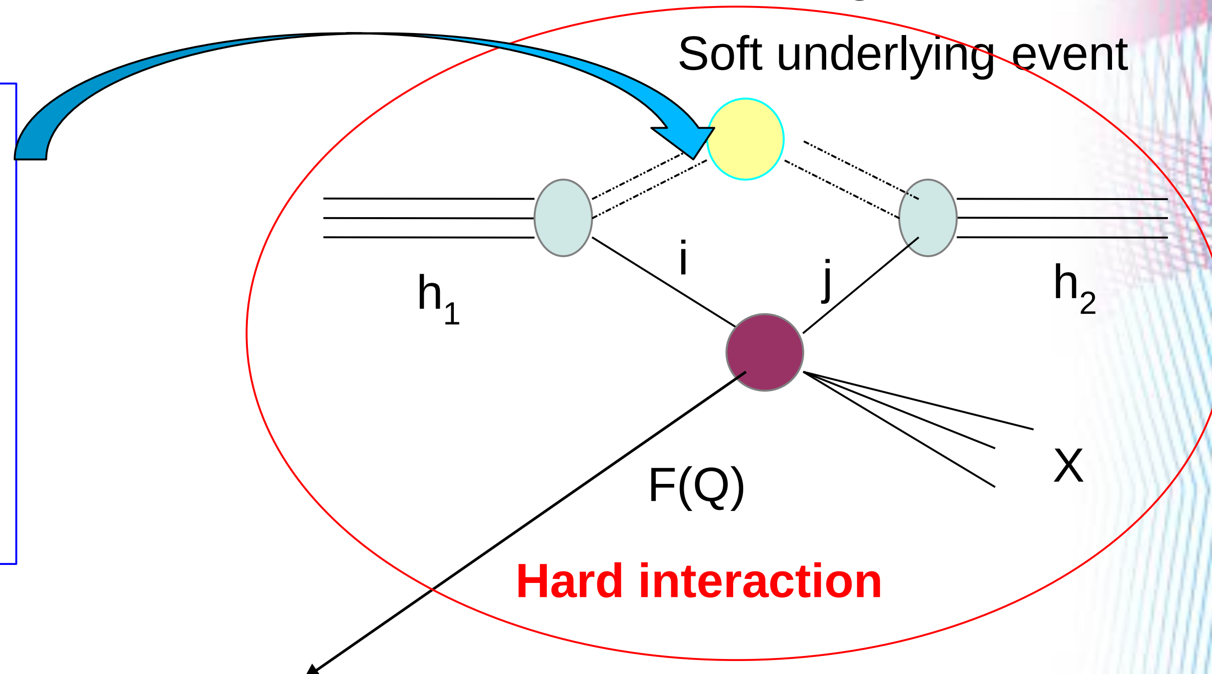
- QCD is the constituent of the Standard Model which deals with strong interactions
- The verification of the QCD validity is the first step towards the new Physics.
    - QCD processes are background to the Higgs production, SUSY, many BSM models, rare processes that are scope of the Standard Model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

QCD at hadron colliders



In hadron collisions all phenomena are QCD related but we should distinguish between Soft and Hard physics.





Factorization theorem

$$\sigma(P_{h_1}, P_{h_2}) = \sum_{i,j} \int dx_1 dx_2 f_{i/h_1}(x_1, \mu_F^2) f_{j/h_2}(x_2, \mu_F^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2; \mu_F^2, \mu_R^2)$$

Parton distribution function (PDF)

Partonic cross-section computed in pQCD

$p_1 = x_1 * P_1$, $p_2 = x_2 * P_2$

μ_F – factorization scale separates long and short distance physics

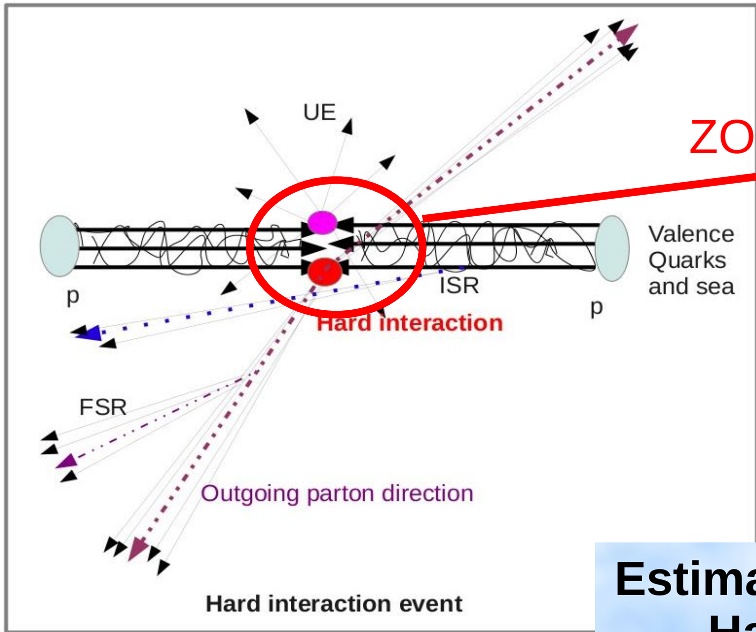
α_S (μ_R) – running coupling constant

$Q^2 = -q^2$ – transferred momentum

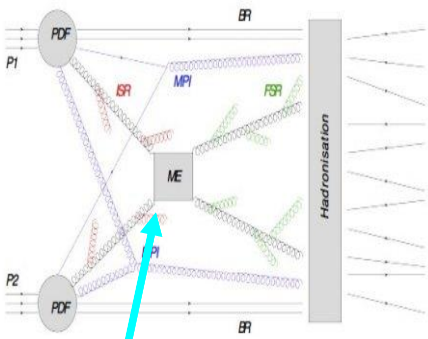
$$\hat{\sigma}_{ij} = \alpha_S^k \sum_n \left(\frac{\alpha_S}{\pi}\right)^n \sigma_{ij}^n$$

Lattice calculation
Fixed-order QCD:LO, NLO,NNLO + PS

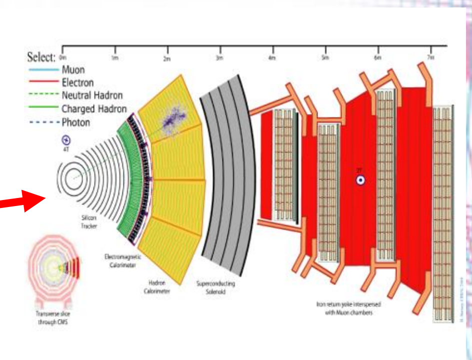
How do we proceed



ZOOM



particles



2 step unfolding
meet at particles level

Reconstructed particles, reconstructed jets

Differential Cross-sections
Multiplicity
Rapidity
Momentum of Particles and Jets,
missing E_T

Estimate:

- Hard interaction cross-section
- Parton Distribution Functions
- Parton showering details

Theory approximations
Perturbative QCD (pQCD):
LO, NLO, NNLO calculations, ME + parton showering, threshold resummation
non-pQCD: (Multi-parton interactions (MPI), String/Cluster fragmentation models)

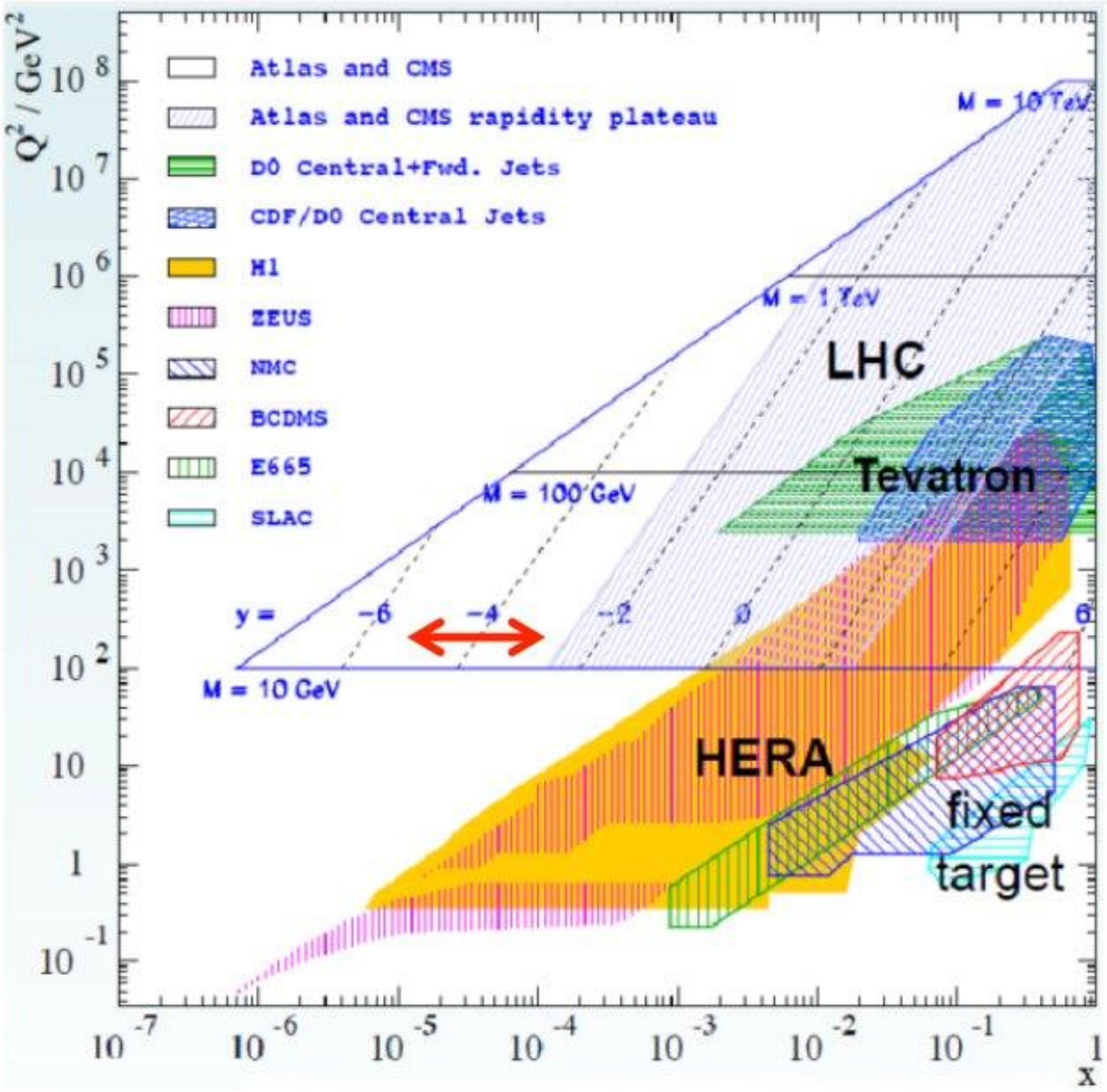
Where we are now

Probing the new territory (x,Q^2) range

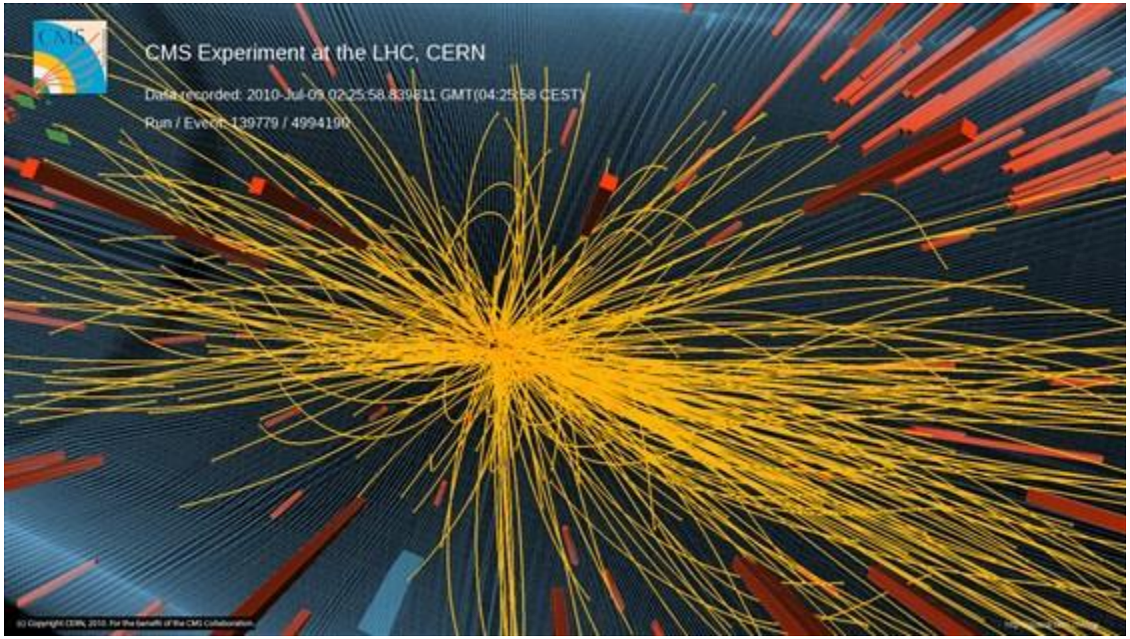
QCD is always present

Important background for new physics searches

- **enormous cross section: QCD can hide many possible signals of new physics**

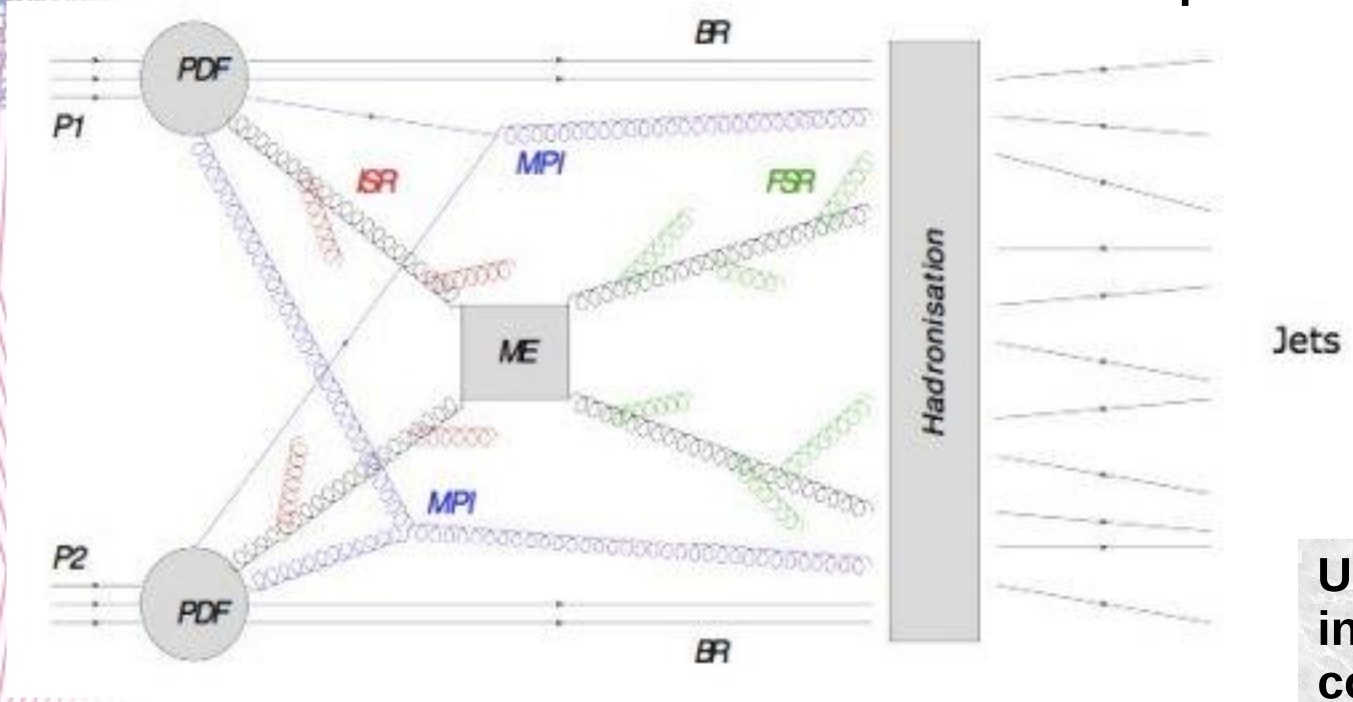


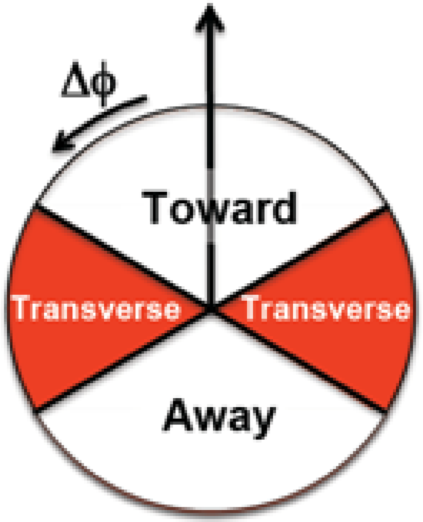
Soft particles production, Underlying event (UE)



Underlying event

Soft and hard components





UE activity is typically studied in the transverse region in pp collisions as a function of the hard scale of the event, and at different centre-of-mass energies (√s):

Particle production in MinBias events or events with high energy track or jet (hadronic events)

Drell-Yan events

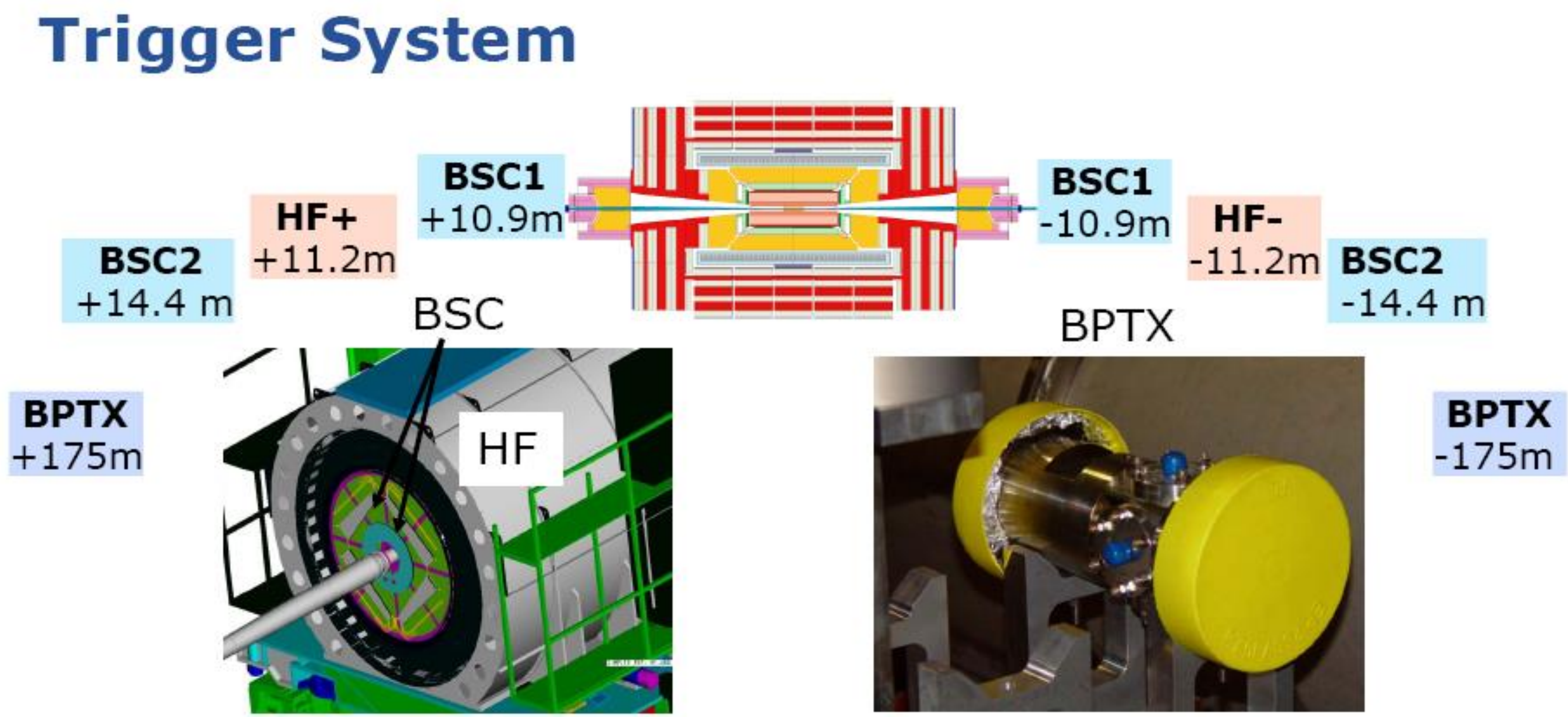
Everything in event that is not hard interaction (ME): soft&semi-hard interactions which are not described with pQCD

Beam remnants (BR): what remains after the interacting partons left the hadron

Initial (ISR) and final (FSR) state radiation

Multiple Parton Interactions (MPI). If higher pt interactions → Double Parton Scattering

MinBias (MB) events selection



Trigger :

Beam crossover

Activities in forward calorimeters & scintillators

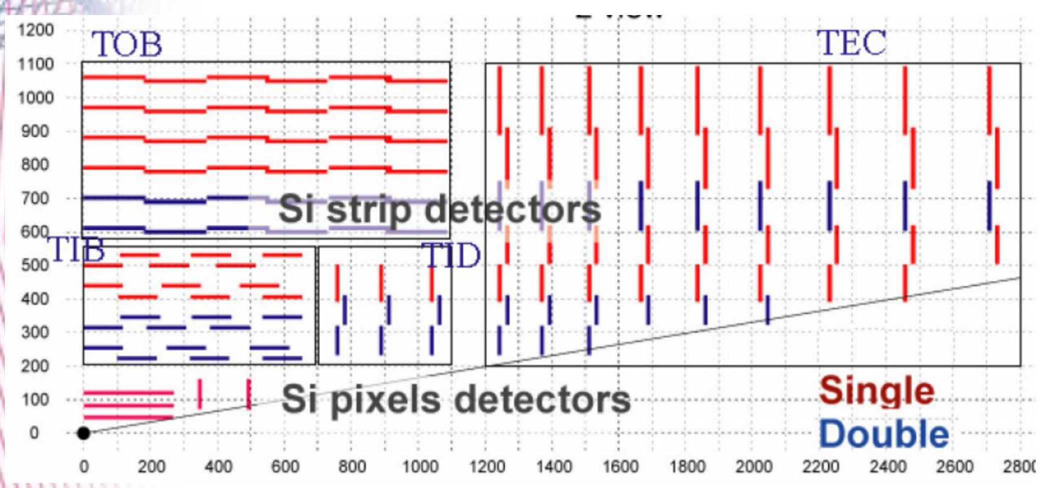
Offline event selection :

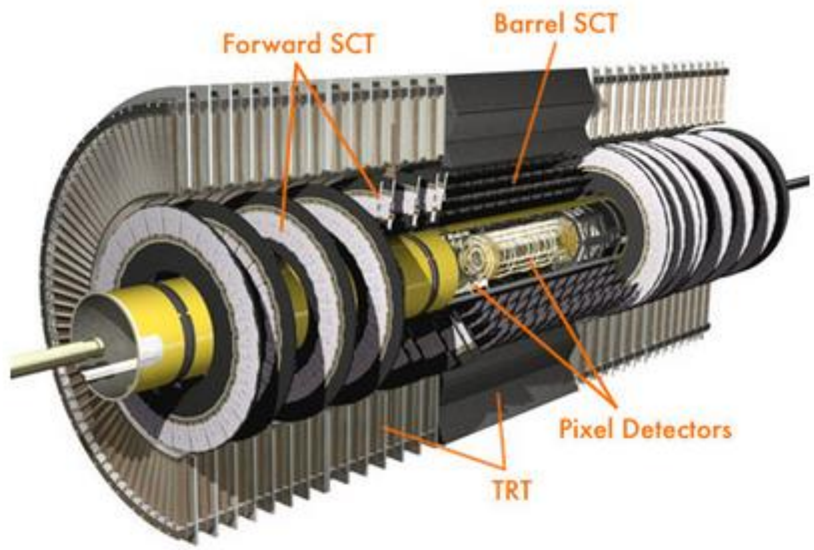
rejection of the beam halo & beam background

selection of main primary vertex

some diffraction rejection cuts if needed

Charged particles reconstruction





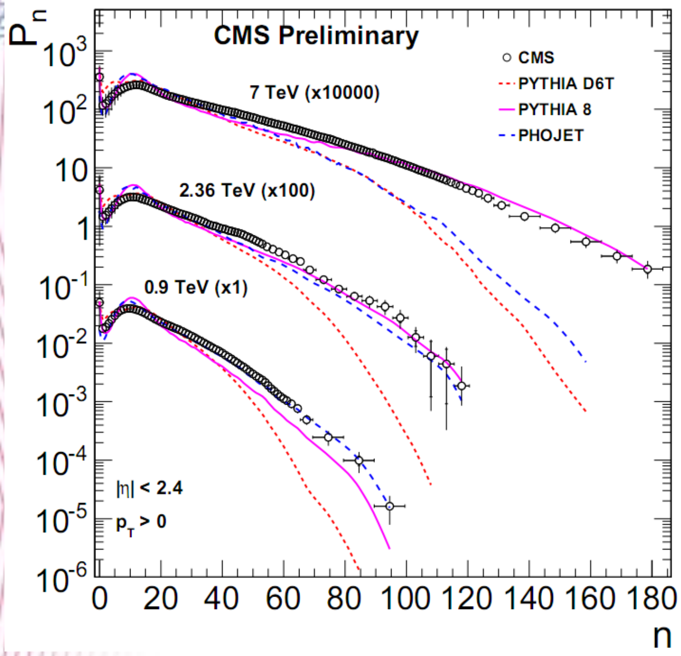
Acceptance |η|<2.5

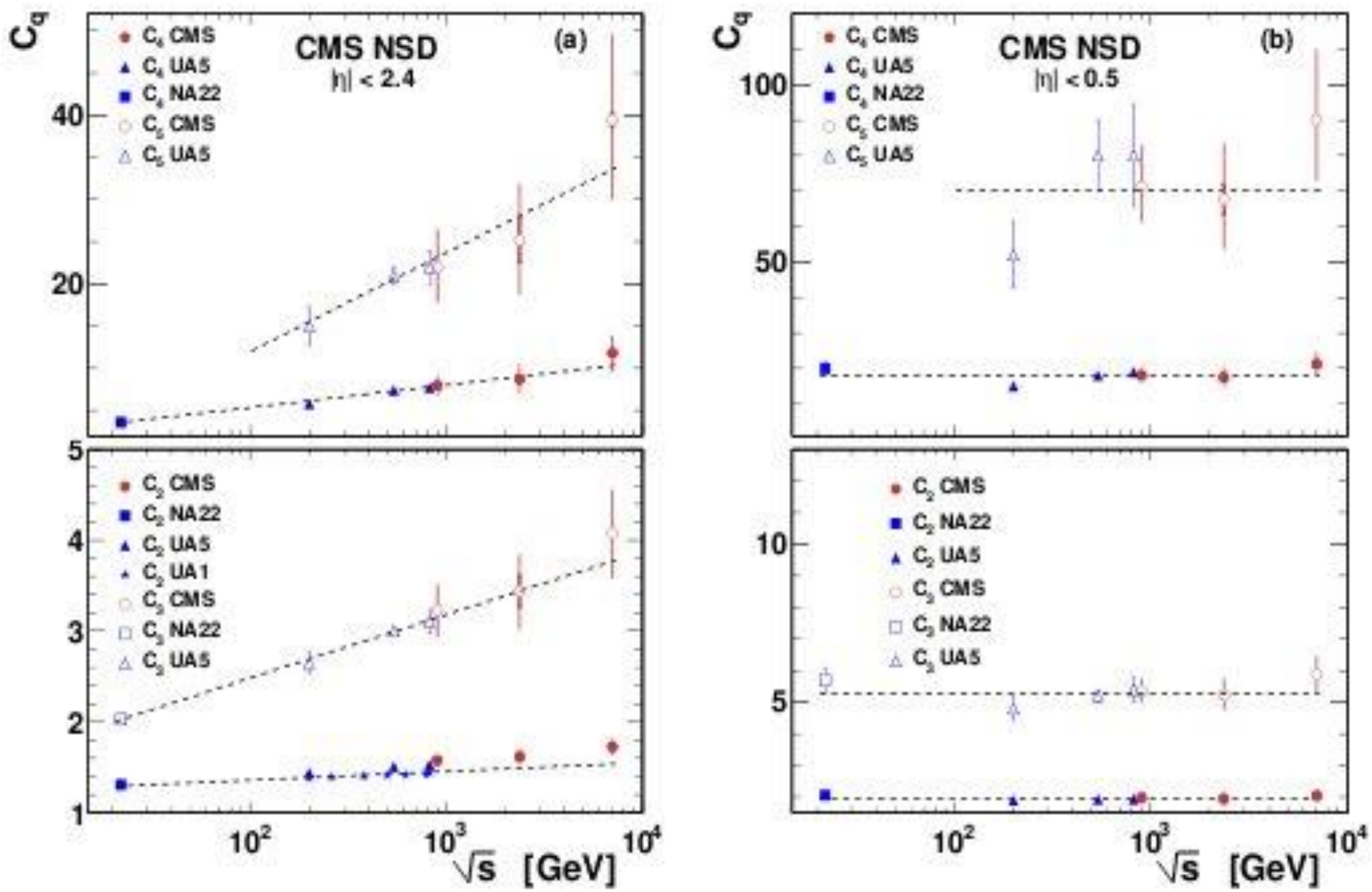
Standard tracking down to 100 MeV

Dedicated low p_T tracking used for some measurements

Particles identification is available for low-p_T hadrons via energy losses in: pions, kaons, protons

Charged particles multiplicity





Evidence of the multi-component structure (change of the slope at n~20)

Violation of the KNO (Koba-Nielsen-Olesen) scaling (z=n/<n> distribution independent on collision energy) in the range |η|<2.4

Still KNO scaling in the range |η|<0.5

KNO scaling suppose the independence of C_q on the collision energy.

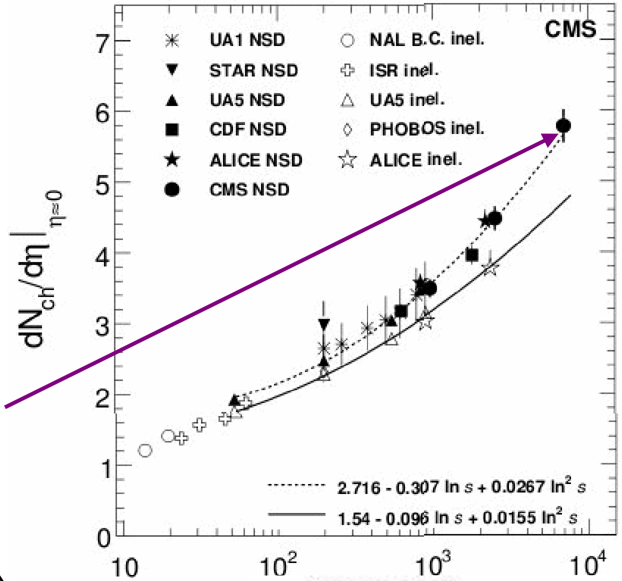
$$C_q = \frac{\langle n^q \rangle}{\langle n \rangle^q}$$

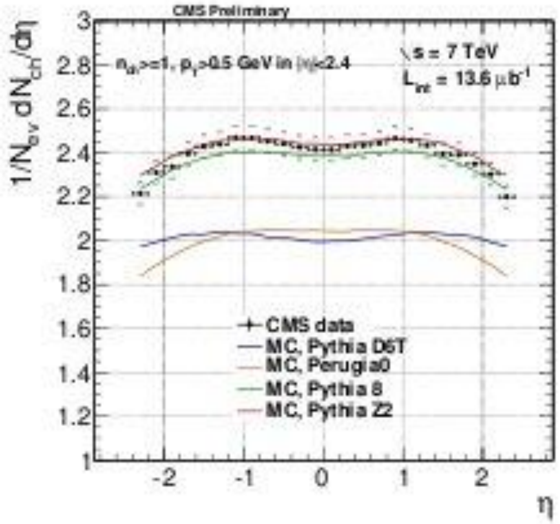
JHEP01(2011)079

Charged particles density p_T, η (0.9 TeV-8 TeV)

Measured NSD multiplicity is higher then most of the predicted:

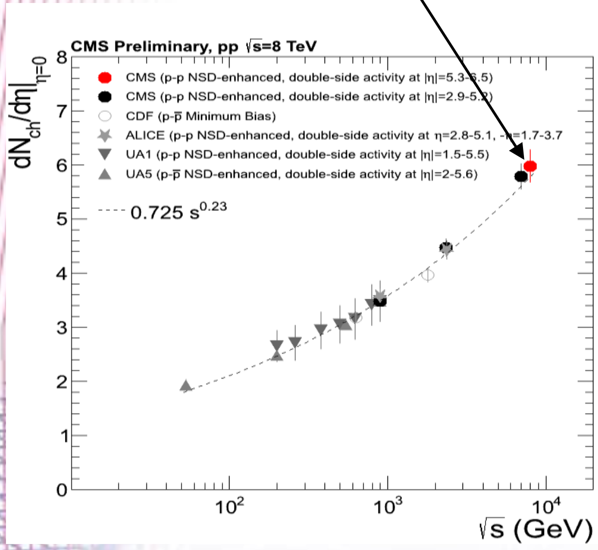
new input to the dynamics of soft hadronic interactions

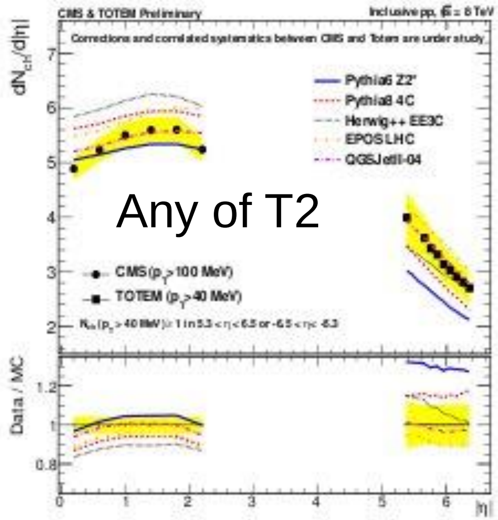


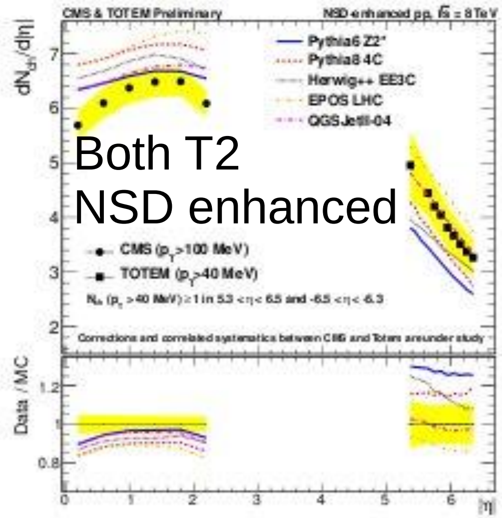


p_T>0.5 GeV/c

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



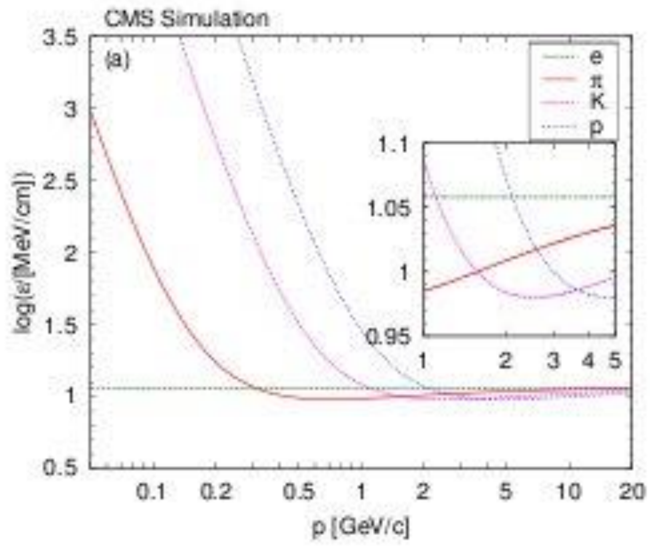


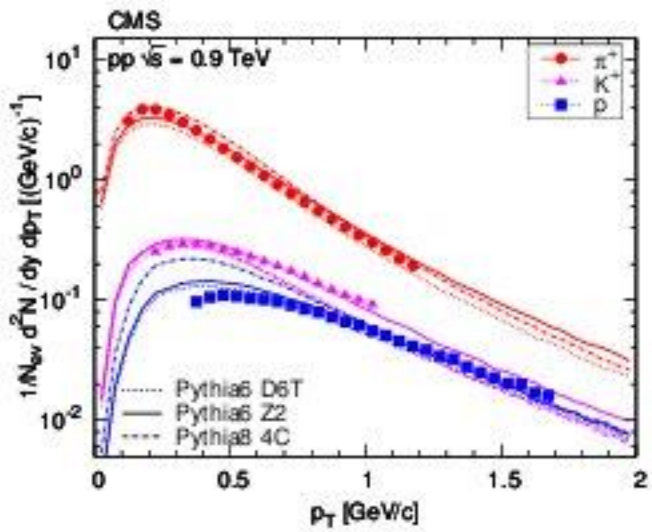


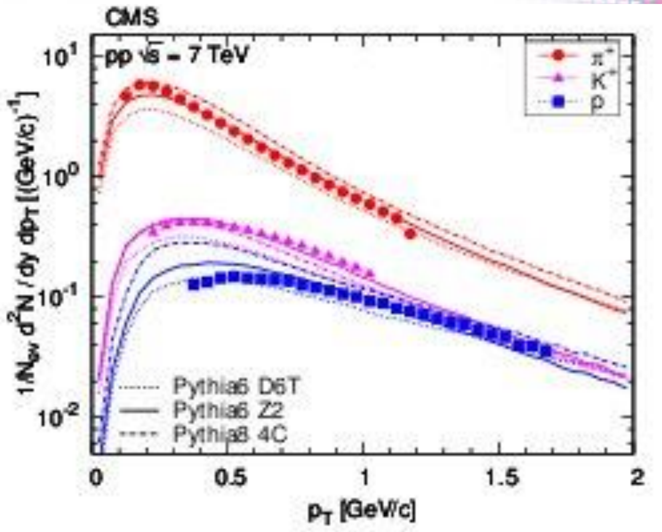
8 TeV: Triggered by Totem T2

PRL 105(2010) 022002
CMS-PAS-FSQ-12-026
CMS-PAS-QCD-10-024

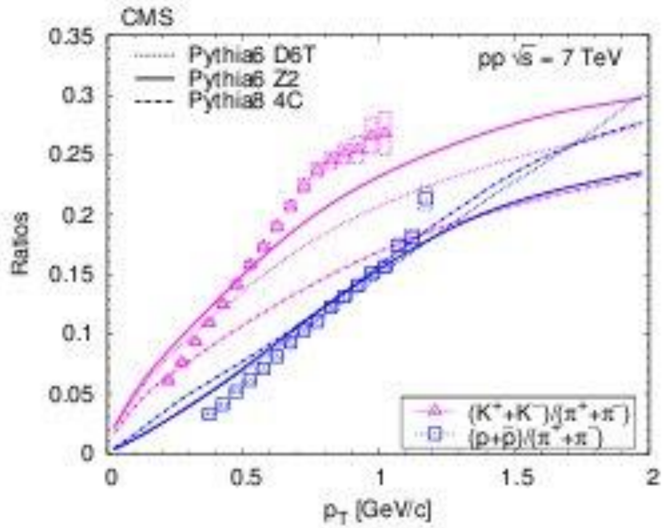
Identified particle spectra

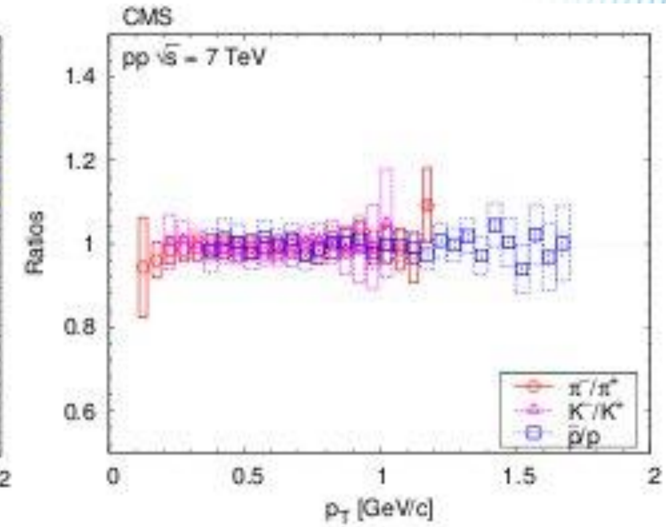






Identified via dE/dx in the silicon layer of the tracker and number of hits per track, track quality in η-p_T bins: combined fit.



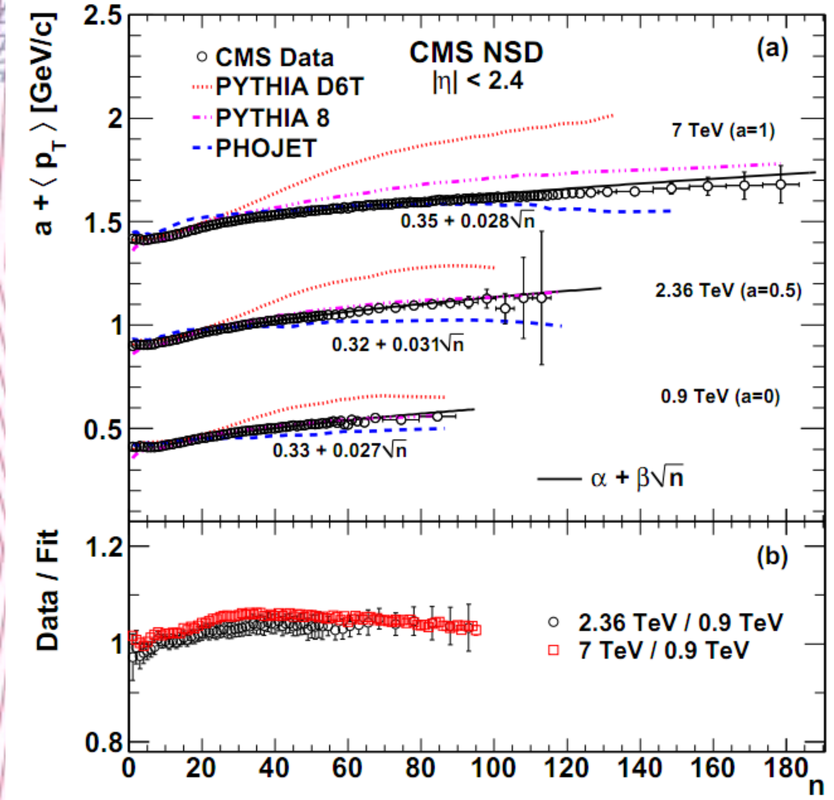


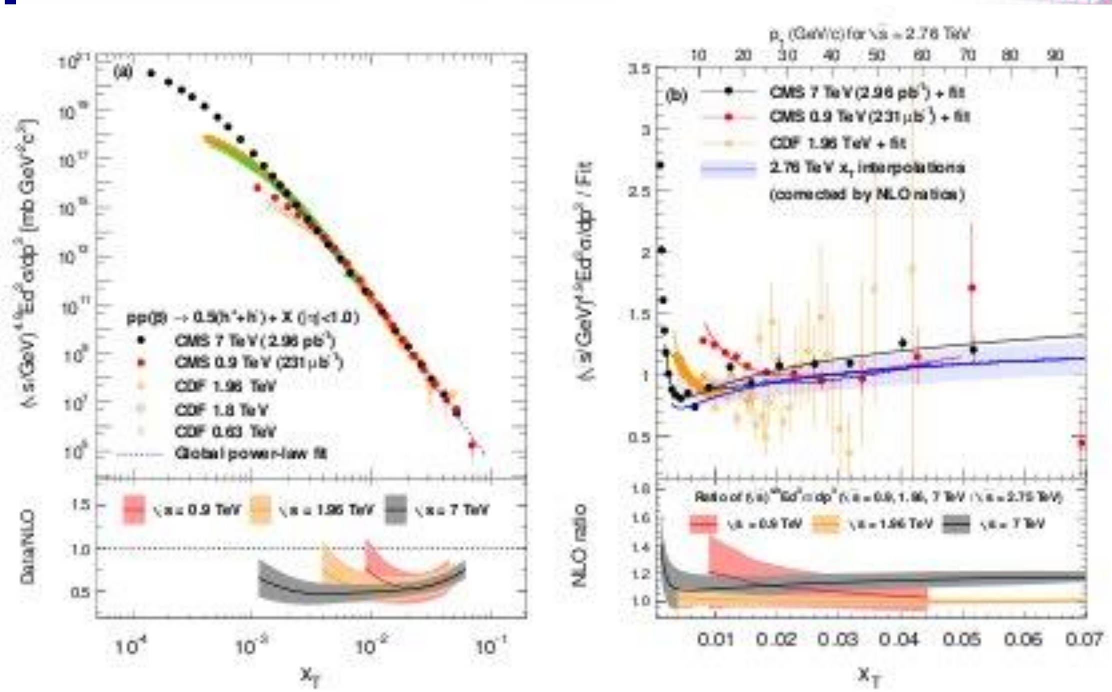
Charged hadrons: pions, kaons protons in p_T range 0.1-2 GeV

CMS results consistent with existing results at low √s. Spectra also measured differentially in bins of particle multiplicity, to further constrain hadron production models.

EPJC72 (2012) 2164

p_T&x_T-Scaling





Soft particles:
The rise of the <p_T> with multiplicity is energy independent

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

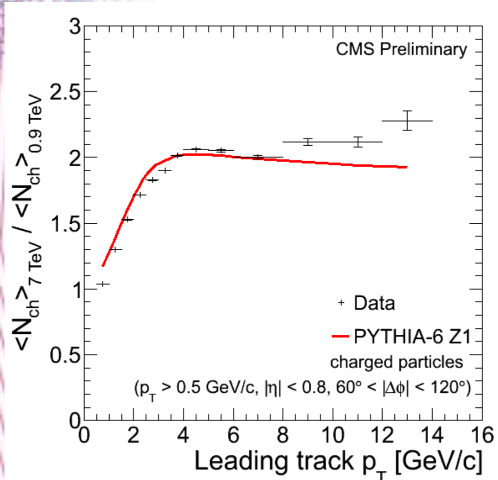
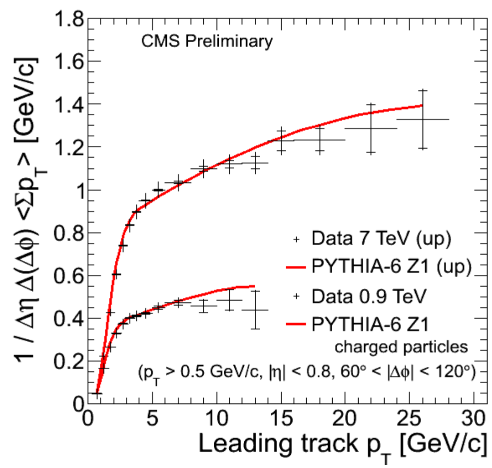
NLO calculations overestimates cross-section twice at all energies for high p_T hadrons

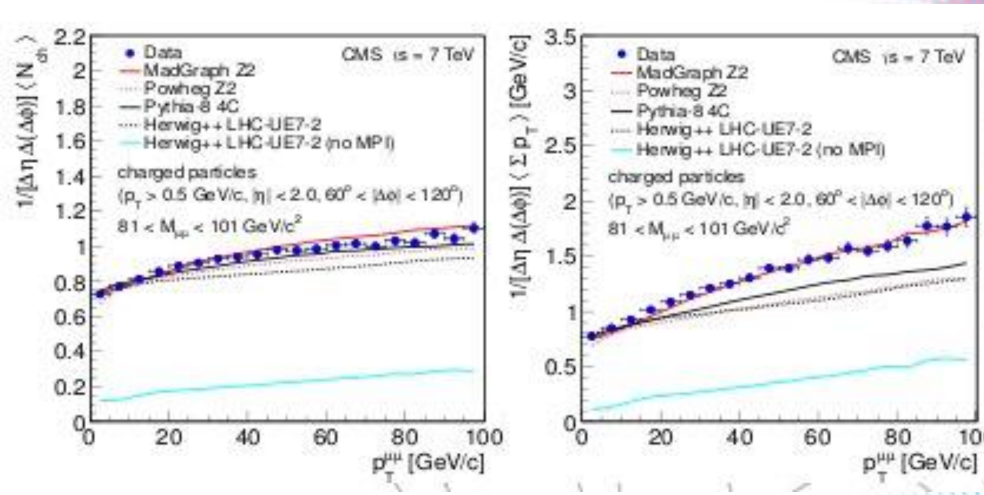
Sensitive to the interplay between soft, semi-hard and hard particles production

JHEP 08 (2011) 086
JHEP 01 (2011) 079

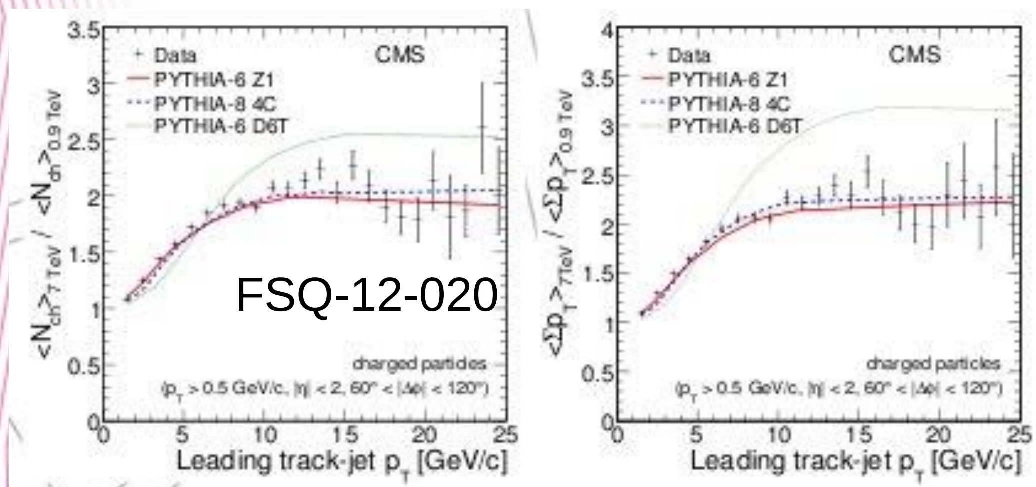
Underlying event

JHEP 09 (2011) 109
CMS-PAS-FSQ-12-020
EPJC 72 (2012) 2080

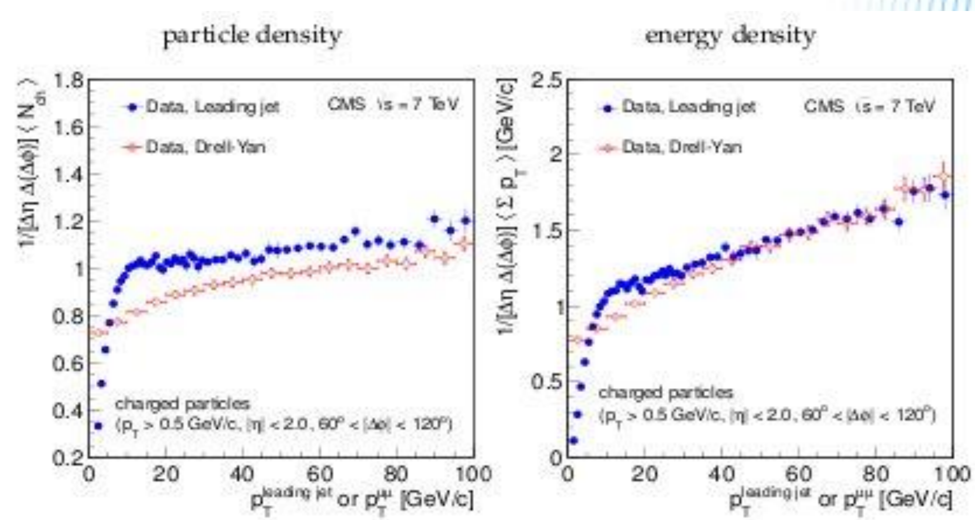





UE in DY events

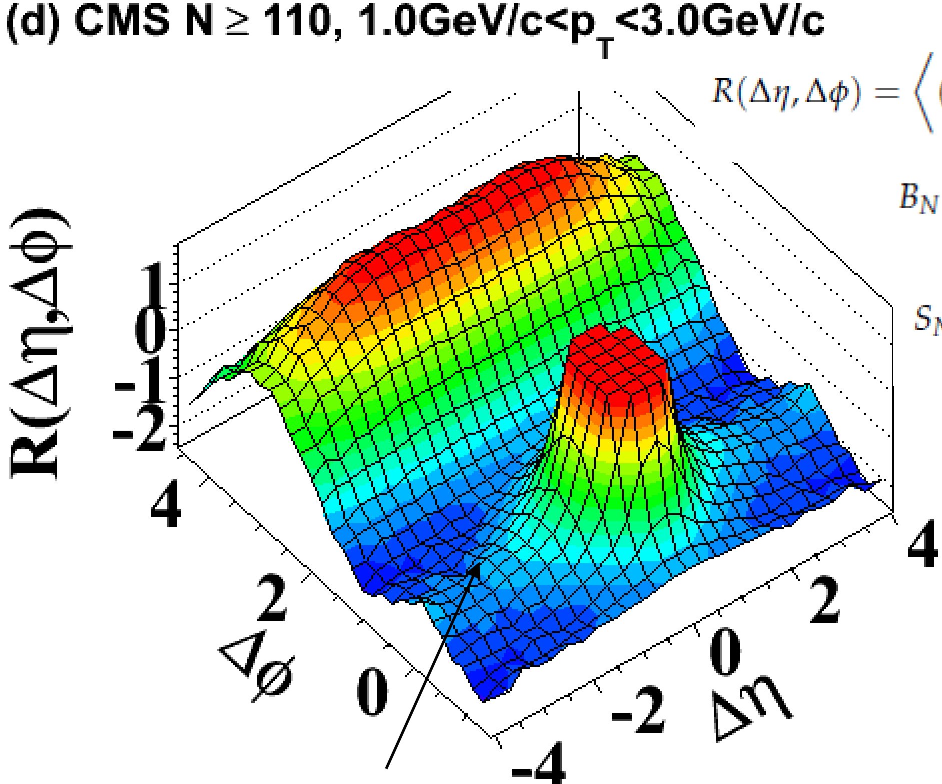


UE in hadronic events with leading track or track jet reflecting the direction of the parton. Sensitive to ISR,FSR,MPI



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

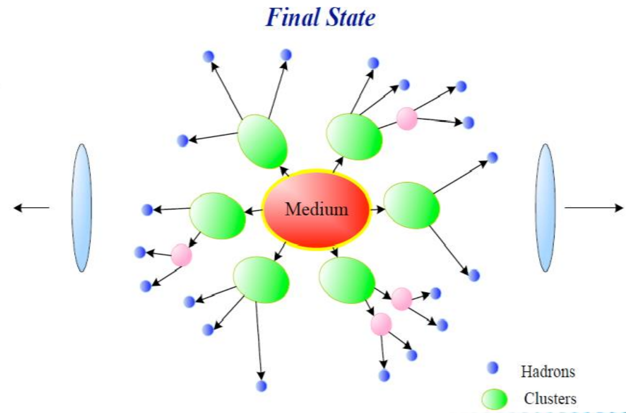
Long range correlations

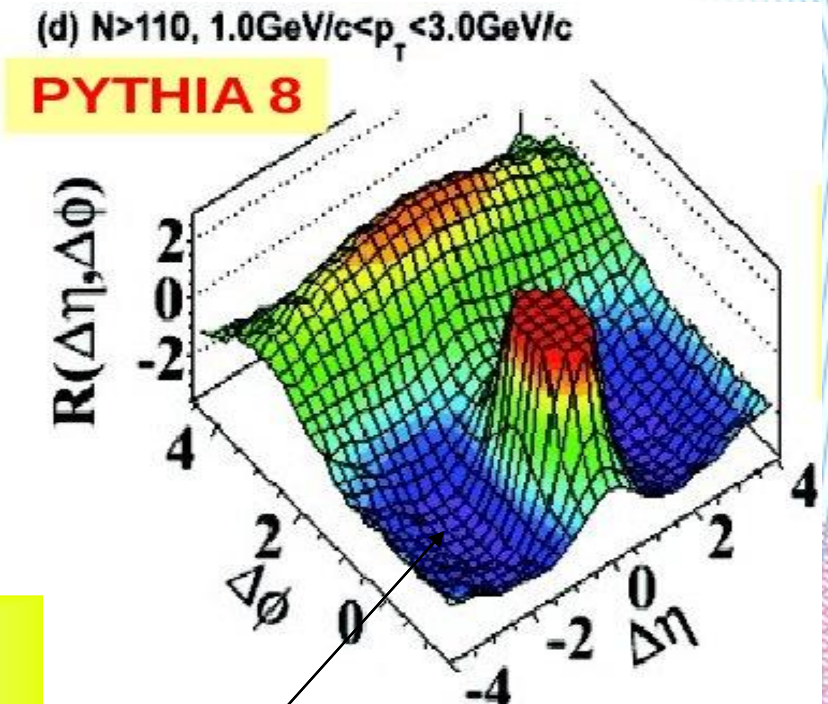


$$R(\Delta\eta,\Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

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

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





Observation of a LongRange, NearSide angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at $\Delta\varphi \sim 0$)

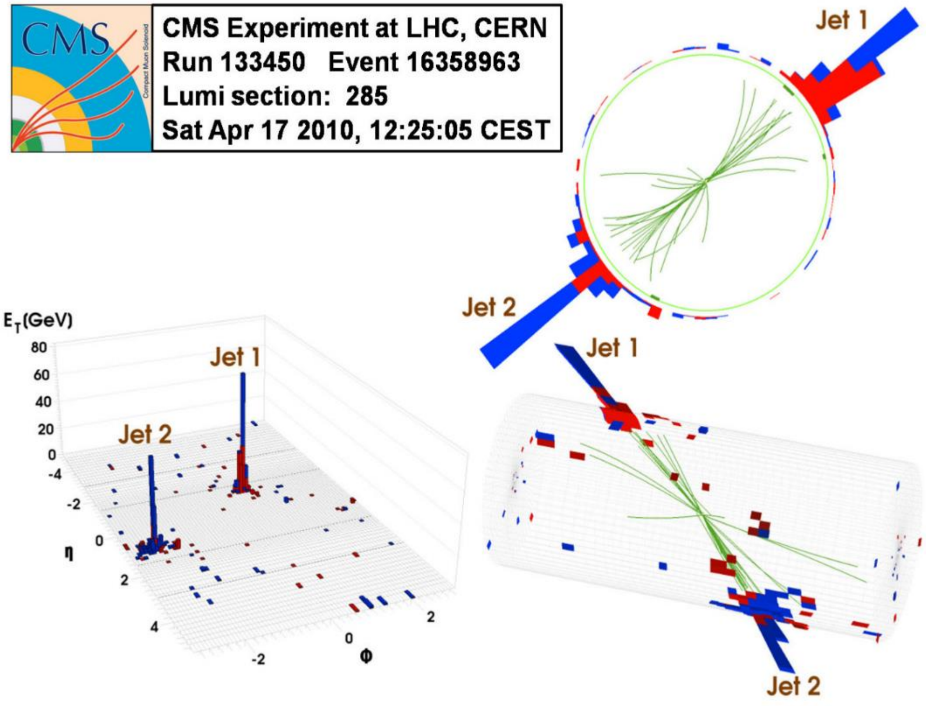
Firstly observed At RICH in Au-Au collisions

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

Hard interactions



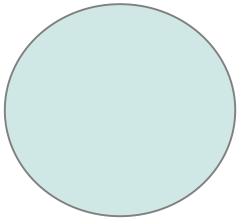
CMS, 7 TeV, 2010 year

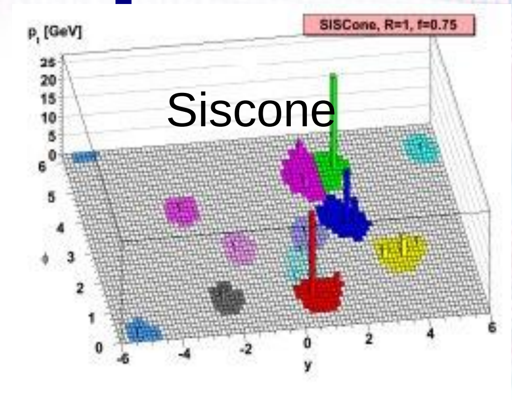
Jet clustering techniques

Fixed cone algorithms:

Iterative Cone (CMS) / JetClu (ATLAS)
Midpoint algorithm (CDF/D0)
Seedless Infrared Safe Cone (SISCone)

Iterative cone



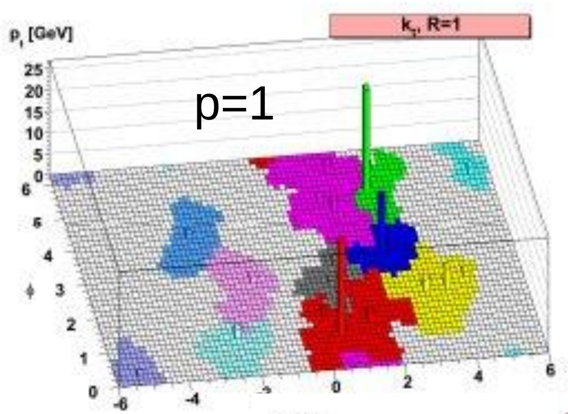


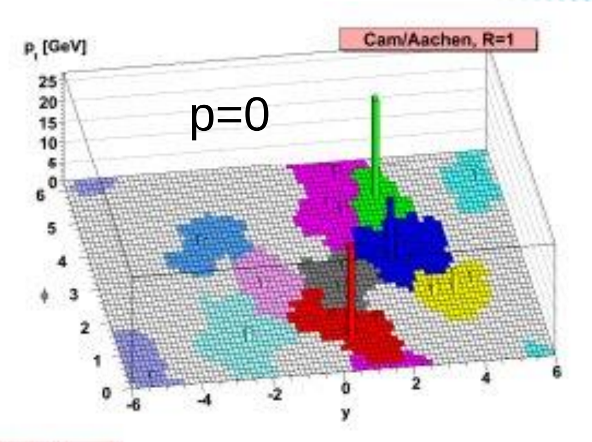
Successive recombination algorithms:

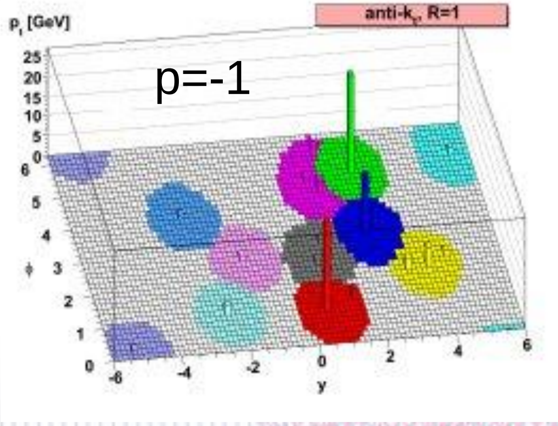
$$d_{ij} = min\left(k_{ti}^{2p}, k_{tj}^{2p}\right)\frac{\delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p}$$

if($d_{ij} < d_{iB}$) add i to j
and recalculate p_j







p=1 ->k_T jet algorithm
p=0 ->CA jet algorithm
p=-1 ->“Anti-k_T” jet algorithm

Typical size in $\eta-\phi$ space: $0.5<R<1$

JHEP04(2008)063

Jets reconstruction in subdets

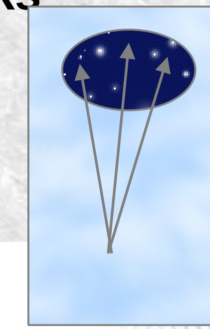
Calorimeter jets (CaloJets):
Jet clustered from Calorimeter Towers
Subdetectors: ECAL, HCAL

CaloMET

Selected subdetectors participate in reconstruction

Tracker jets:
Jet clustered from Tracks

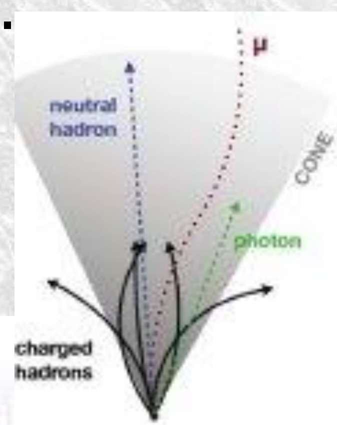
Subdetectors: Tracker



All subdetectors participate in reconstruction:
particle flow reconstruction in two branches
Full Light

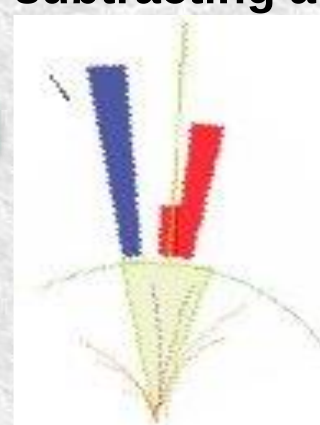
ParticleFlow jets full (PFJets):
Jet clustered from Particle Flow objects (a la generator level particles) which are reconstructed based on cluster separation.
Subdetectors: ECAL,HCAL, Tracker, Muon

PFMET

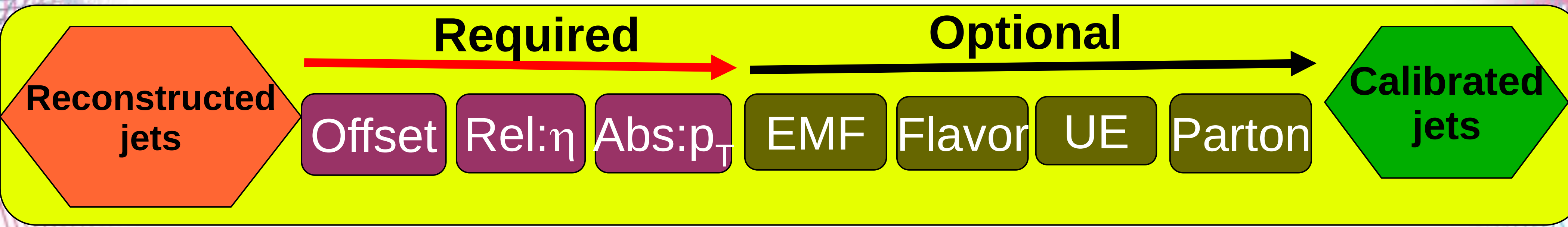


The residual jet energy corrections is applied on top of all algorithms

Particle flow light:
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



Jet energy corrections schema



Factorized approach for jet energy corrections:

"Offset" - removes unwanted contribution from noise and pileup

"Relative" - removes variation of response vs η w.r.t the central region (in-situ: dijet p_T balance)

"Absolute" - removes variation of jet response vs jet p_T (in situ: Photon+jet p_T balance, MPF method)

"Residual" - remove the residual difference between JES in MC and Data

Two sources of the correction:
Monte-Carlo simulations
In-situ measurements with physics process

We correct for:

Calorimeter response

Magnetic field

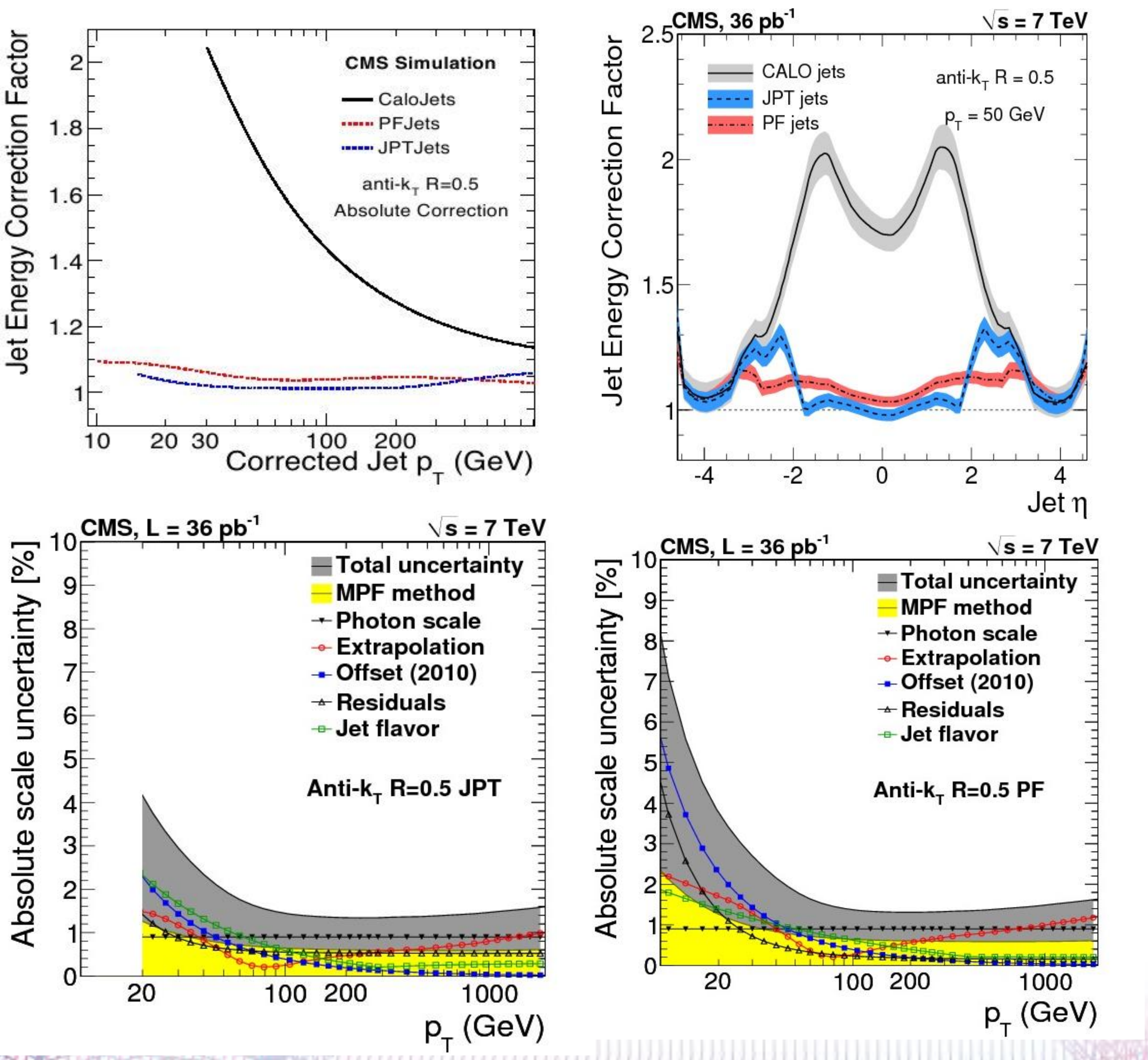
Electronic noise/tower thresholds

Dead materials and cracks

Longitudinal leakage

Shower size, out of cone loss

Jet performance



use of tracker detectors decreases the value of the residual corrections.

The better we know response function the more exact measurements deconvolution we can perform

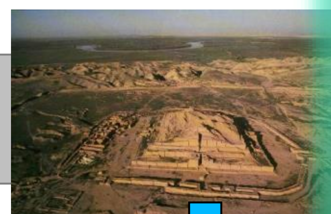
JINST 6 P11002 (2011)

Two notes towards jet production measurement

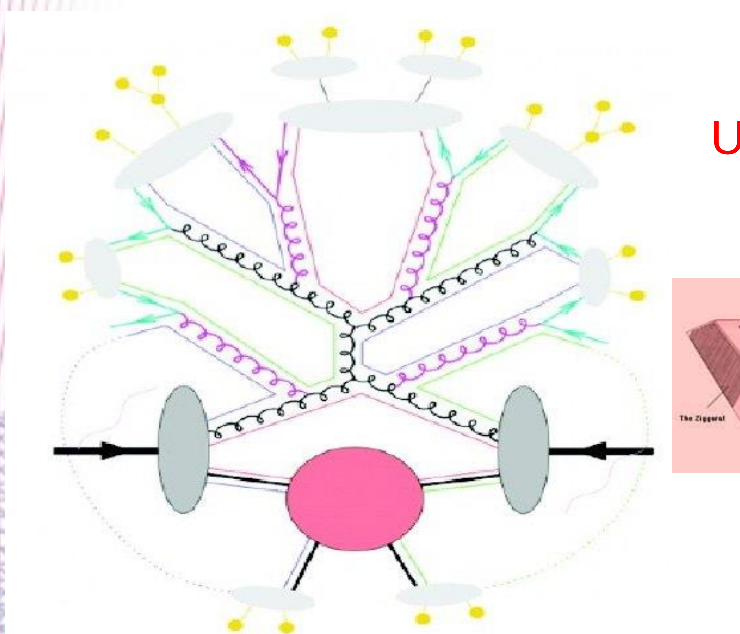
Measurements

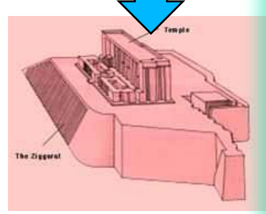
Measurements are corrected to particle level via either unfolding procedure or bin-to-bin corrections

Detector vision



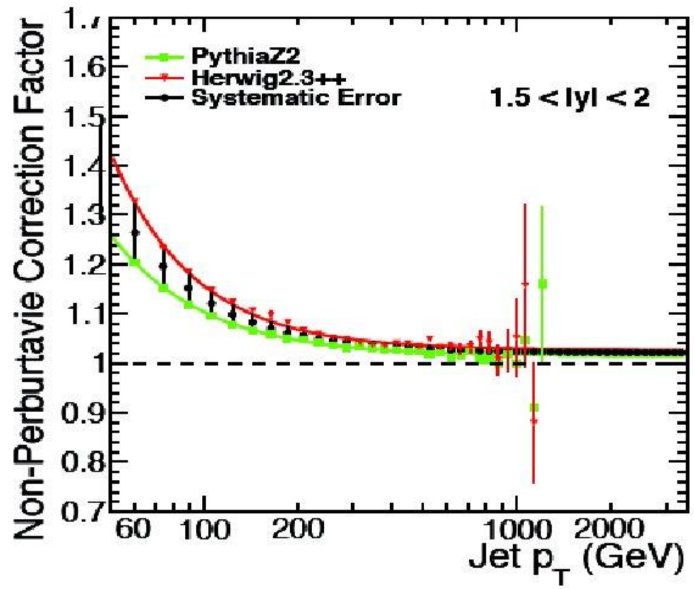
Unfolding





Theory

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

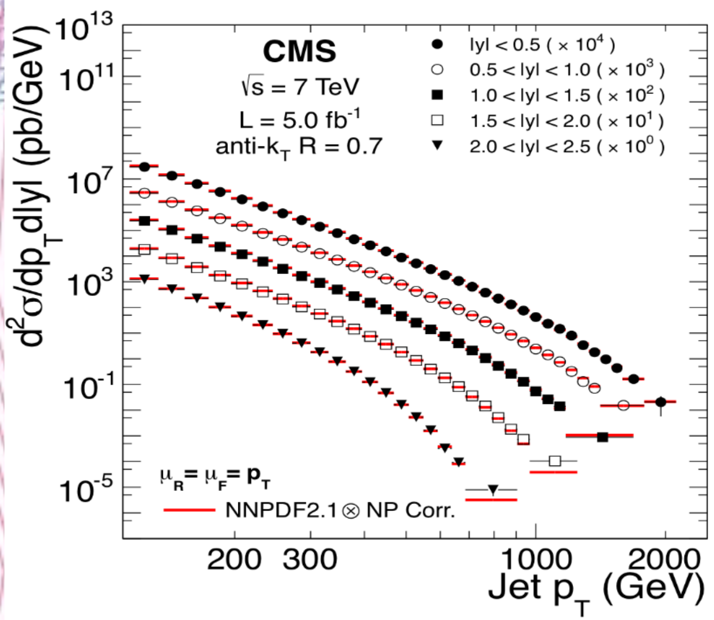


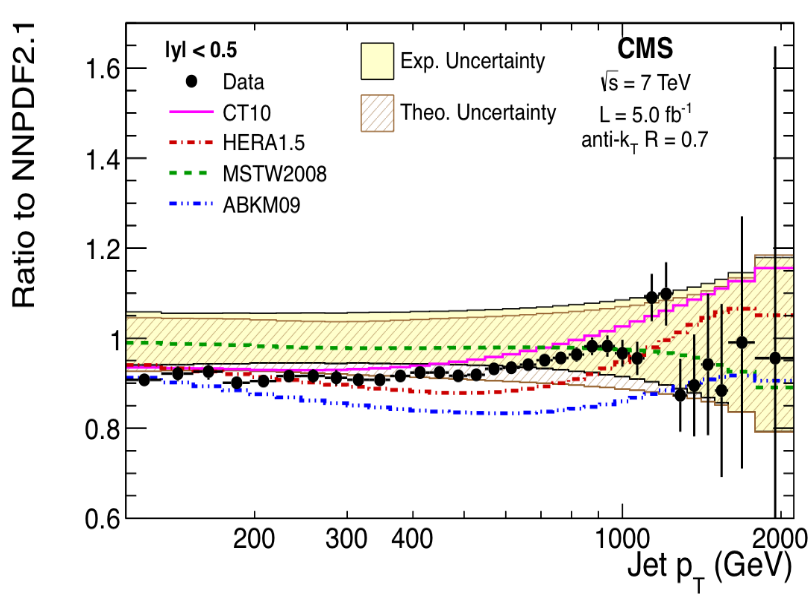
PDFs parametrization depends on the choice of the input data, order of pQCD, heavy Qs treatment, correlations between PDFs and aS, treatment of uncertainties

Inclusive central jets production

Jets: |η|<2.5

Motivation: constrain PDFs, differentiate between the different PDF sets: CT10,HERA1.5,MSTW2008,ABKM09





7 TeV

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

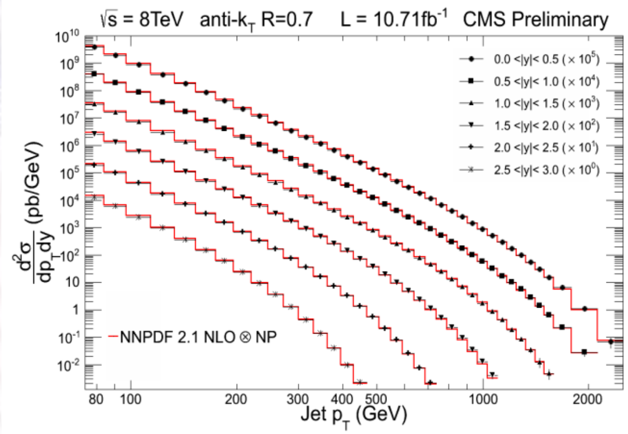
NLO calculations with non-perturbative (NP) corrections are used for comparison with data. NP corrections are got as averaged value estimated with PYTHIA and HERWIG.

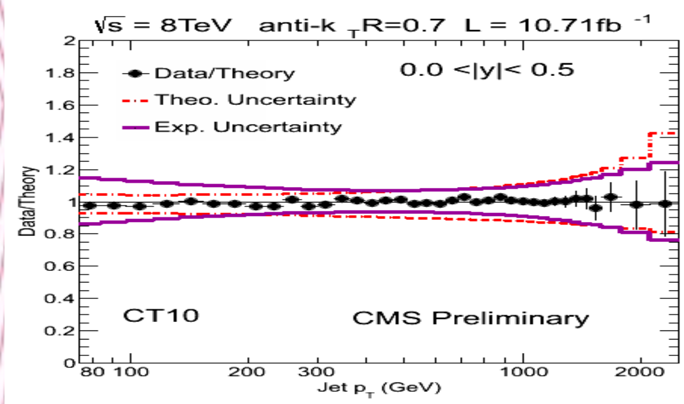
A set of the different NLO PDFs is used to account for PDF uncertainty.

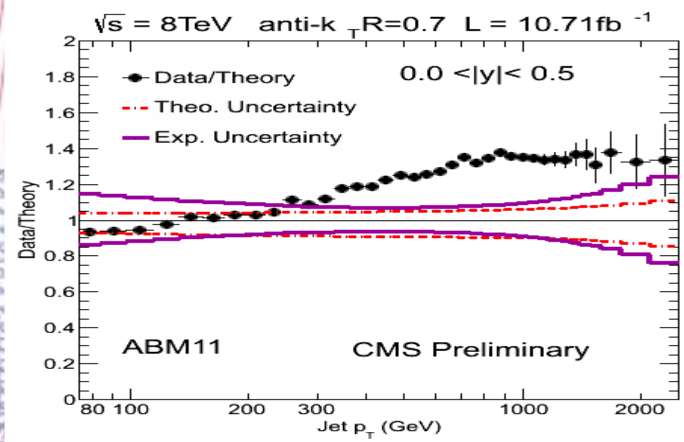
Data are in agreement with NLO calculations within systematic uncertainties although NLO calculations are systematically overestimate cross-section in all rapidity bins.

Phys. Rev. D 87 (2013) 112002

Inclusive central jets production







PDF sets considered: ABM11, HERA1.5, CT10, MSTW2008, NNPDF2.1

Jets: |η|<3

8 TeV

The total experimental uncertainty gets contribution from JES(12%-30%)
Luminosity(4.4%)
Unfolding(1%-10%)
resulting into 15%-40% total relative experimental uncertainty on the measured cross-section.
The total theory uncertainty gets contribution from PDF(5%-30%)
Scale(5%-40%).
PDF uncertainty for CT10 in outer bins 100%

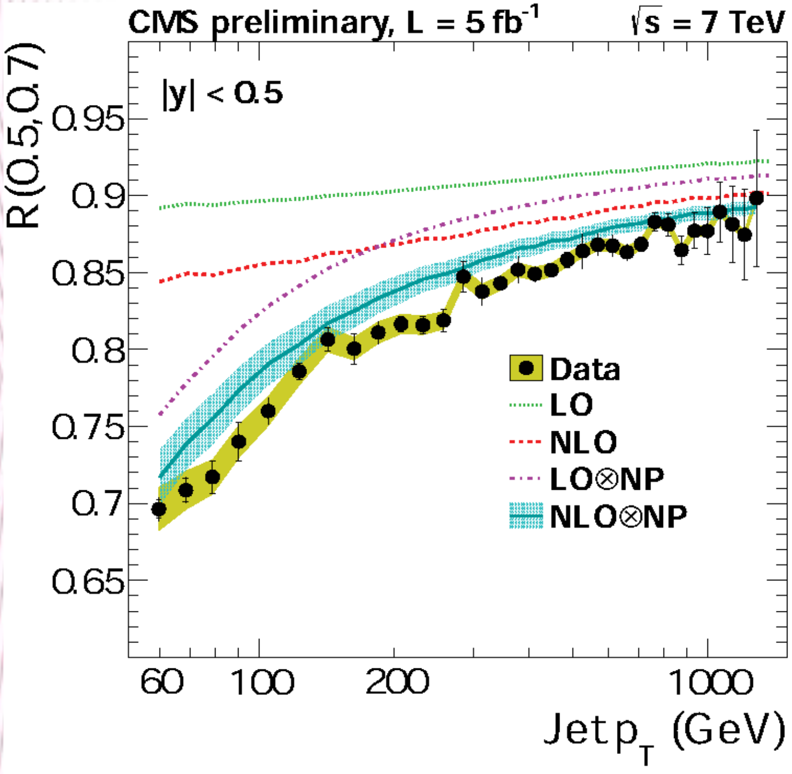
The tested parton momentum fraction is 0.019<x<0.625

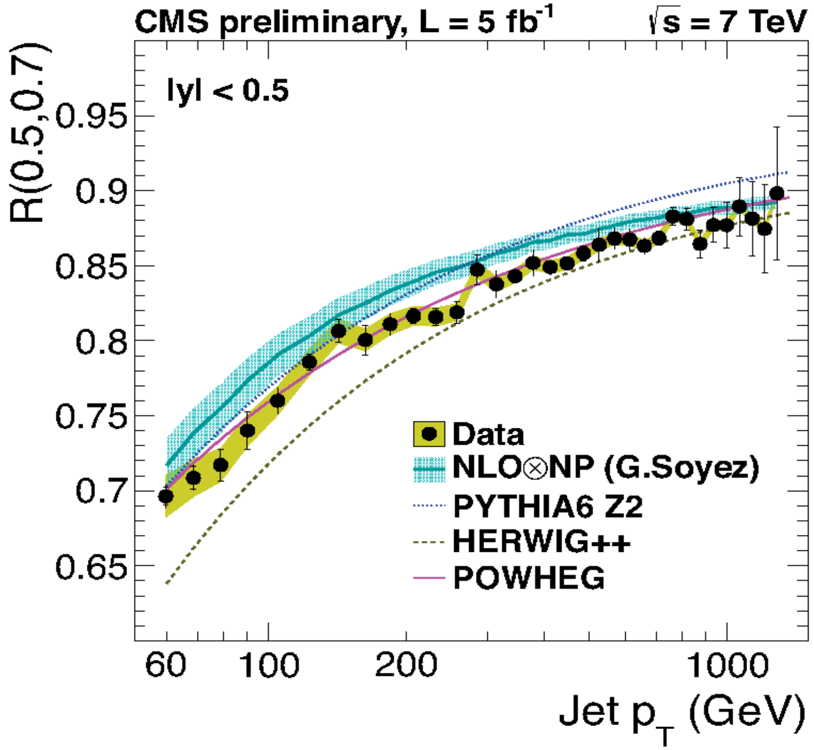
Data are in agreement with NLO calculations within systematic uncertainties for all considered PDFs sets except ABM11 PDF set

CMS-PAS-SMP-12-012

Inclusive Jet AK5/AK7 Cross-section ratio

Measurement at 7 TeV with different jet sizes R=0.5 (AK5), 0.7 (AK7)
Ratio of cross sections R(0.5, 0.7) vs p_T and rapidity

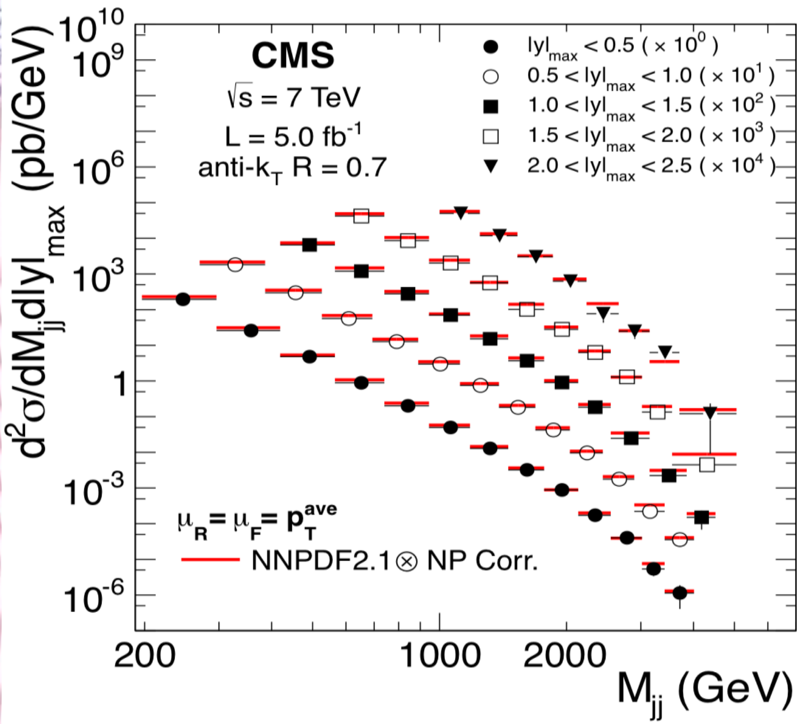




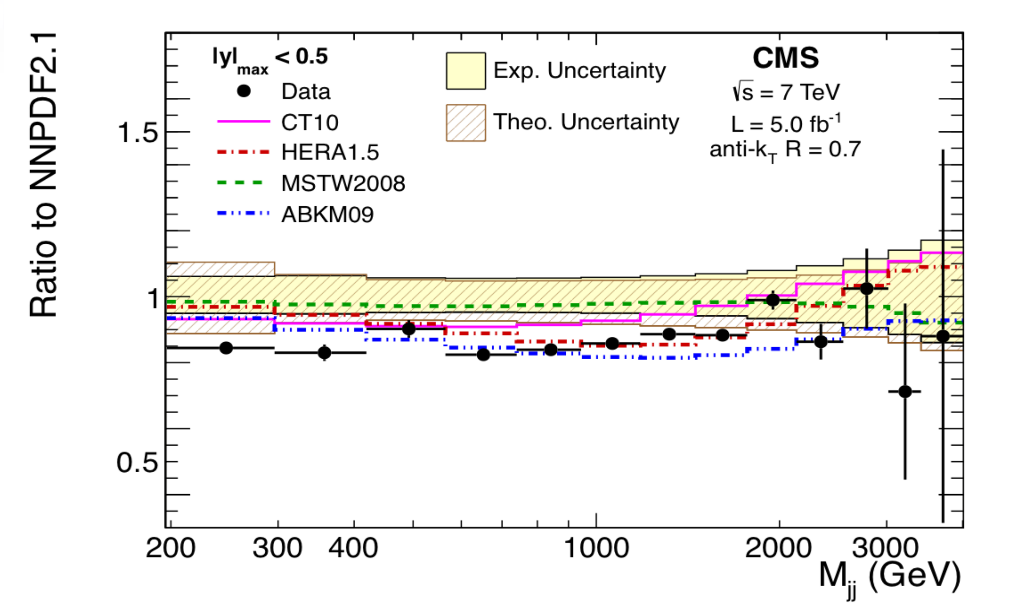
Several systematic uncertainties cancel in ratio
The ratio gradually increases towards unity with increasing Jet-p_T.
Powheg(NLO+PS) prediction has the describes the data best

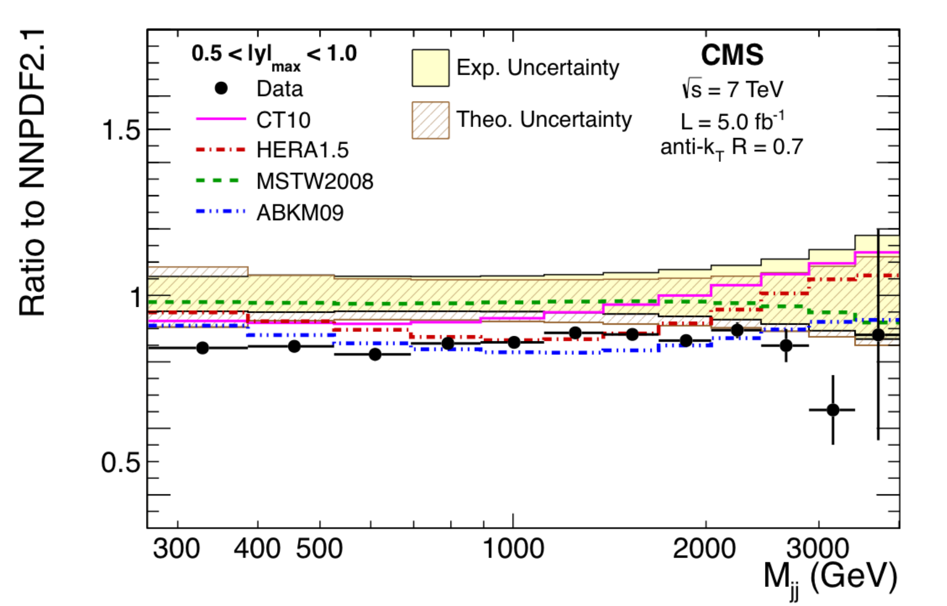
CMS-PAS-SMP-13-002

Dijet production



7 TeV





NLO QCD (NLOJet++) + NP corrections

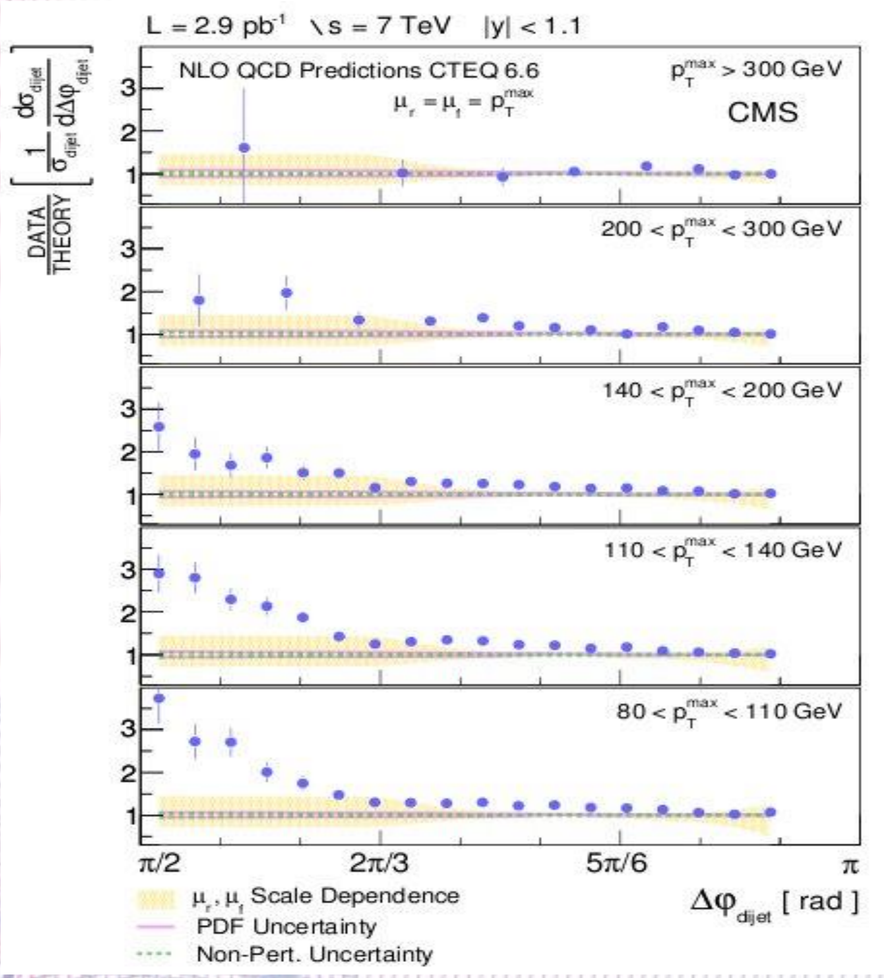
Comparisons with dats are done for the different PDFs in the different rapidity bins.

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

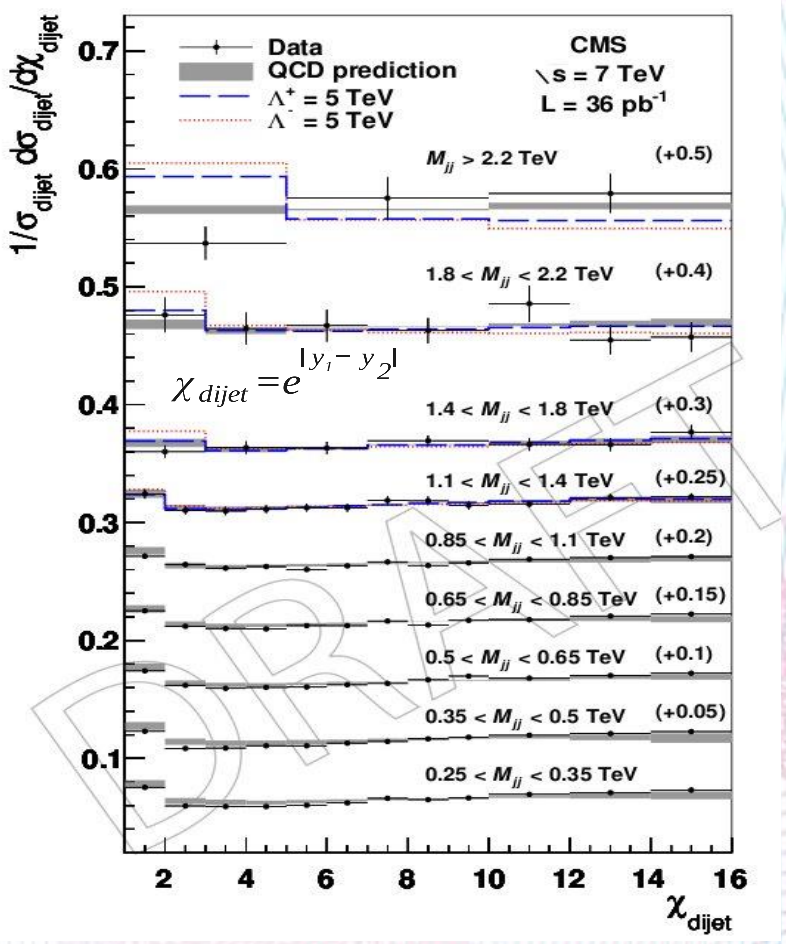
Phys. Rev. D 87 (2013) 11200

Dijet production: Δϕ,Δη

Sensitivity to the initial and final state radiation.
NLO QCD (NLOJet++) + NP corrections disagree with data at small Δϕ where multiparton radiation effects dominate.



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.



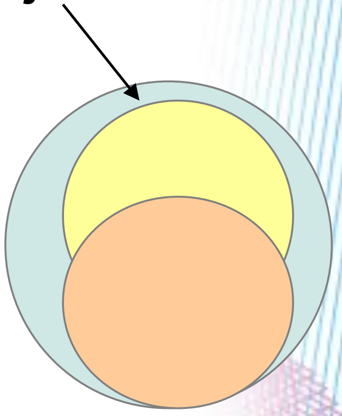
Phys. Rev. Lett. 106 (2011) 201804
Phys. Rev. Lett. 106 (2011) 122003

Dijet Mass and Jet substructure

Differential distributions in jet mass for inclusive dijet events, defined through the anti-k_T algorithm for a size parameter of 0.7 for jets groomed through filtering, trimming, and pruning.

Benchmark for them Massive particles search:

W, Z, massive particles are produced with large boost resulting in "massive" jet



After initial clustering

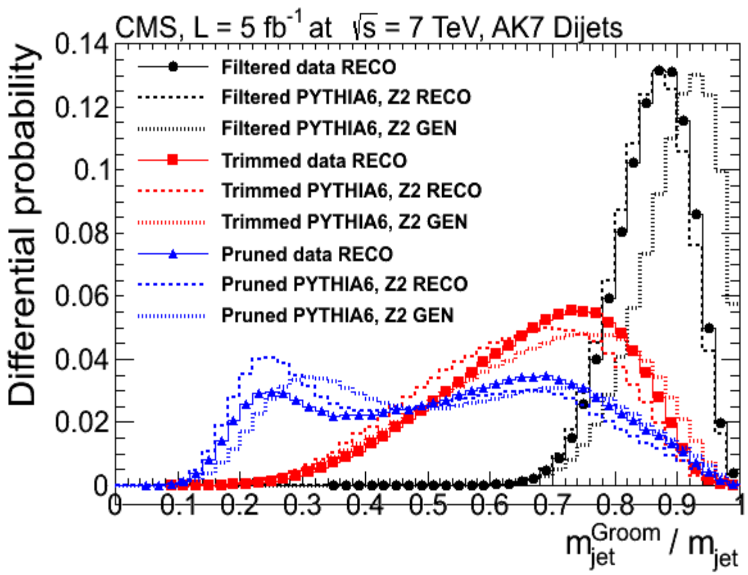
Filtering:
recluster jet with CA with R=0.3, take the 3 highest subjets, re-estimate the 4-vector of jet from 3 subjets

Trimming:
Ignores particles falling below dynamic threshold
Recluster with k_T with Rsub (0.2) and keep subjets with $p_{T\ sub} > f_{cut} \times \lambda_{hard}$; $f_{cut} = 0.03$

Pruning:
Recluster jet with CA, using the same distance as initial algo but with additional parameters

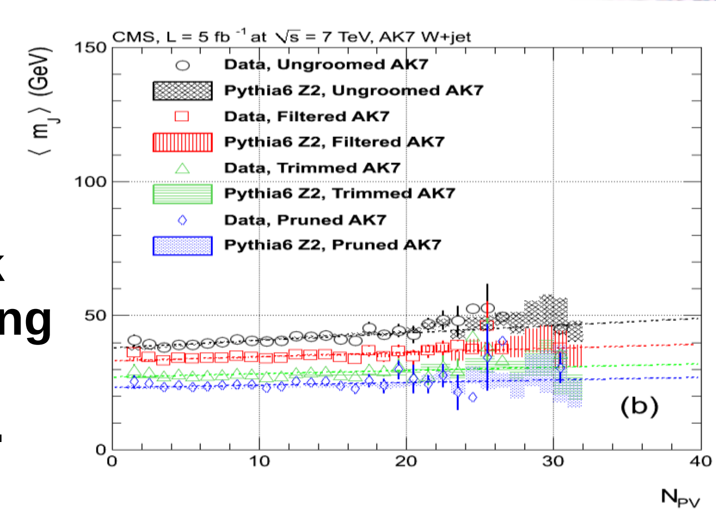
JHEP05(2013)090

Dijet Mass and Jet substructure

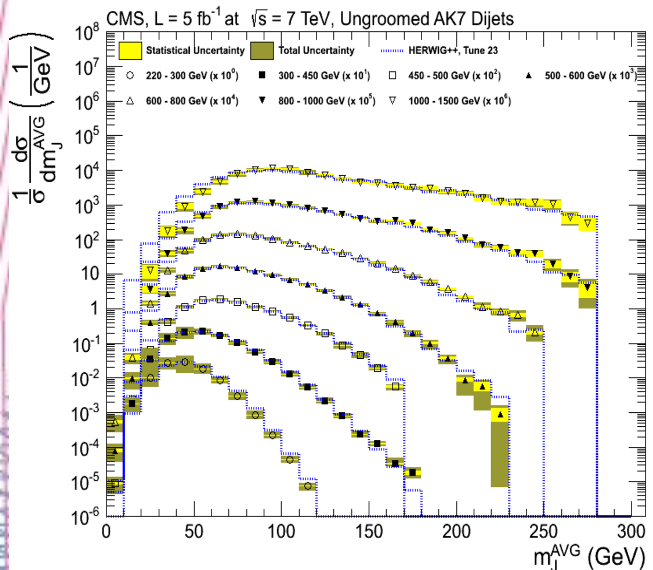


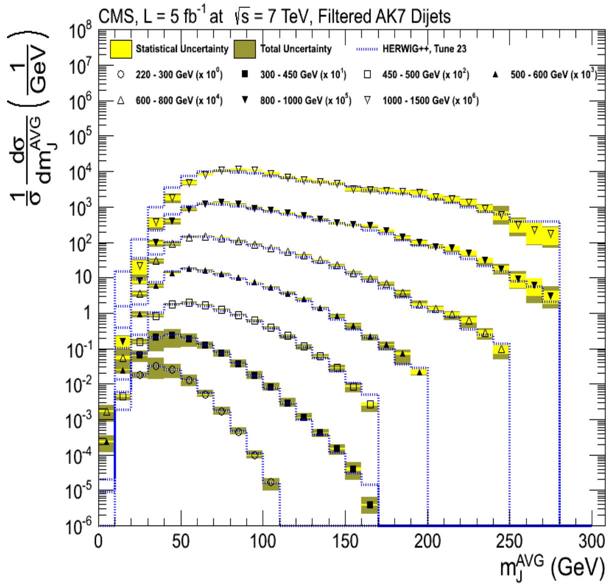
Pruning algorithm
Is the most aggressive

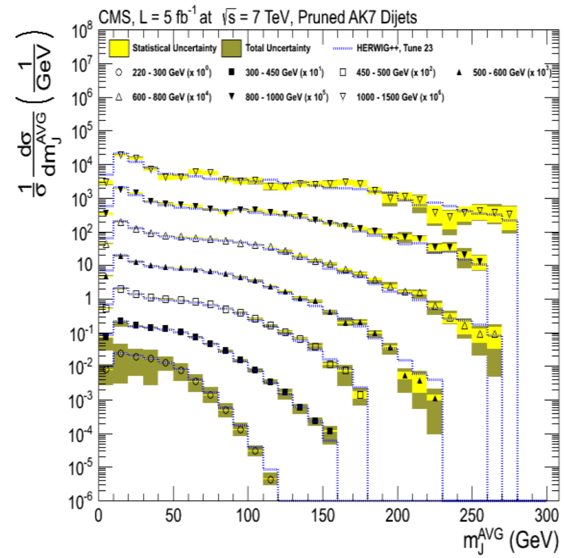
Groomed jets are stable
w.r.t pileup – favorize the use
With high-lumi runs



important benchmark
for use of the grooming
algos in searches
for massive particles.

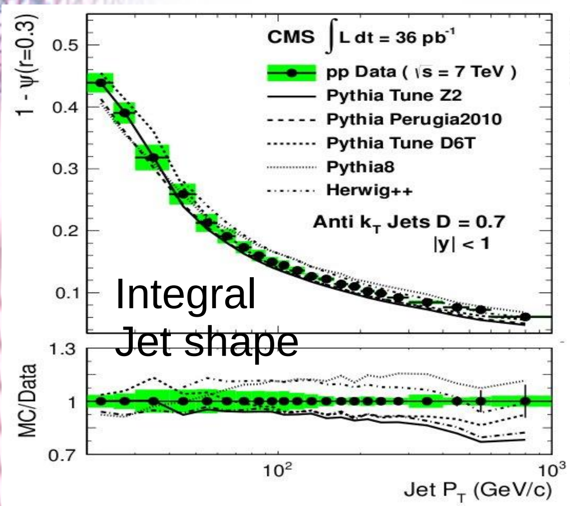


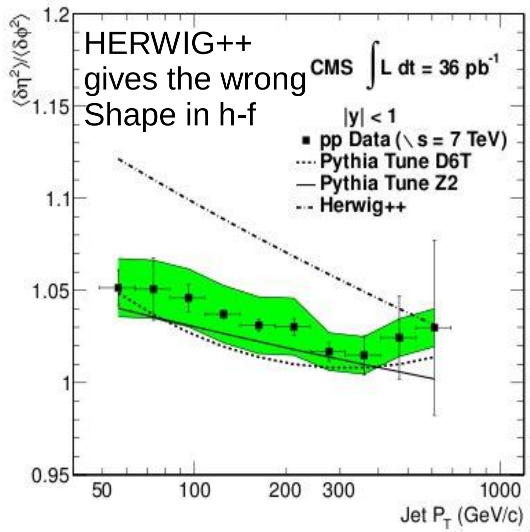




JHEP05(2013)090

Jets properties: charged particles multiplicity, shape

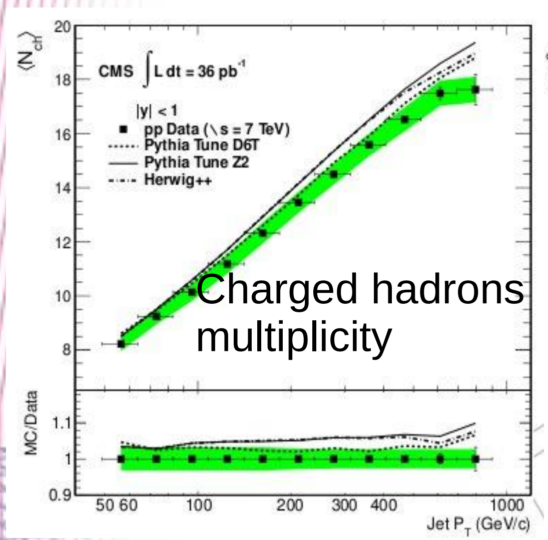


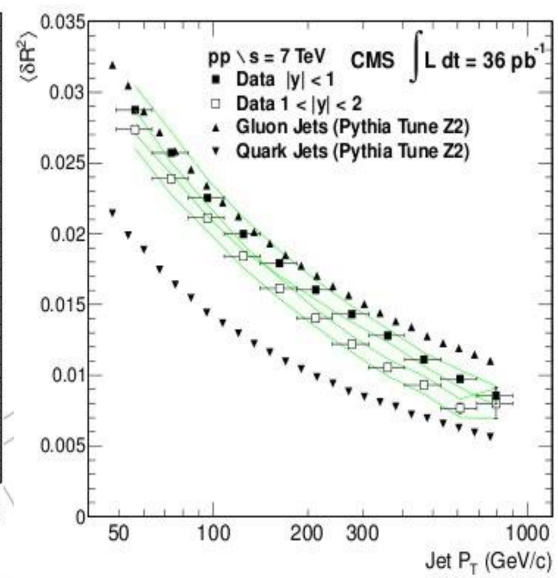


$$\langle \delta R_2 \rangle (p_T) = \langle \delta \phi_2 \rangle (p_T) + \langle \delta \eta_2 \rangle (p_T)$$

$$\langle \delta X^2_{jet} \rangle (p_T) = \frac{\sum_{i \in jet} (X_i - \langle X \rangle)^2 \cdot p_{Ti}}{\sum_{i \in jet} p_T^i} \quad X=\eta \text{ or } \phi$$

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|

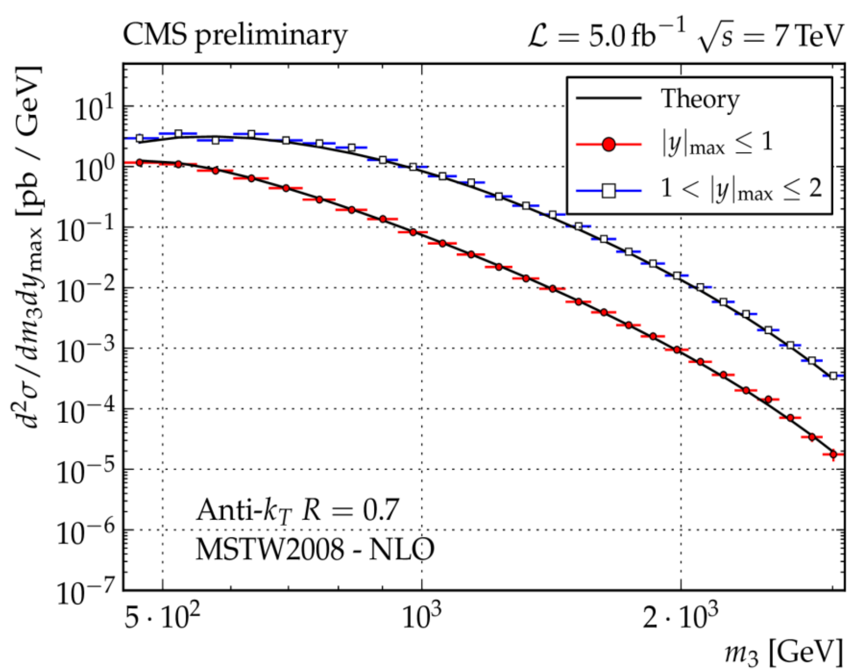
Agreement with predicted increase in the fraction of quark-induced jets at higher jet p_T and |y|

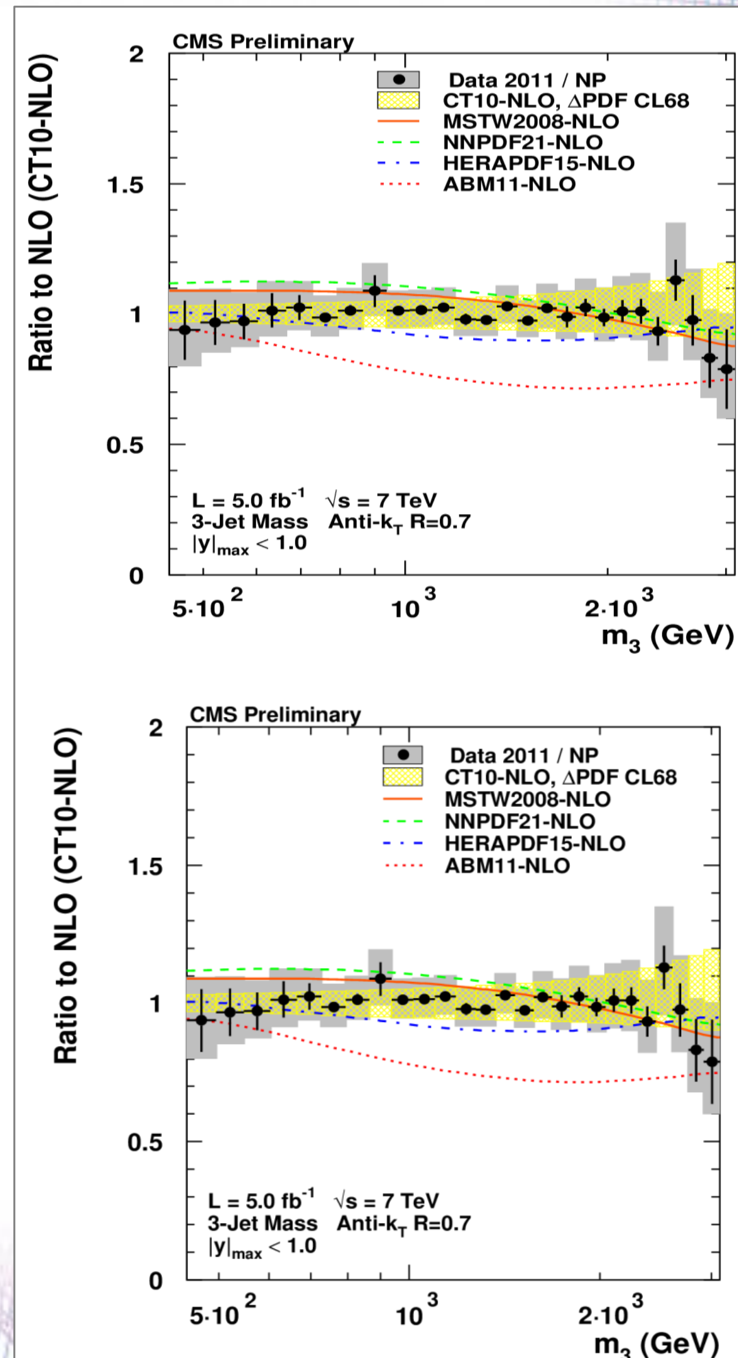
Results gives impact to modeling PDFs, parton showering, fragmentation function

Multijet production (3 jets)

Measurement of double diffrential cross section:
$d2\sigma/dm_3dy_{max}$
sensitivity to PDFs and α_S
$m_3^2 = (p1+p2+p3)^2$, $|y_{max}|=max(|y_1|,|y_2|,|y_3|)$, $Q=m_3/2$

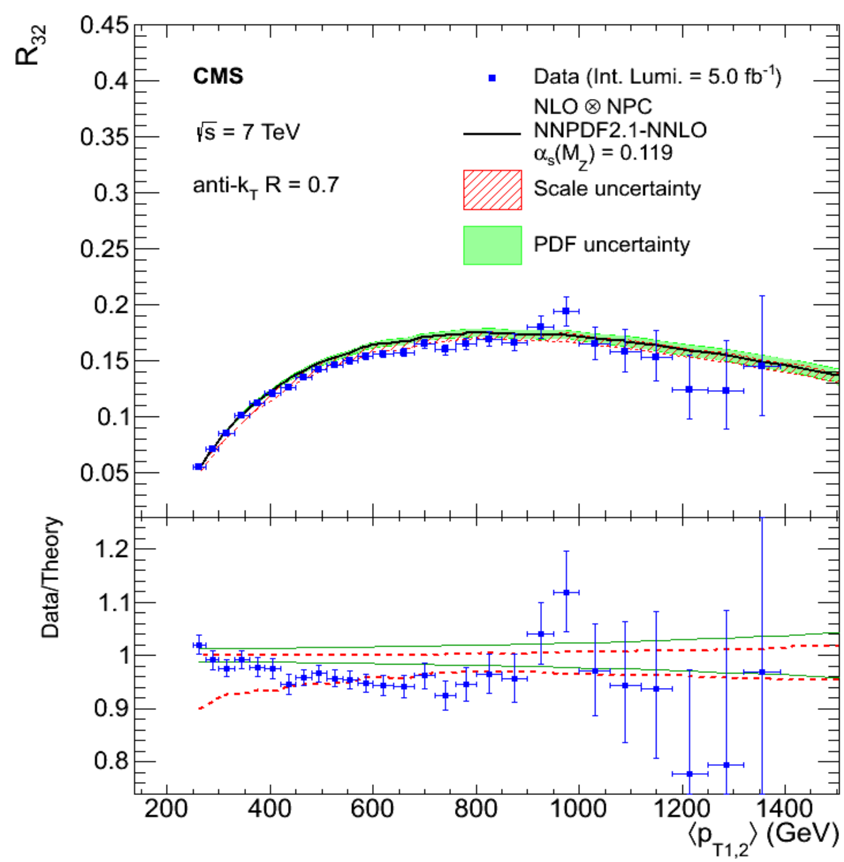
Require jet p_T > 100 GeV
Regions: $|y_{max}|$ < 1 and $1<|y_{max}|<2$ - reach up to m_3 ~ 3 TeV
Agreement with pQCD @ NLOxNP
(NP correction 8% -> 1%)
Deviations observed with NLO + ABM11 PDF

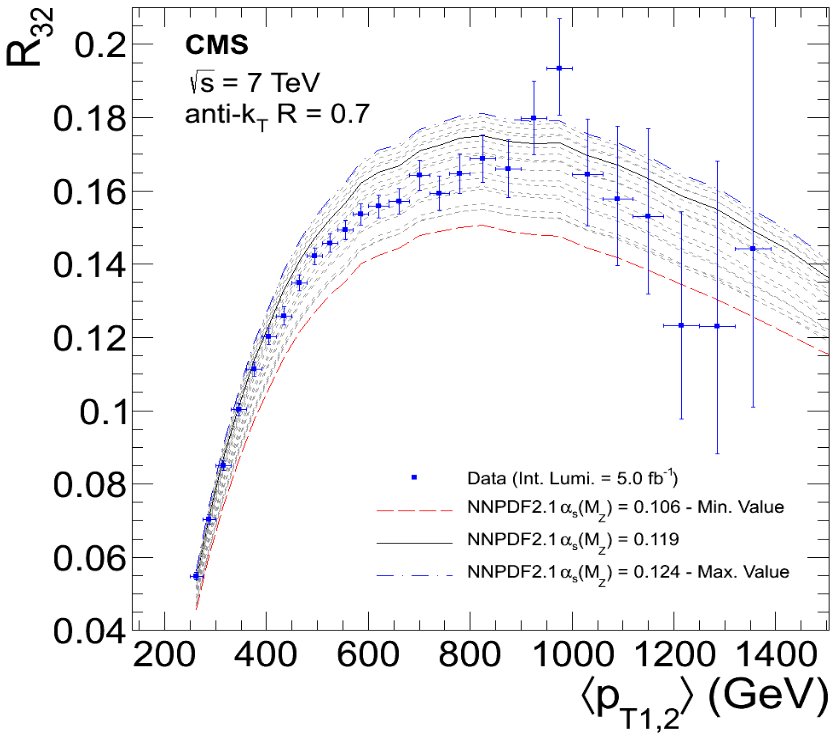




CMS-PAS-SMP-12-027

3-jet over 2-jet cross section ratio





Cross-section ratio R32:
- **inclusive 3-jet over 2-jet production**
- **sensitive to α_S**

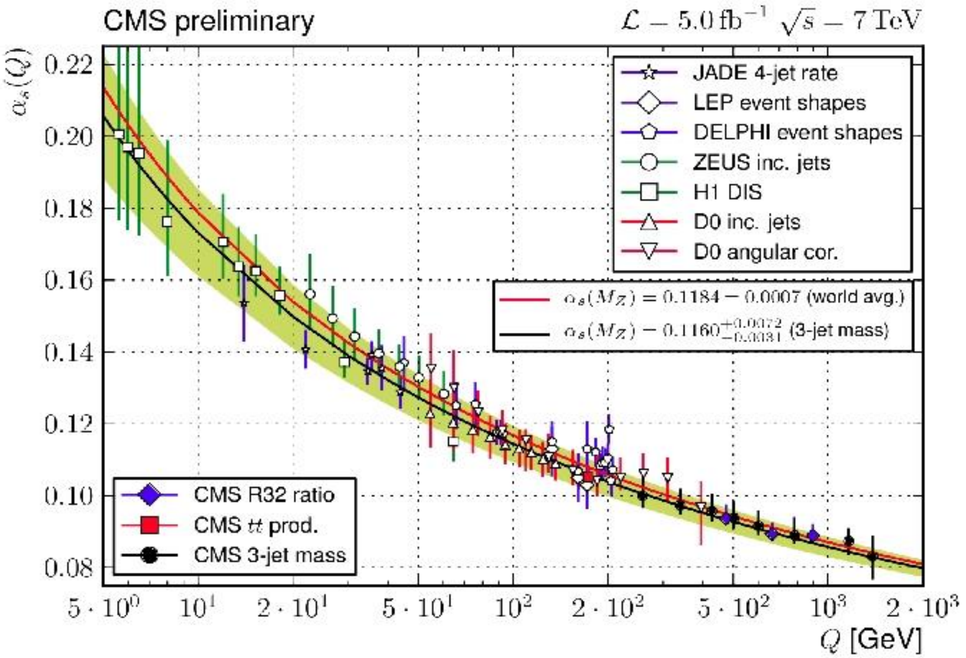
Multiple alternative phase-space options
- **depending on the cut imposed on the 3rd jet p_T**
- **measuring the α_S: vital to reduce scale uncertainty**

R32=σ(njet>=3)/σ(njet>=2)

CMS-PAS-QCD-11-003
arXiv:1304.7498

α_S (M_Z) extraction from 3-jet events

1. From the ratio of the 3 jets/2 jets cross-sections
2. Fit of the data to theory predictions in 8 regions of the 3-jets mass using MSTW2008-NLO PDF set and NLO evolution order from Eur. Phys. J. C 5 (1998) 461



CMS-PAS-QCD-11-003
CMS-PAS-SMP-12-027

- Results are comparable with world average $\alpha_S(M_z)$= 0.1184 ± 0.0007
- For the first time probing the > 1 TeV scale, reaching up to ~ 1.4 TeV
- Dominated by theoretical uncertainties (PDF and scale)

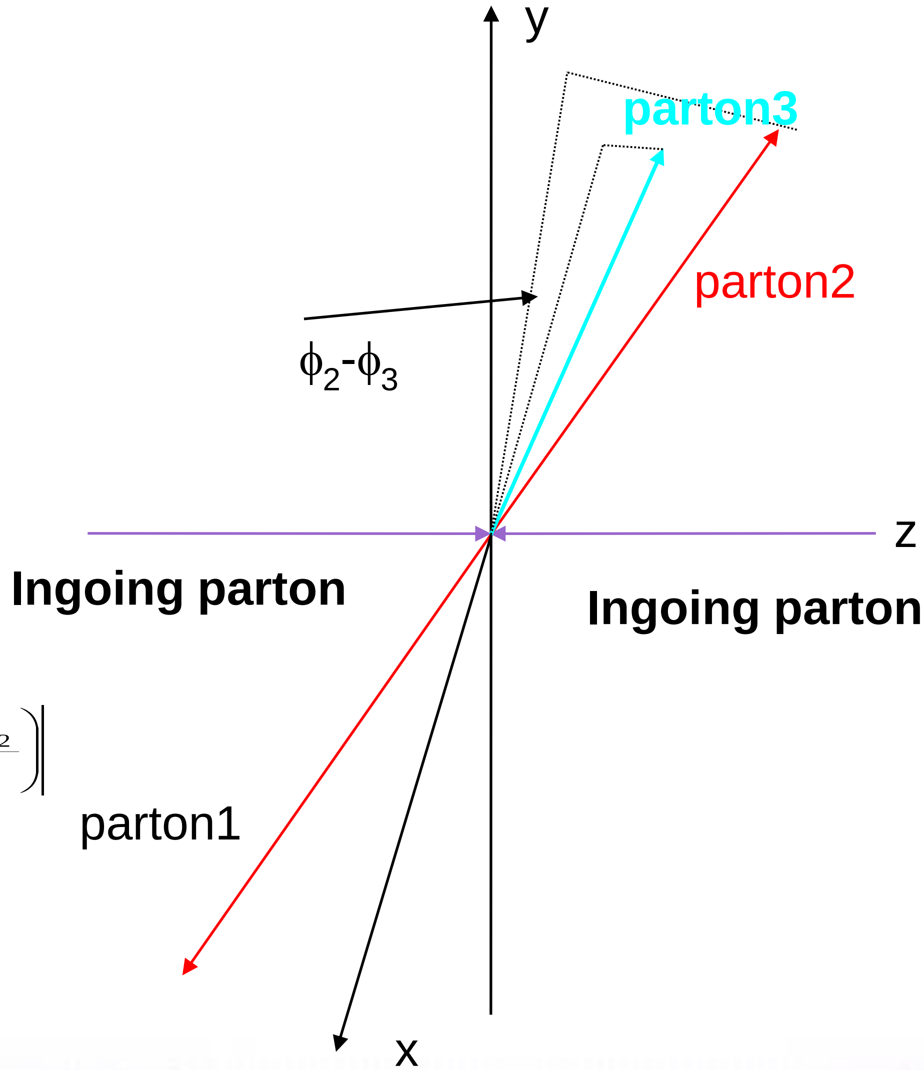
R_{32}: α_S(Mz)=0.1148 ± 0.0014 (exp.) ± 0.0018 (PDF)+0.0050 -0.0000 (scale)

3-jet mass: α_S(Mz) = 0.1160+0.0025 – 0.0023 (exp, PDF, NP)+0.0068-0.0021 (scale)

7 TeV, 36 pb-1

Color coherence

Outgoing partons produced in the hard interaction continue to interfere with each other during their fragmentation phase.



Observable:

$$\beta = \left| \arctan\left(\frac{\varphi_3 - \varphi_2}{\eta_3 - \eta_2} \right) \right|$$

In the presence of the color coherence third parton tends to be in the plane defined by beam and the second parton e.g. β->0 or β->π

In the absence of the color coherence there is no preferred direction in the emission of the third parton around radiating parton

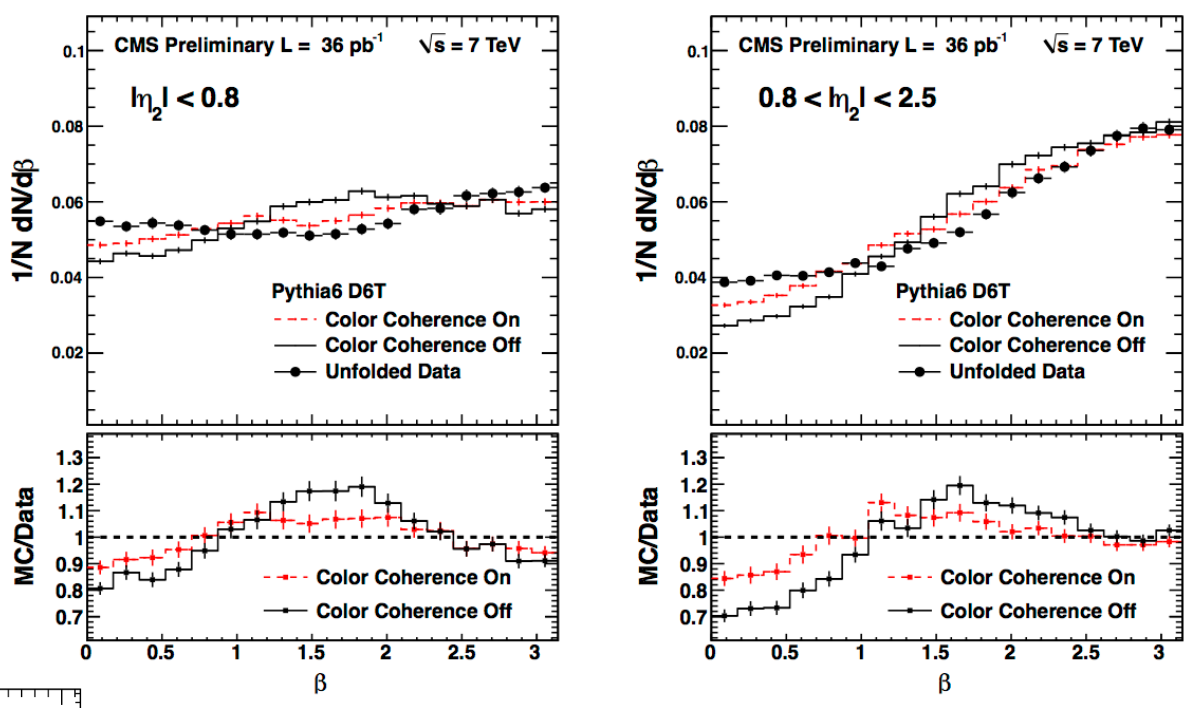
CMS-PAS-SMP-12-010

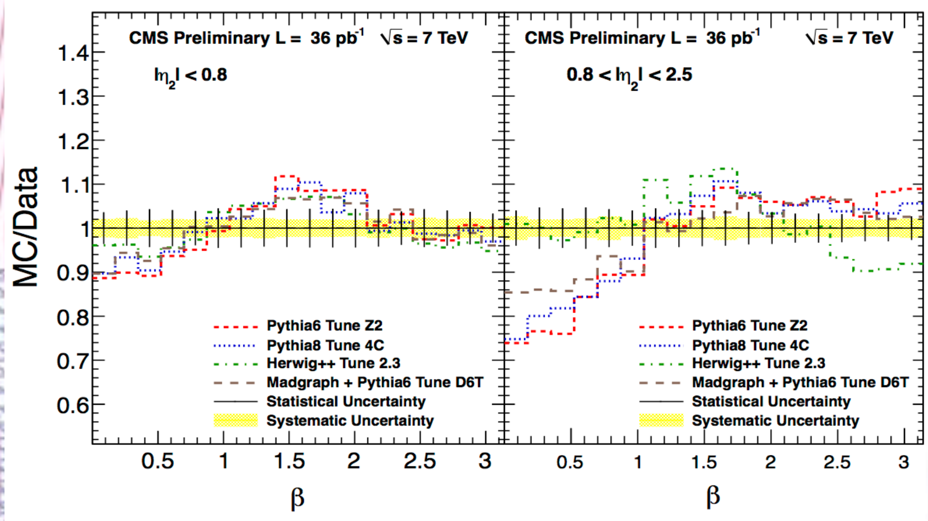
Color coherence

7 TeV, 36 pb^{-1}

Analysis of the color coherence was done with 3 jet events:

$p_{T1} > p_{T2} > p_{T3}$
$|\phi_1 - \phi_2| > 2.7$ (back-to-back)
$P_{T1} > 100$ GeV
$P_{T2} > 30$ GeV
$M_{12} > 220$ GeV
$0.5 < \Delta R_{23} < 1.5$





β is sensitive to the color coherence effect

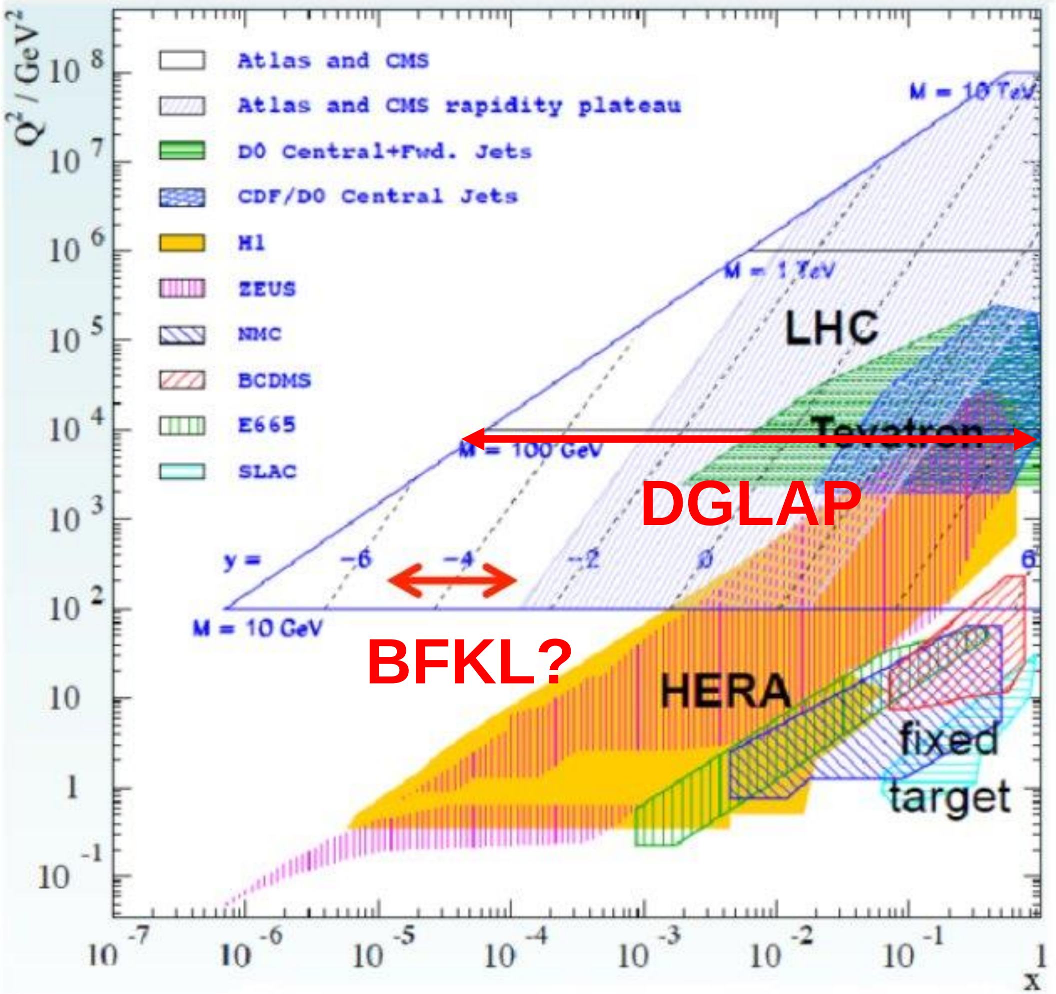
Considered MC models have the implementation Of the color coherence but none of them is fully successful

Small-x QCD

Connection between various scales in QCD (for instance, between PDF and the high-momentum scattering) is performed via evolution differential equations.

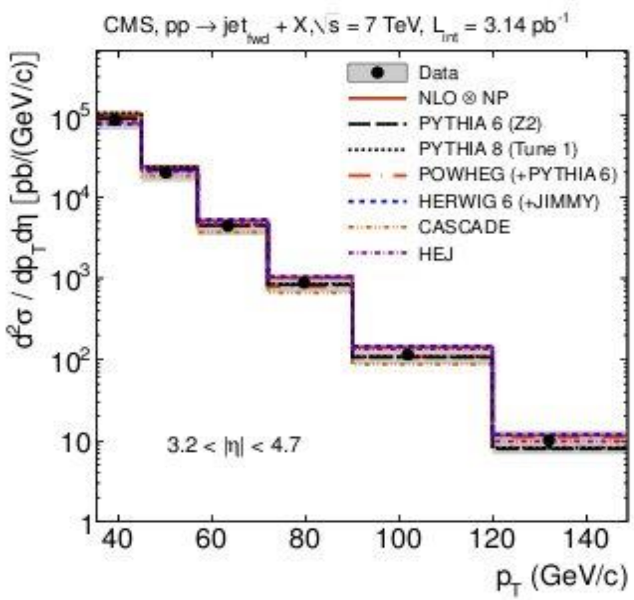
In small-x region standard approach to NLO QCD perturbative calculations. DGLAP (expansion in terms of power of $a_S \ln(Q^2)$) is predicted to be not sufficient. An alternative approach is BFKL (expansion in terms of ln(1/x)).

Non perturbative effects, Multi Parton Interaction (MPI) etc. models have to be tuned to data.



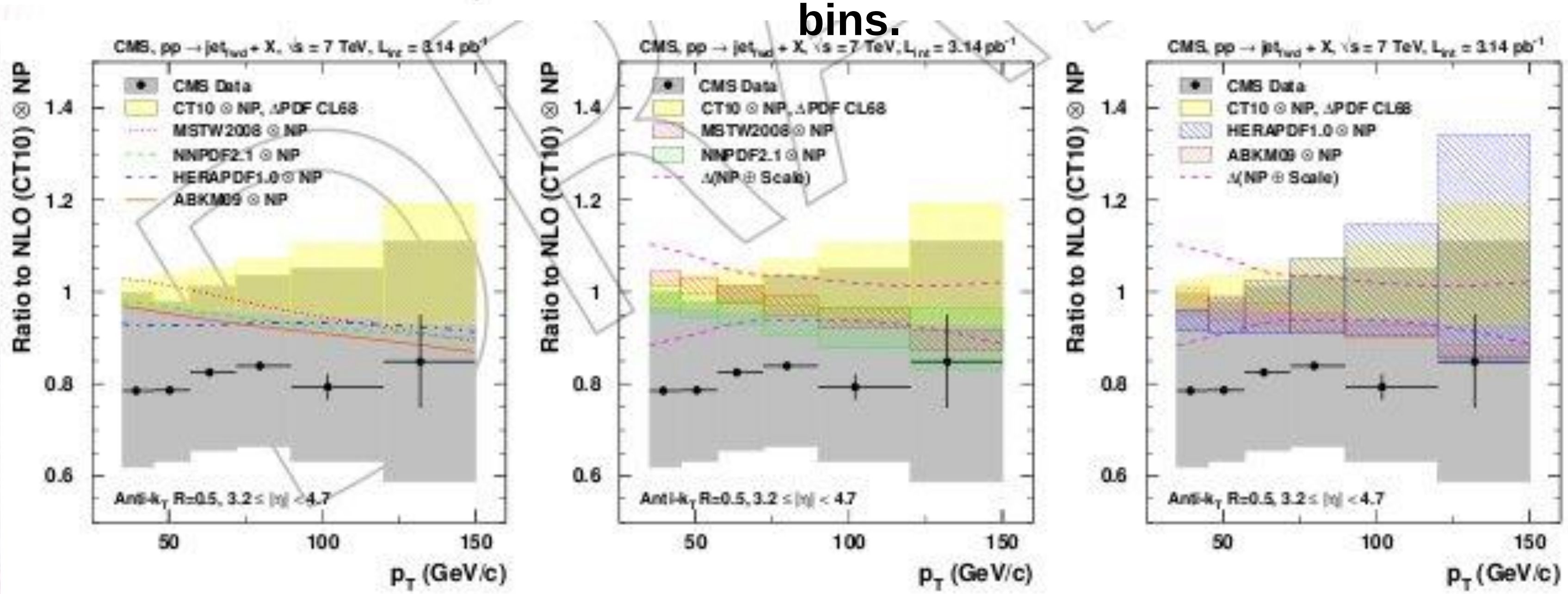
Inclusive forward jets at 7 TeV

Jet 3<|η|<5



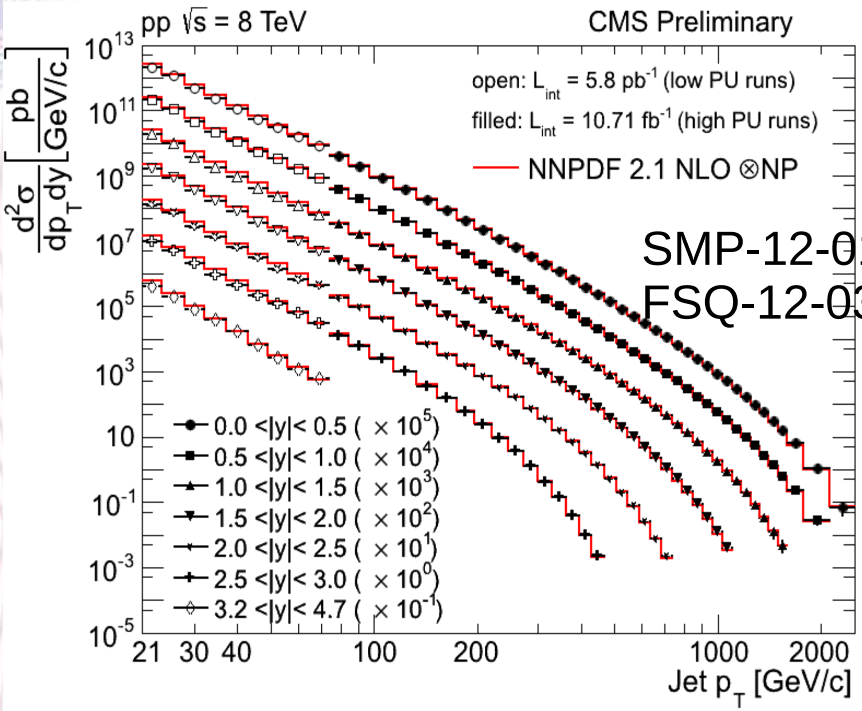
1. **DGLAP evolution + parton showering (PYTHIA6/8, HERWIG 6) with the different UE tunes DGLAP with angular ordered shower (HERWIG++ 2.3)**
2. **NLO (POWHEG)+PYTHIA6 or HERWIG 6**
3. **NLO (NLOJET++)+NP corrections**
4. **CCFM/BFKL evolution (CASCADE,HEJ) + uPDF**

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

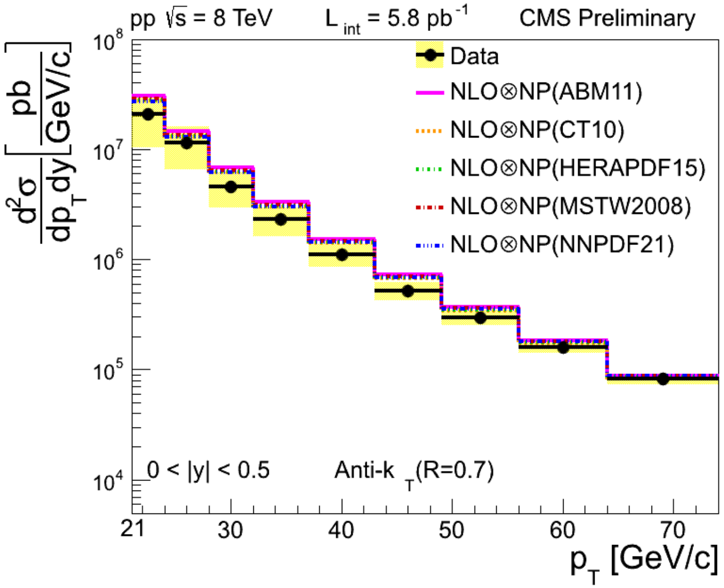


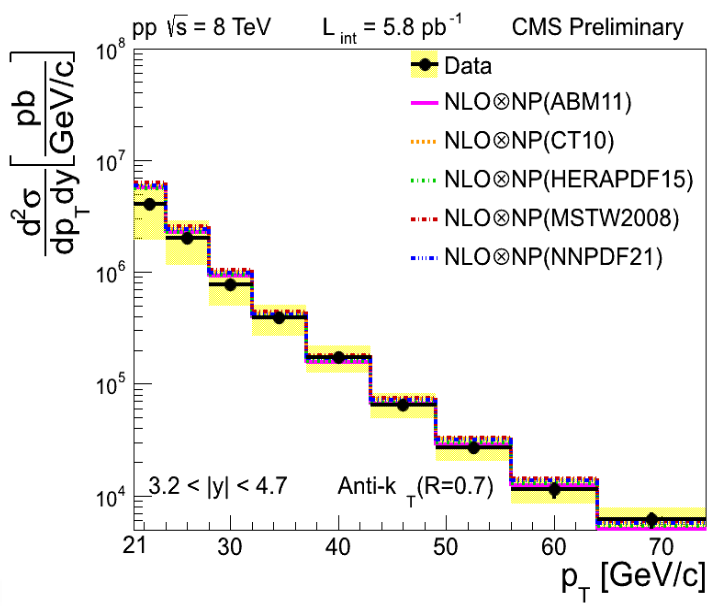
JHEP06(2012)036

Low pt jets at 8 TeV



SMP-12-012
FSQ-12-031

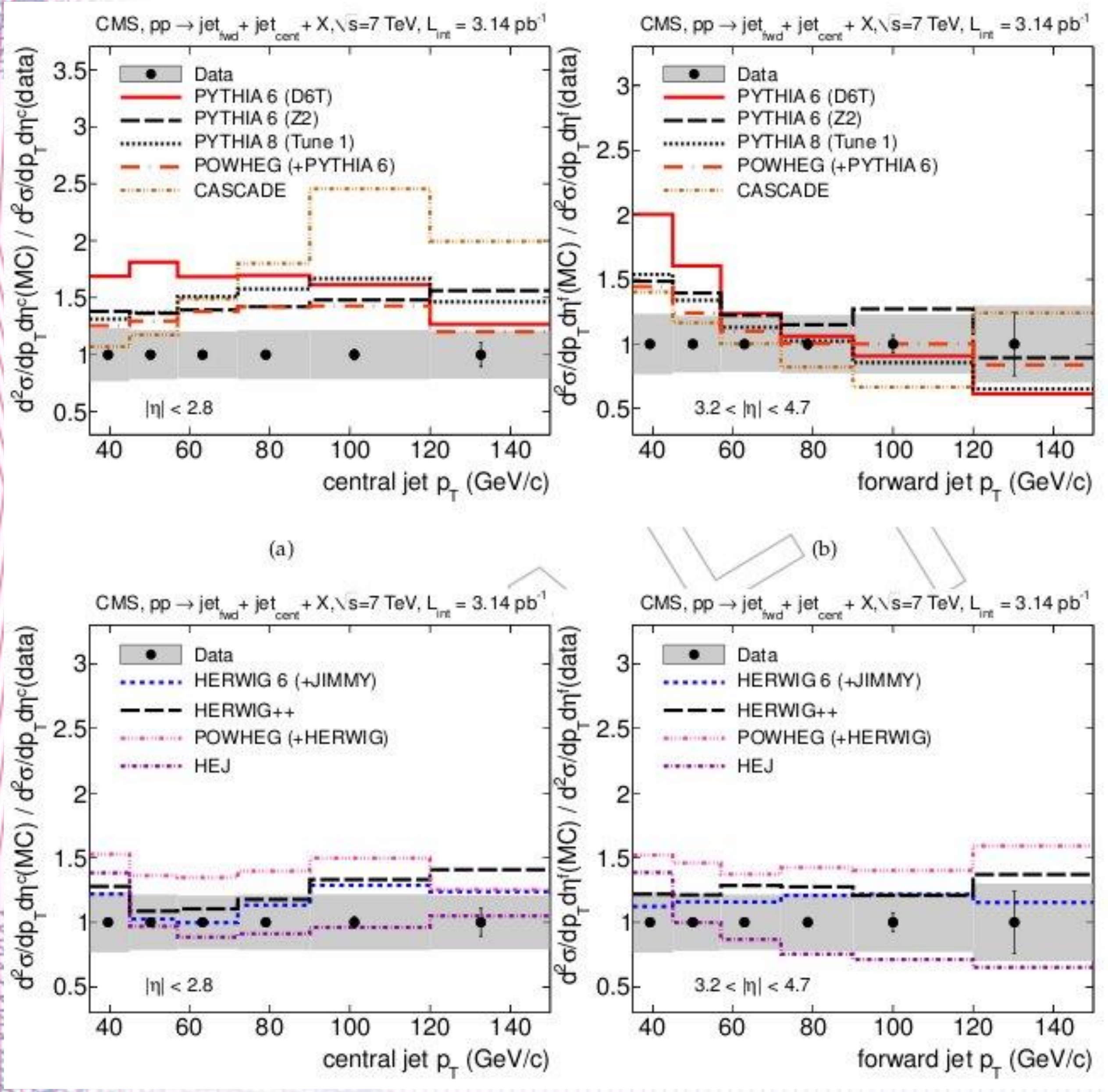




Theoretical predictions systematically overestimate x-section for both central and forward rapidity, but within experimental and theoretical uncertainties.

CMS-PAS-FSQ-12-031

Central-forward dijets



One jet $|\eta|<2.8$
Second jet $3<|\eta|<5$

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

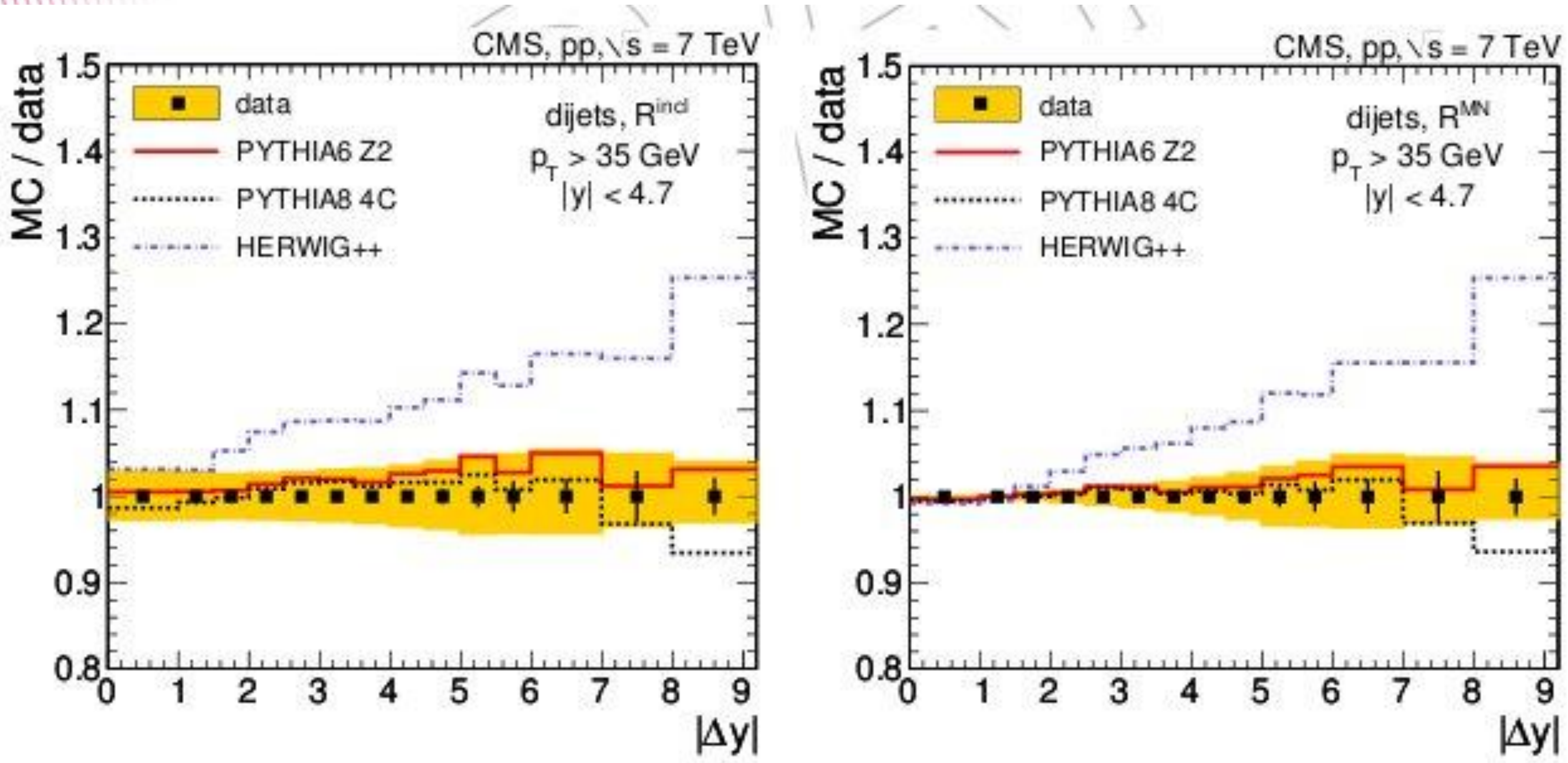
JHEP06(2012)036

Dijet production vs Δy gap

$R_{inc} = \sigma(N_{jet}>=2)/\sigma(N_{jet}=2)$
R_{MN} (Mueller-Navelet dijets)– only jets with highest and lowest rapidities are considered

Probe small x regime:
BFKL evolution:
k_T factorization

PYTHIA MC agrees with data while HERWIG predicts higher MC ratio.
BFKL motivated generators (CASCADE and HEJ+ARIADNE) predict significantly stronger rise then observed.



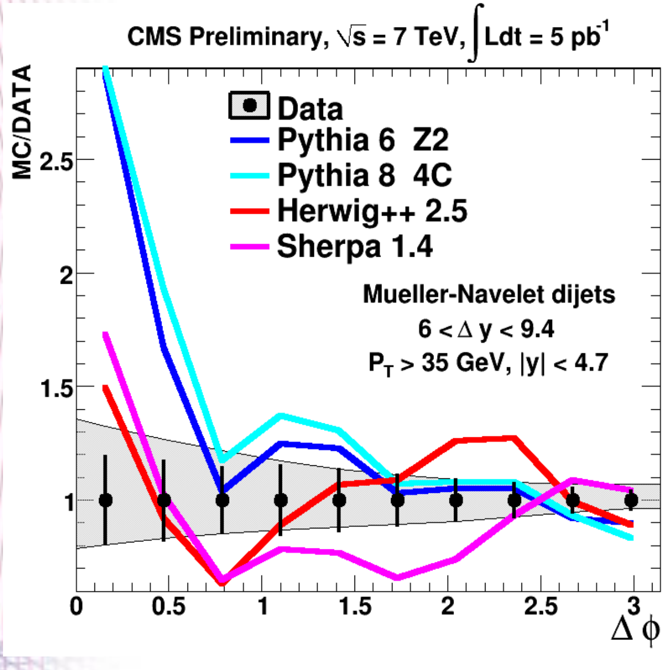
Eur.Phys.J.C(2012)72:2216

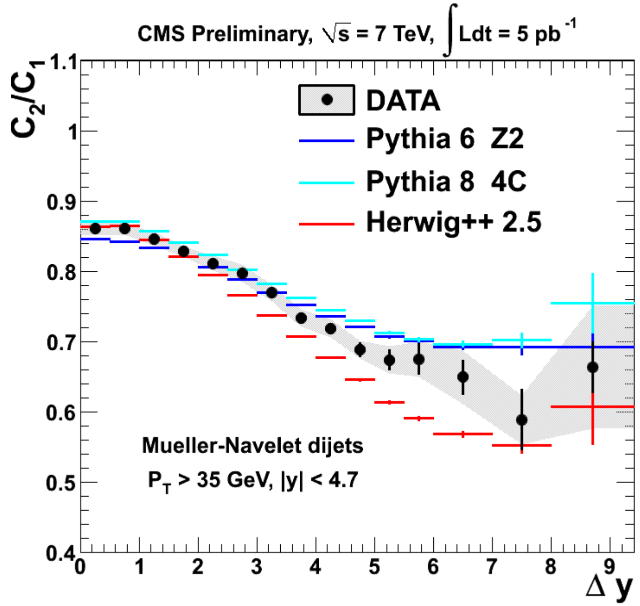
Angular correlations of jets

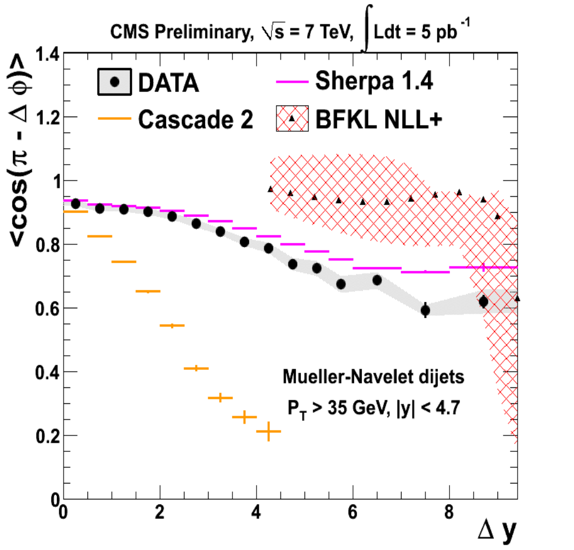
- Events with at least two jets passing cuts: p_T>35 GeV in |η|<4.7.
- For a pair of jets with the largest Δη (Mueller-Navelet dijet) the angular distance is calculated: Δφ = φ1 – φ2
- We study Δφ distributions for different Δη, and correlation factors C1, C2, C3

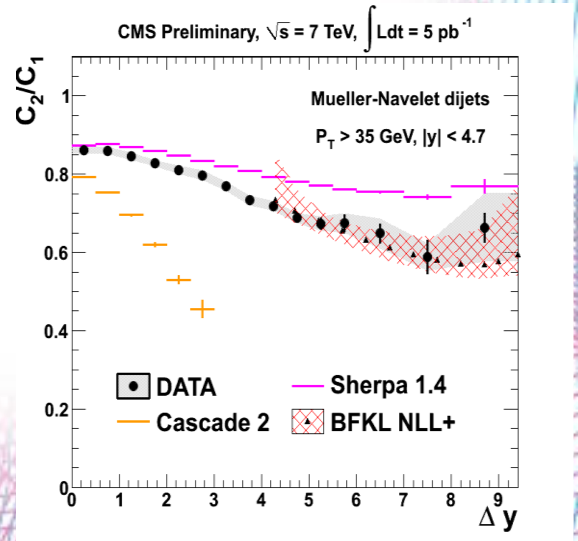
and its ratios C_2/C_1, C_3/C_2

$$C_n(\Delta y, p_{Tmin}) = \langle \cos(n(\pi - \Delta\phi)) \rangle$$





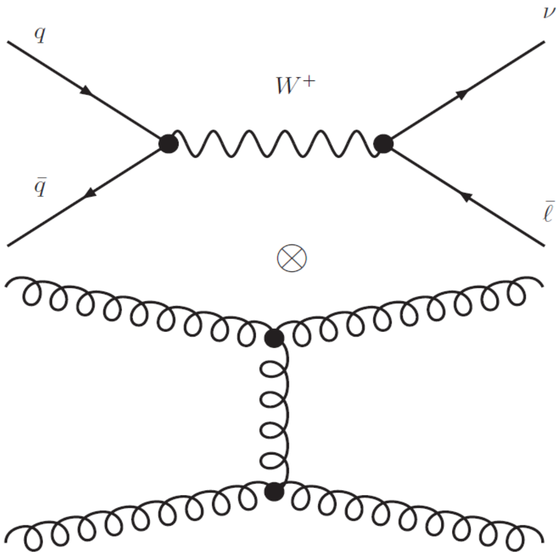




DGLAP generators starts to be worse in high Δy description
BFKL/CCFM generators do not provide good description of data in full Δη range.
Large unc. of NLL BFKL calculations.

CMS-PAS-FSQ-12-002

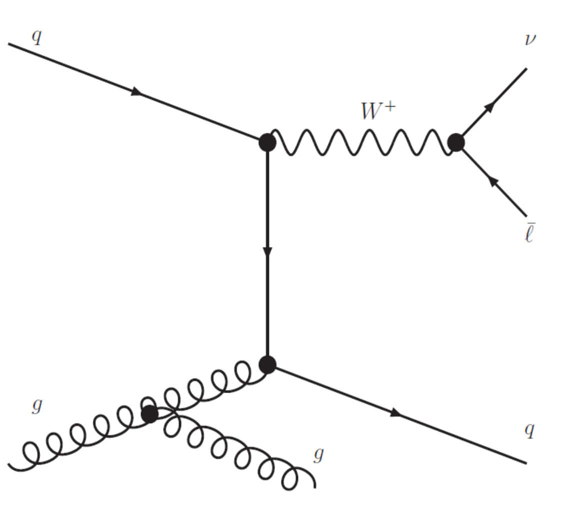
Double parton scattering



Double parton scattering

The measure of the size of DPS contribution

$$\sigma_{eff} = \frac{m}{2}\frac{\sigma_A * \sigma_B}{\sigma^{DPS}_{A+B}}$$

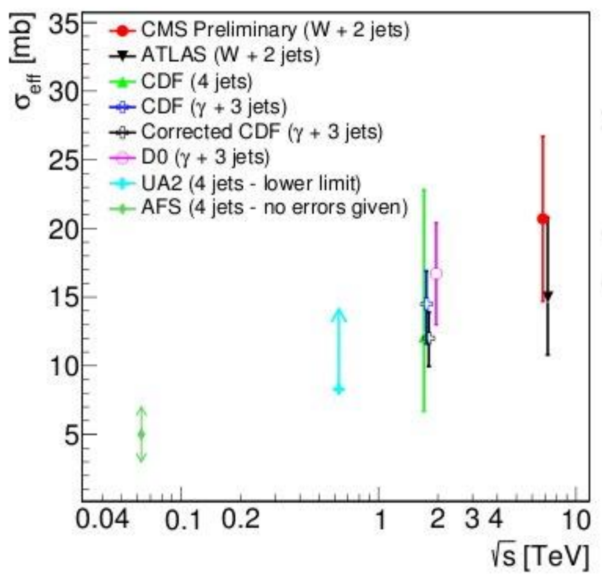


Single parton scattering

Template fit of the sensitive observables to find σ_{eff}:

$$\delta p_T = \frac{p_T(j1,j2)}{(p_T(j1)+p_T(j2))}$$

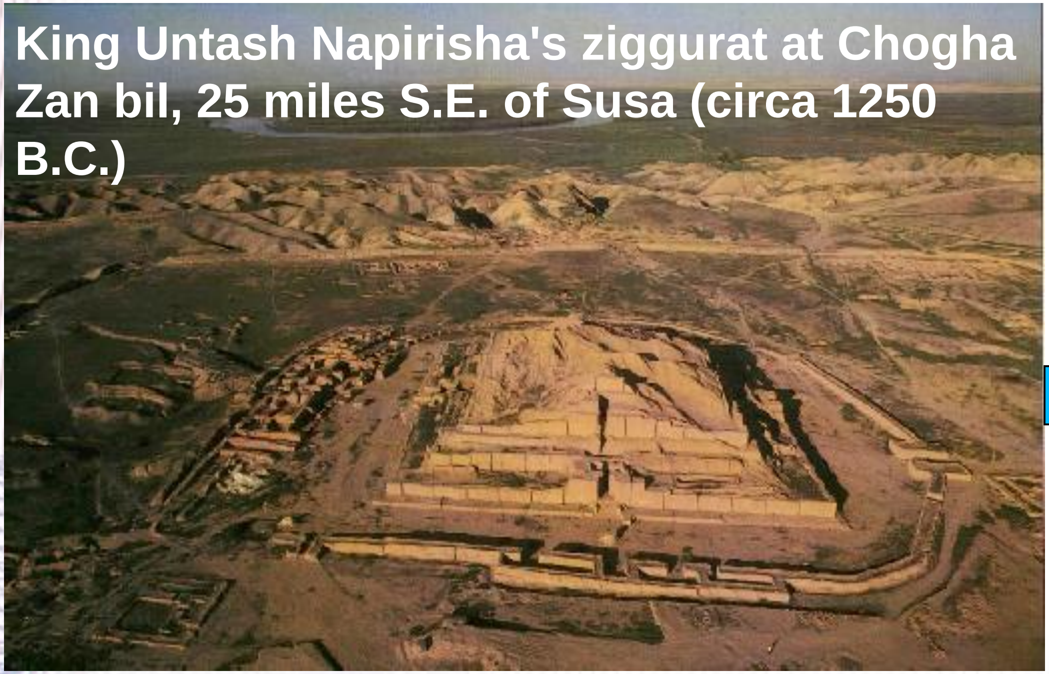
Azimuthal angle between W and dijet vector

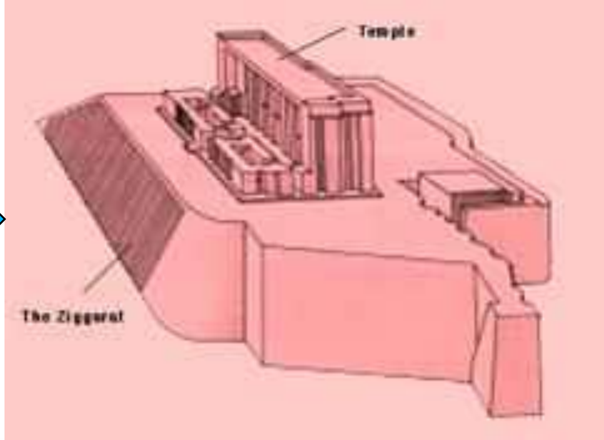


CMS-PAS-FSQ-12-028

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.


King Untash Napirisha's ziggurat at Chogha Zan bil, 25 miles S.E. of Susa (circa 1250 B.C.)



Thank you!

Bonus material

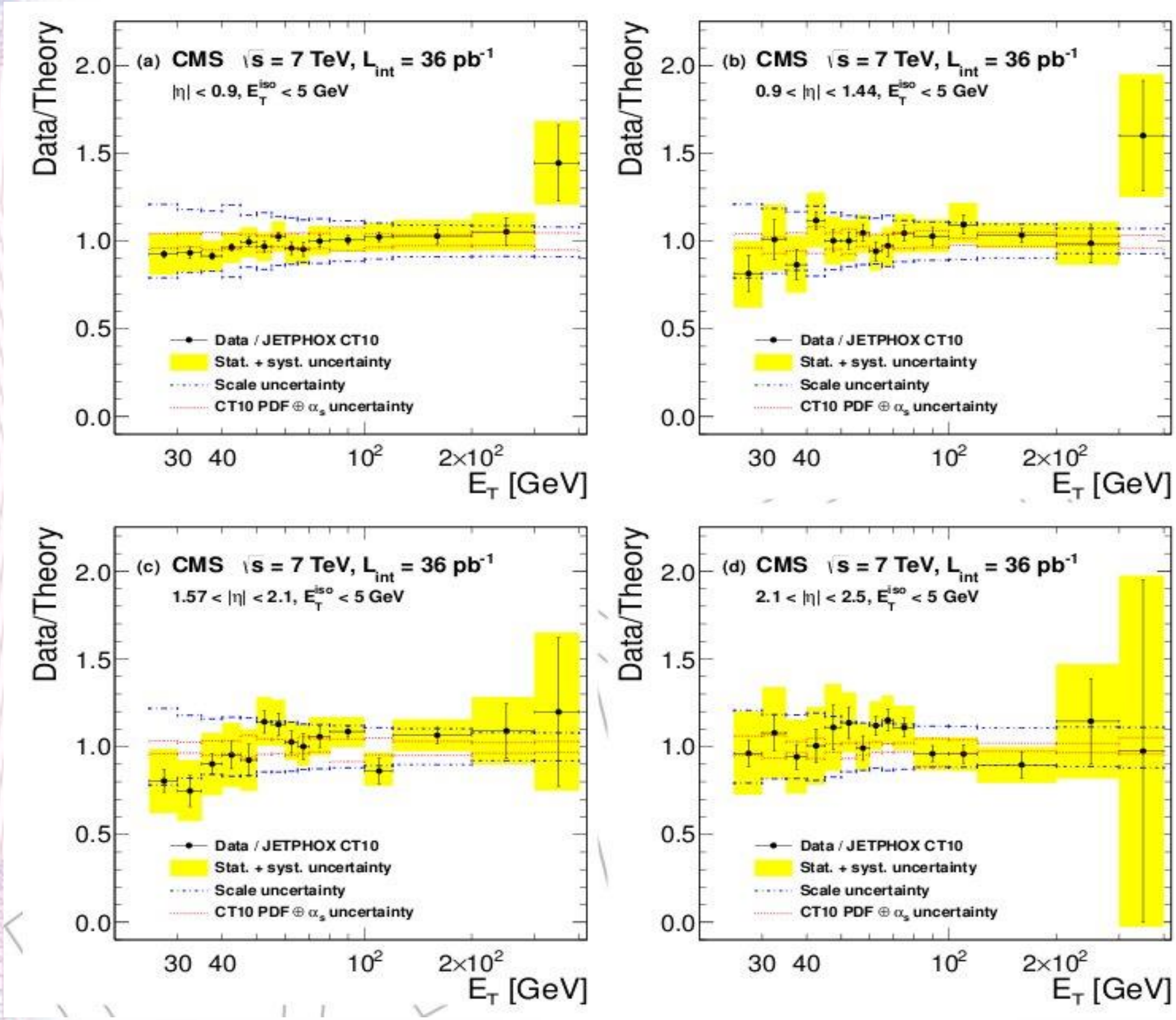
PDFs

- MSTW: global fit of hard scattering data with leading twist fixed order collinear factorization in the MS scheme. Data: HERA DIS (except latest combined HERA-I data), fixed target DIS and DY, Tevatron jet,W,Z
- CTEQ: global fit of hard scattering data in the framework of general mass pQCD.

  Data: same as MSTW (CT10 includes HERA-I+more Tevatron data)
- NNPDF: parametrize PDFs by training a neural network on MC replicas of the experimental data. Data: as above.
- HERAPDF: DGLAP evlution in the MS scheme. QCD prediction for FF is done using convolution of PDFs with general mass variable flavor number RT scheme.

  Data: NC and CC HERA DIS (v1.5), +HERA jets (v1.6)
- AB(K)M: Data: only NC (neutral current) DIS from HERA and fixed target
- GJR : dynamical approach for evolution. Data: DIS, DY, Tevatron jet data.

High-p_T 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 t overestimated data.

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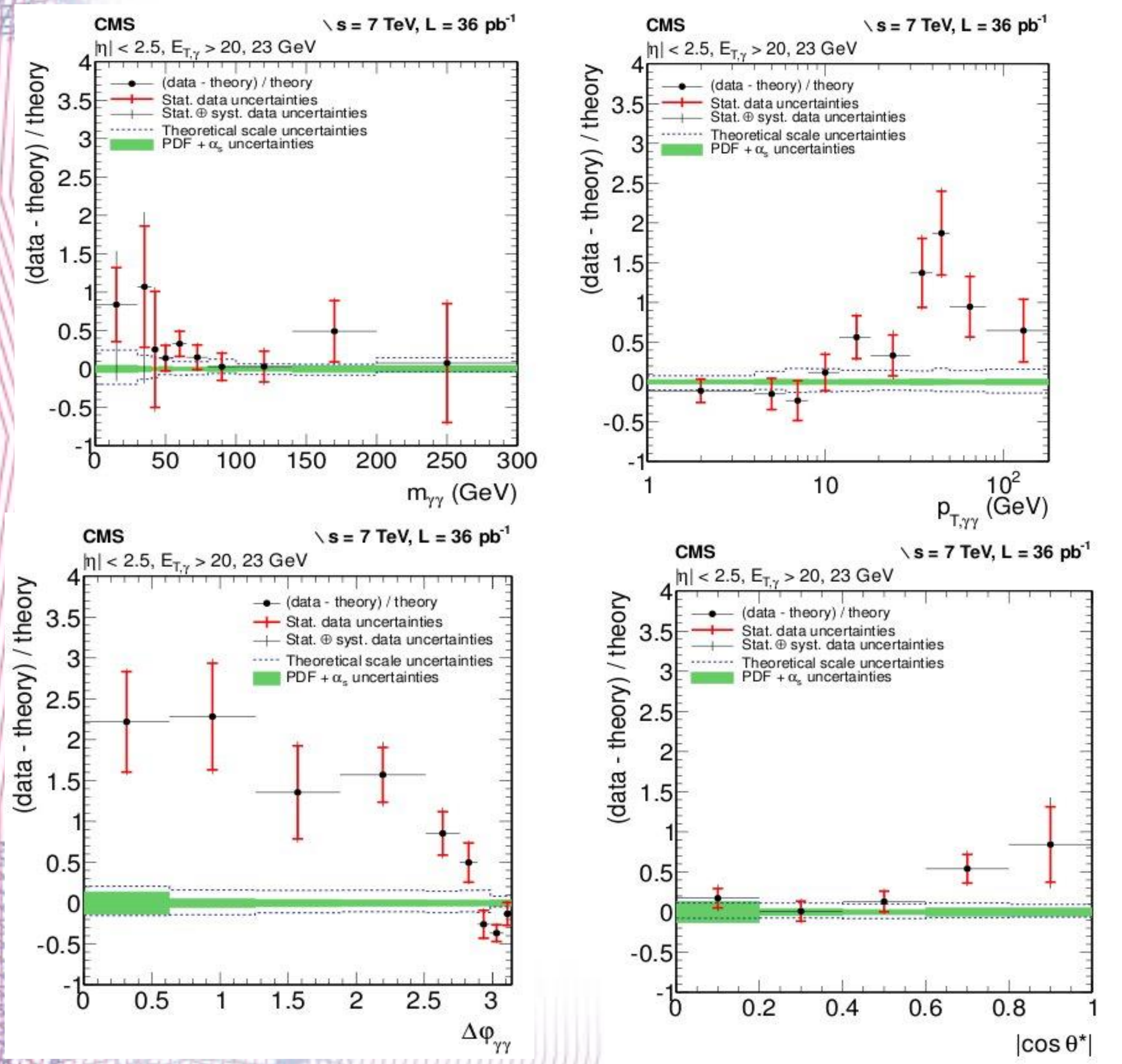
Di-photon production



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 $\Delta\varphi_{\gamma\gamma} < 2.8$

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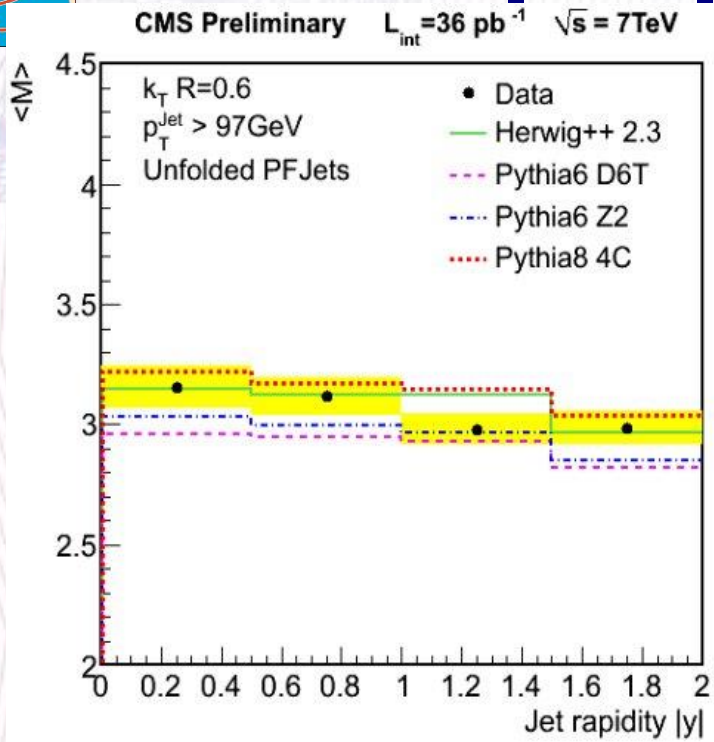
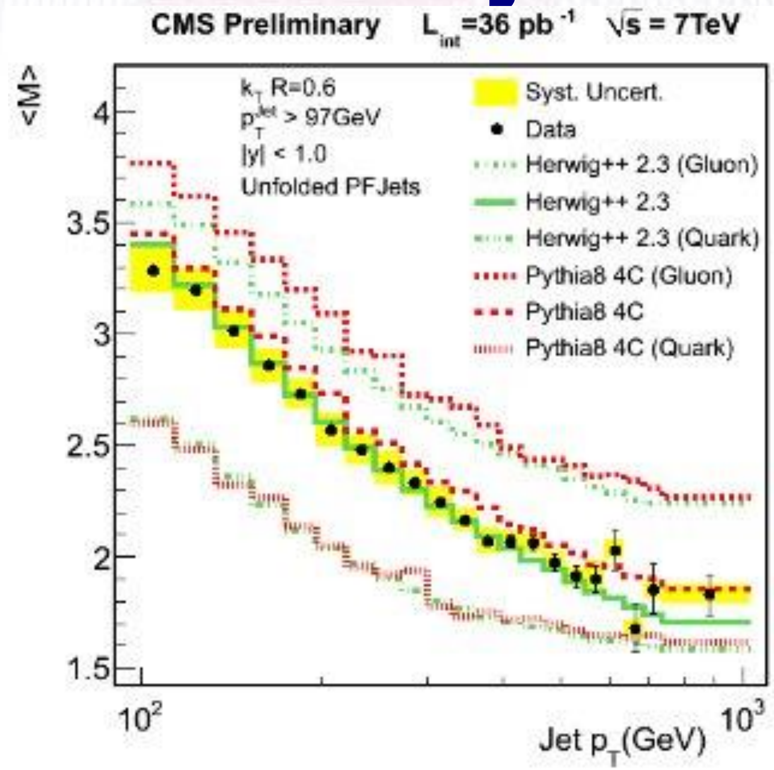
Jet properties: subjets





K_T 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 ♒📪♐ plane)