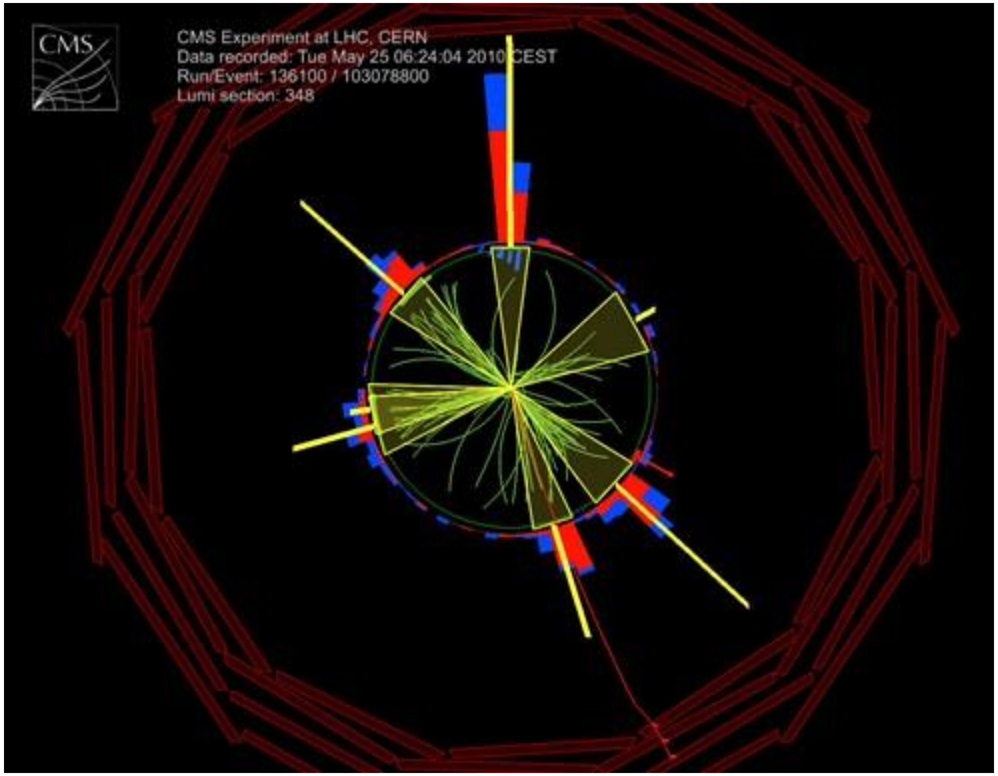
CMS QCD physics results

Olga Kodolova, SINP MSU
on behalf of the CMS Collaboration



Outline

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

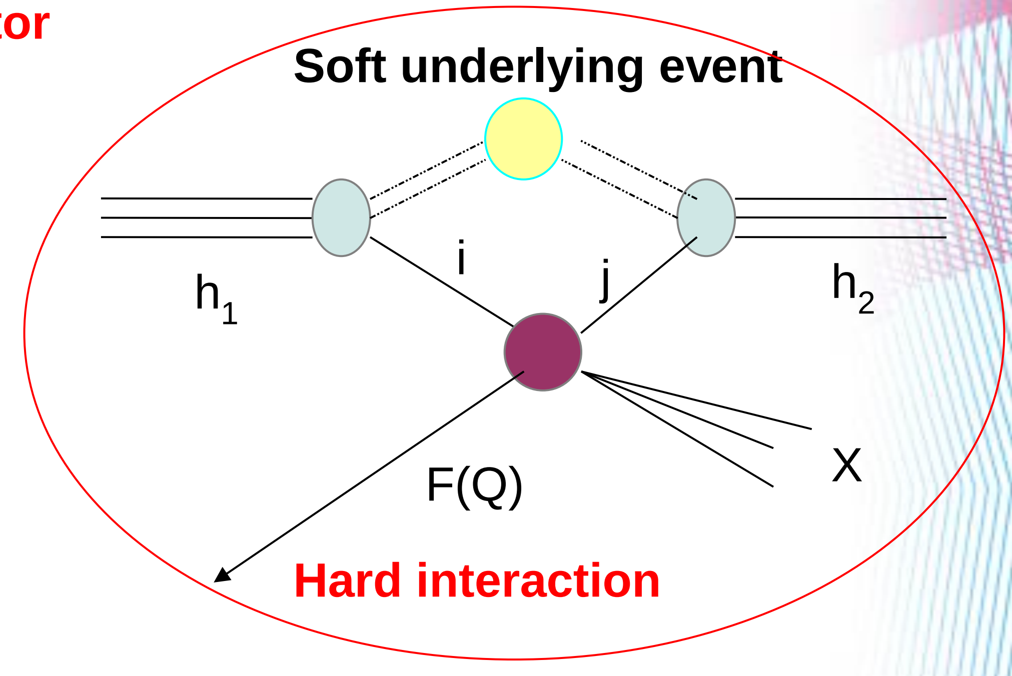
QCD is the theory that explains strong interactions as part of the Standard Model

QCD at hadron colliders

QCD defines the hadronization process of partons whatever interaction mediator is in the hard production vertex

Production of low-p_T hadrons

Soft interaction



Factorization theorem

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

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

Parton distribution function (PDF)

Partonic cross-section computed in pQCD

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

- **μ_F – factorization scale separates long and short distance physics**
- **$\alpha_S(\mu_R)$ – running coupling constant**
- **μ_R – renormalization scale**
- **$Q^2 = -q^2$ – transferred momentum**

Where we are now at LHC

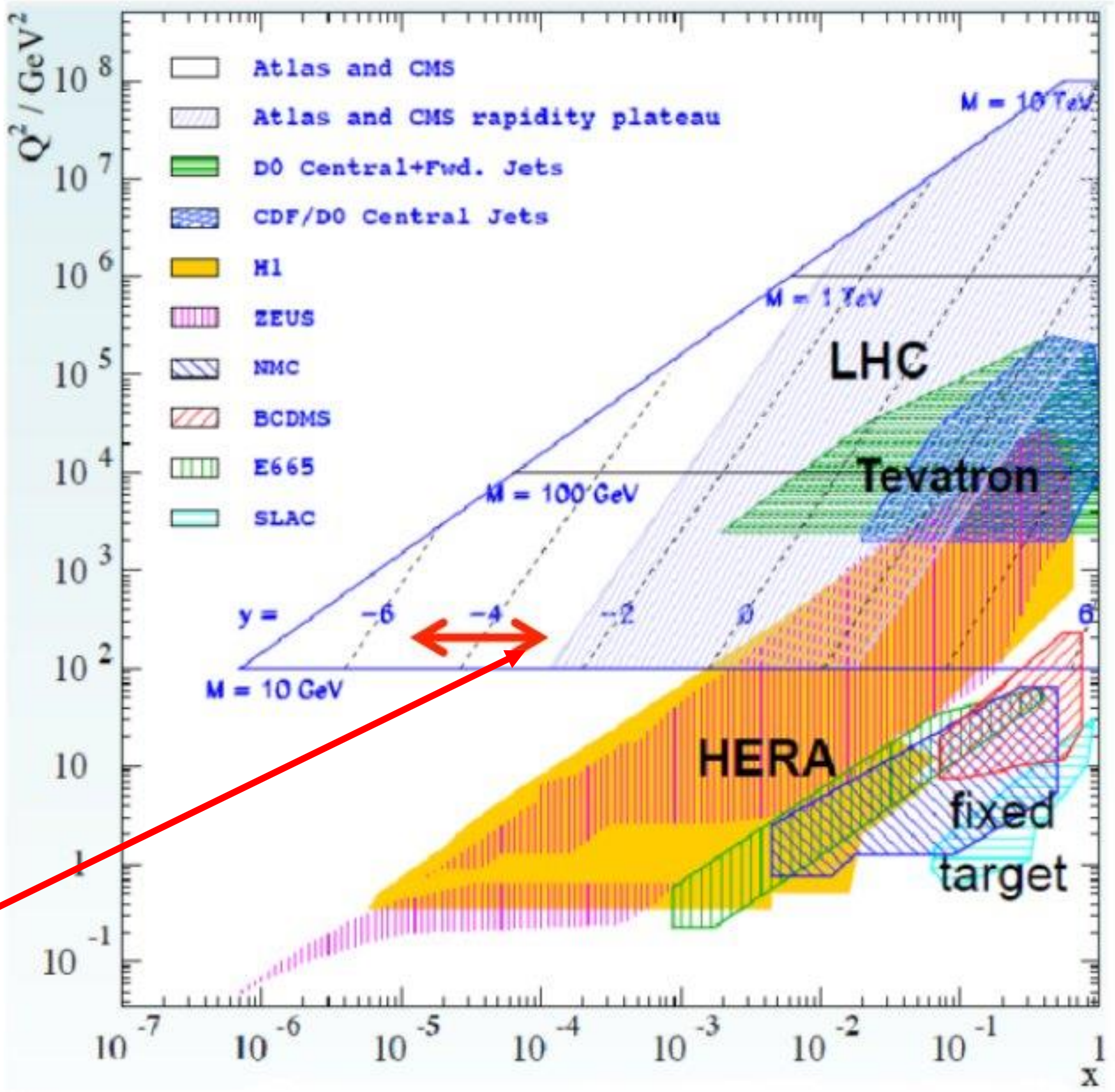
Important background for new physics searches

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

Study the parton structure, constrain the strong coupling, …

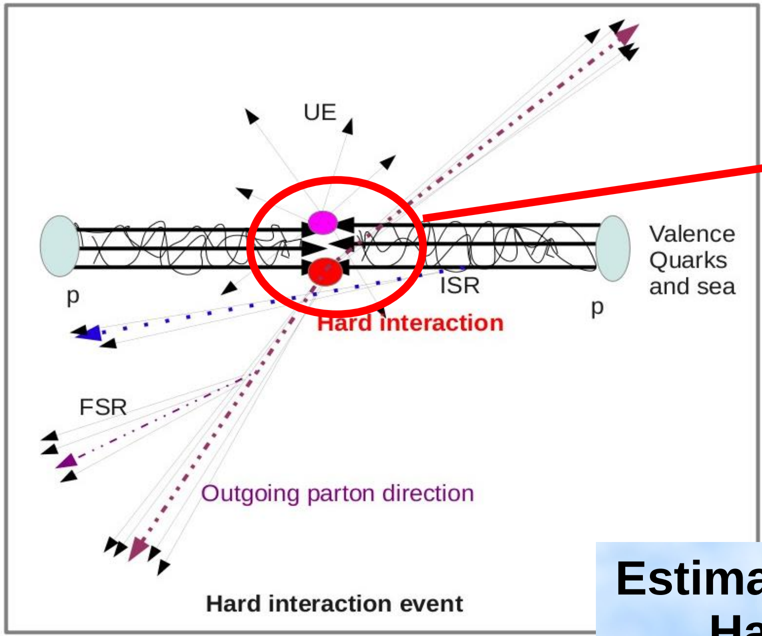
Study non-perturbative effects

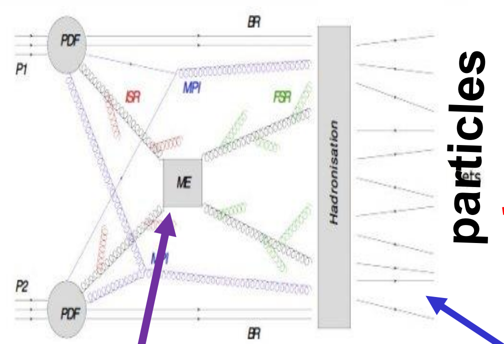
Tune Monte-Carlo generators

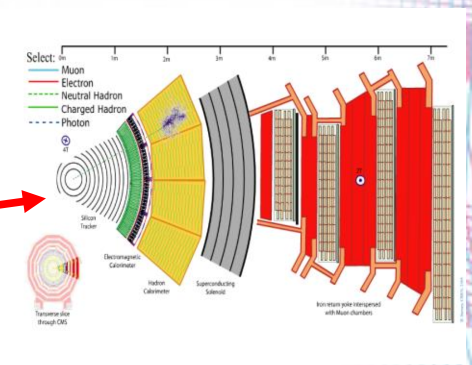


Probing the new territory (x,Q^2) range

How do we proceed







2 step unfolding meet at particles level

Reconstructed particles, reconstructed jets

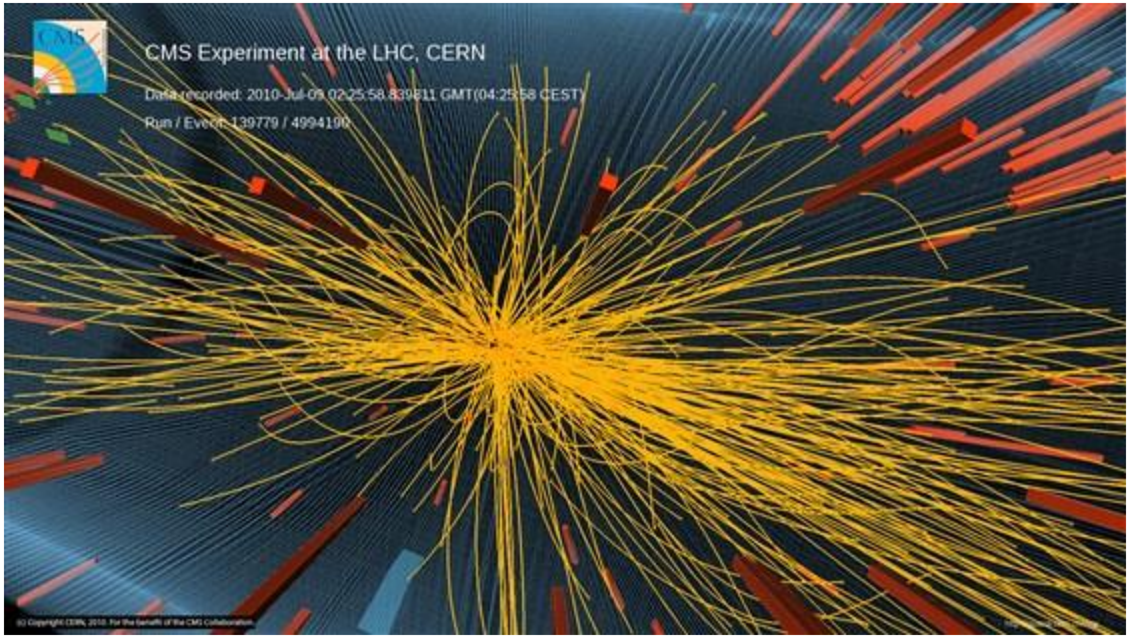
Differential Cross-sections Multiplicity Rapidity Momentum of Particles and Jets, missing E_T

Estimate:

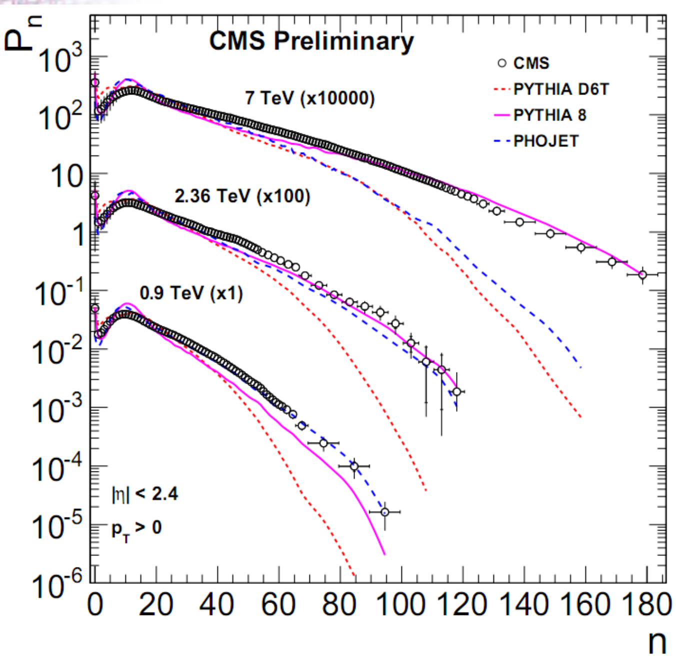
- **Hard interaction cross-section**
- **Parton Distribution Functions**
- **Parton showering details**

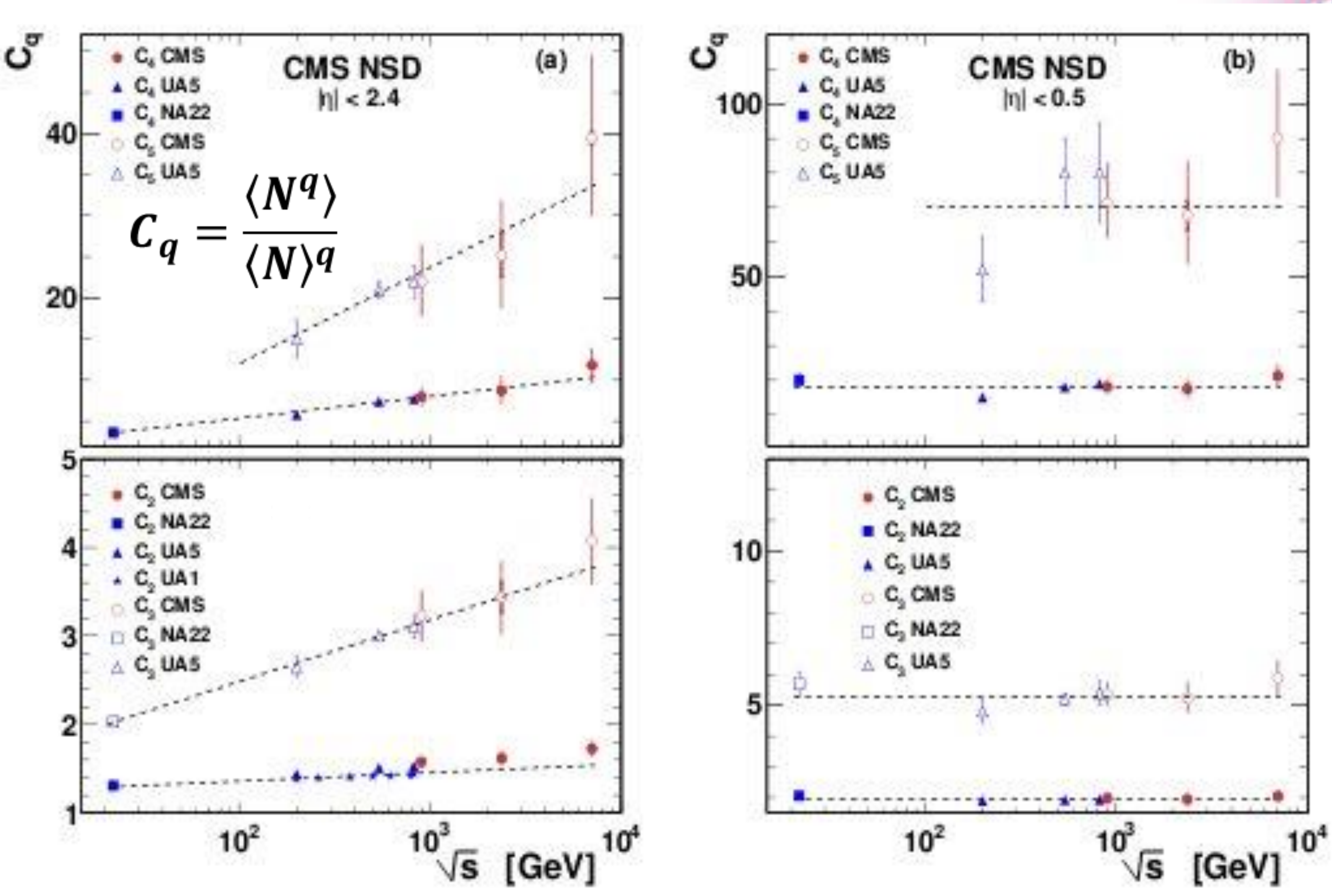
Theory approximations:
Perturbative QCD (pQCD):
LO, NLO, NNLO calculations, ME + parton showering (PS) , threshold resummation
non-pQCD: (Multi-parton interactions (MPI), String/Cluster fragmentation models)

Soft particle production



Charged particle multiplicity



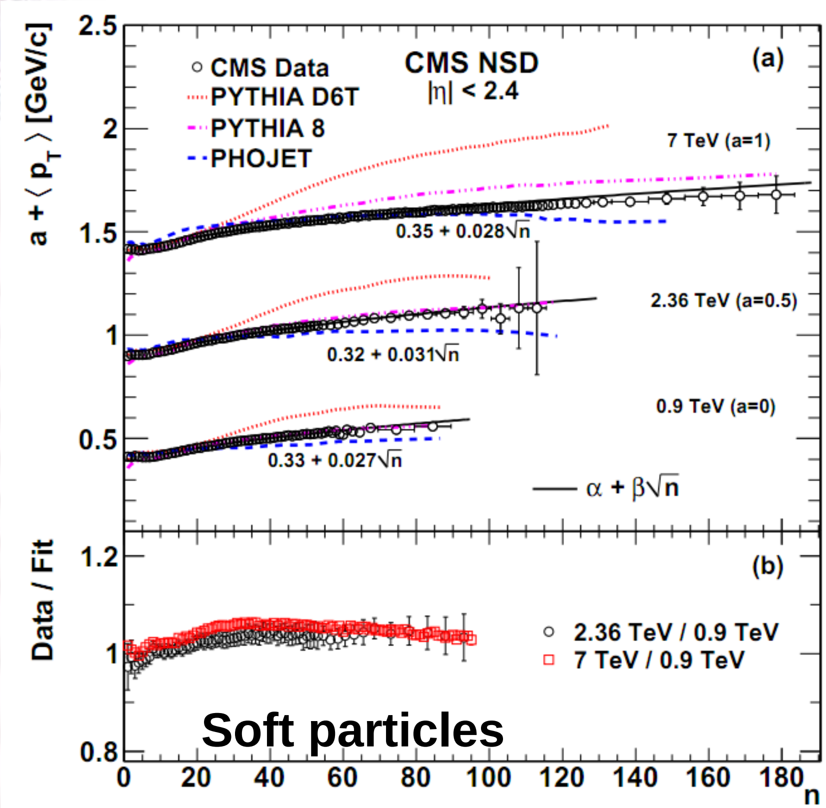


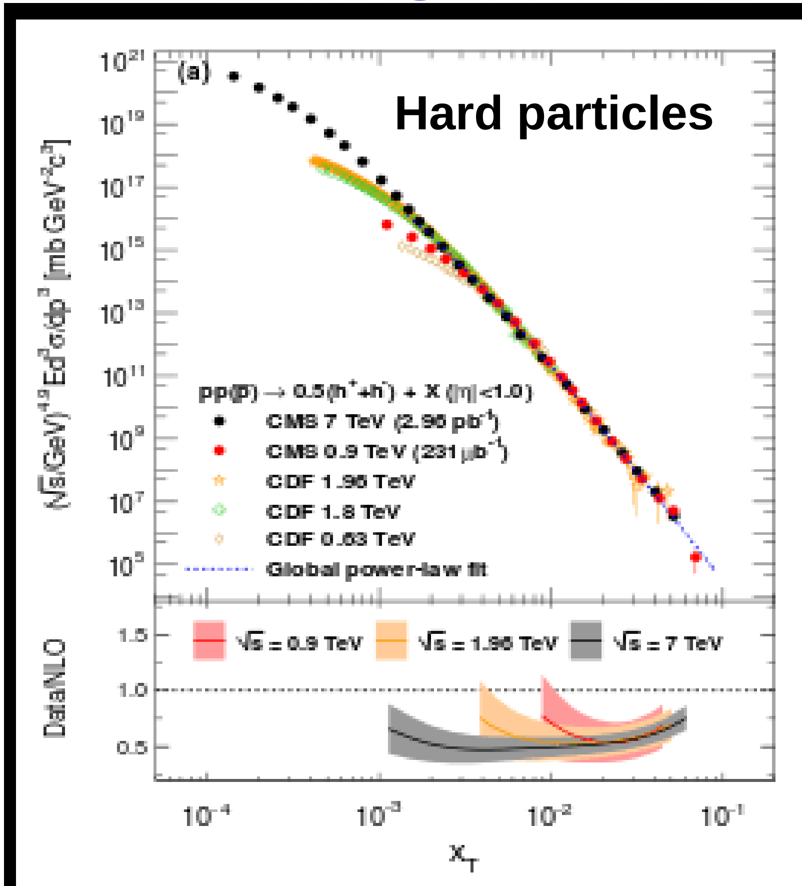
Evidence of the multi-component structure (change of the slope at n~20)
Violation of the KNO (Koba-Nielsen-Olesen) scaling In the range |η|<2.4
Still KNO scaling in the range |η|<0.5

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

JHEP01(2011)079

p_T&x_T-scaling





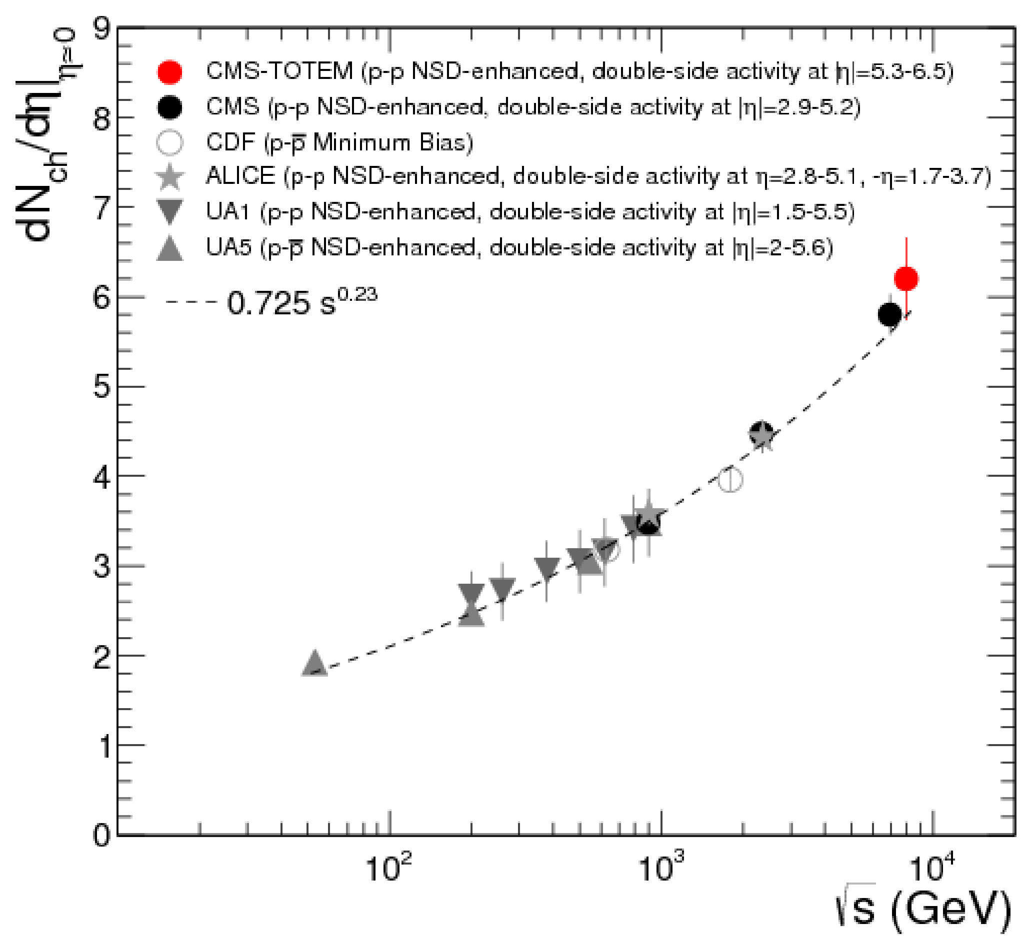
The rise of the $<p_T>$ with multiplicity
Is energy independent

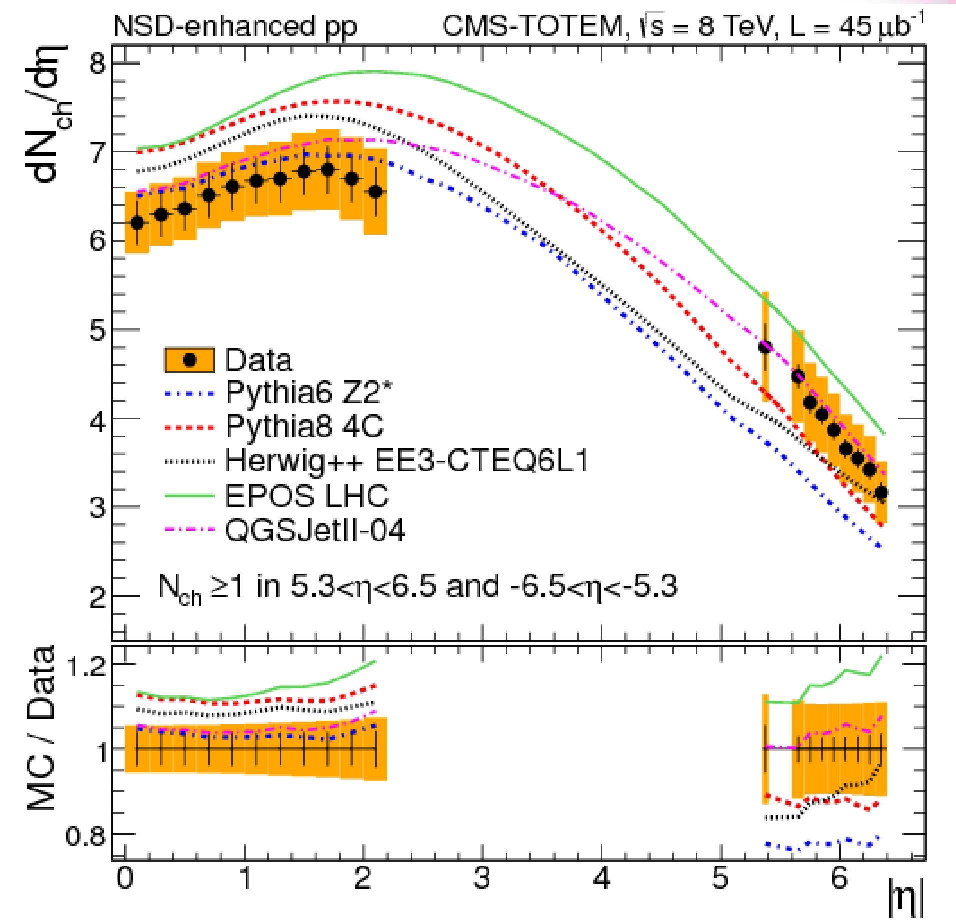
The CMS results are consistent with
$x_T=2p_T/\sqrt{s}$ scaling (pQCD prediction)
with exponent N=4.9 +- 0.1
NLO calculations overestimate
cross-section twice at all energies
for high p_T hadrons

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

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

Charged particle density for √s=0.9 TeV-8 TeV



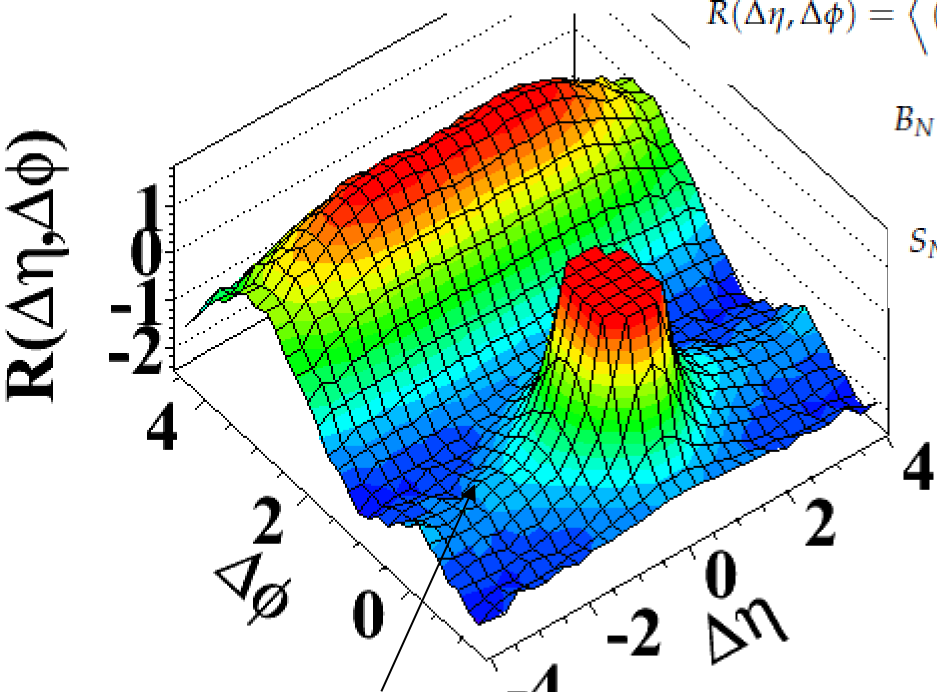


Measured NSD multiplicity is higher then most of the predicted: new input to the dynamics of soft hadronic interactions

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

Long-range correlations

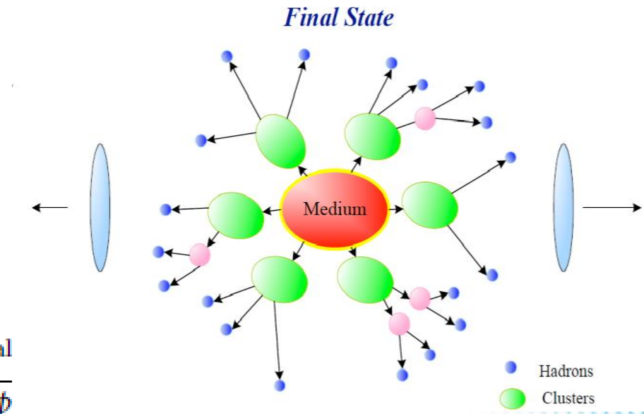
(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c

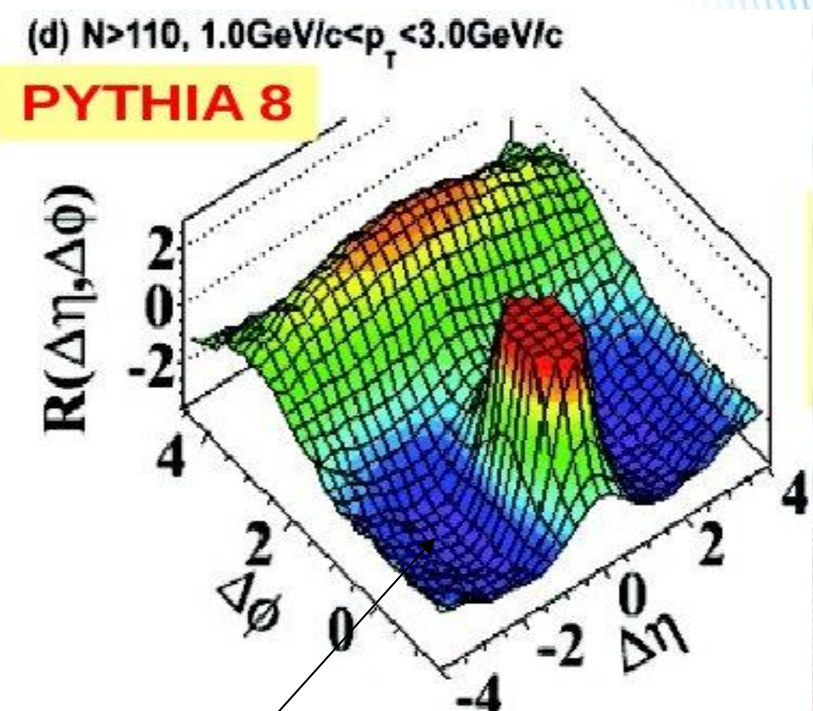


$$R(\Delta\eta,\Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

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

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





Observation of a Long-range, Near-side angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at Δφ ~ 0)

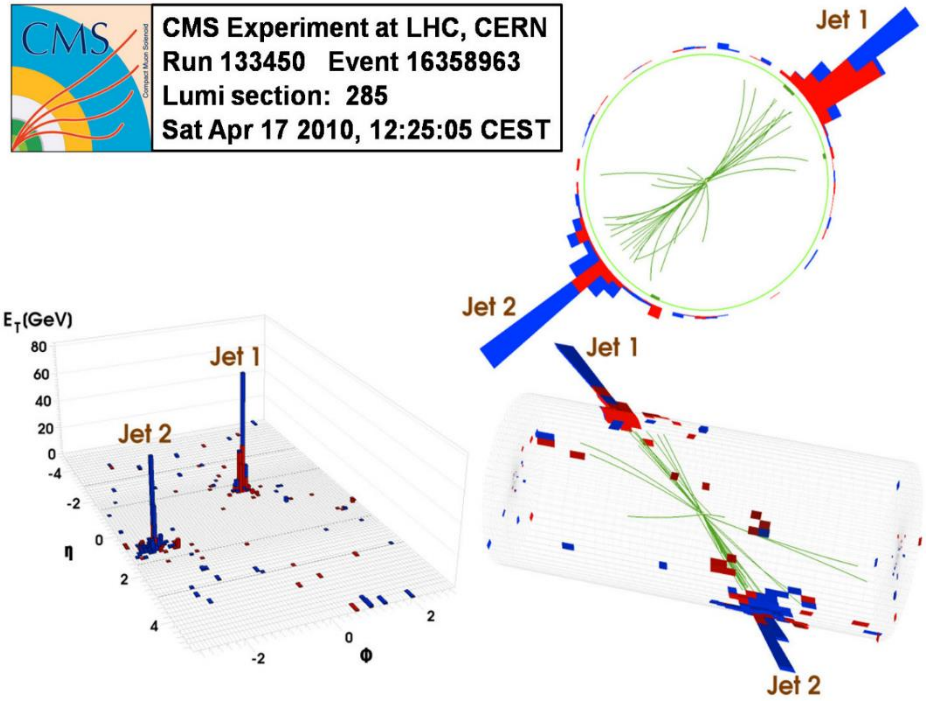
Firstly observed At RHIC in Au-Au collisions

Theoretical hypothesis:
- collective parton flow at the initial or final state
EPOS and some other models can describe the effect

Ridge is not reproduced neither of PYTHIA versions nor MADGRAPH

JHEP 1009 (2010) 091

Hard interactions



Jets reconstruction

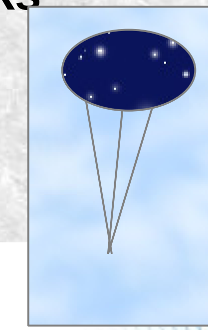
Calorimeter jets (CaloJets):
Jet clustered from Calorimeter Towers
Subdetectors: ECAL, HCAL

CaloMET

Anti-Kt clustering algorithm is applied to the different objects

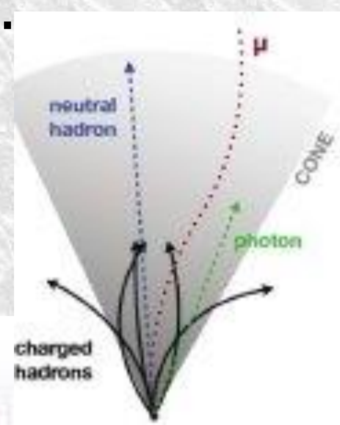
Tracker jets:
Jet clustered from Tracks

Subdetectors: Tracker



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

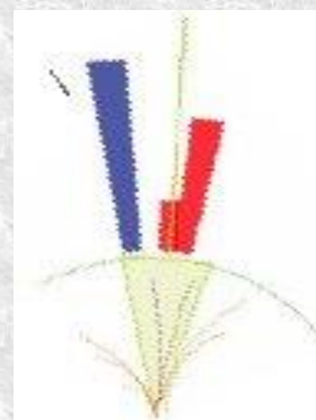
PFMET



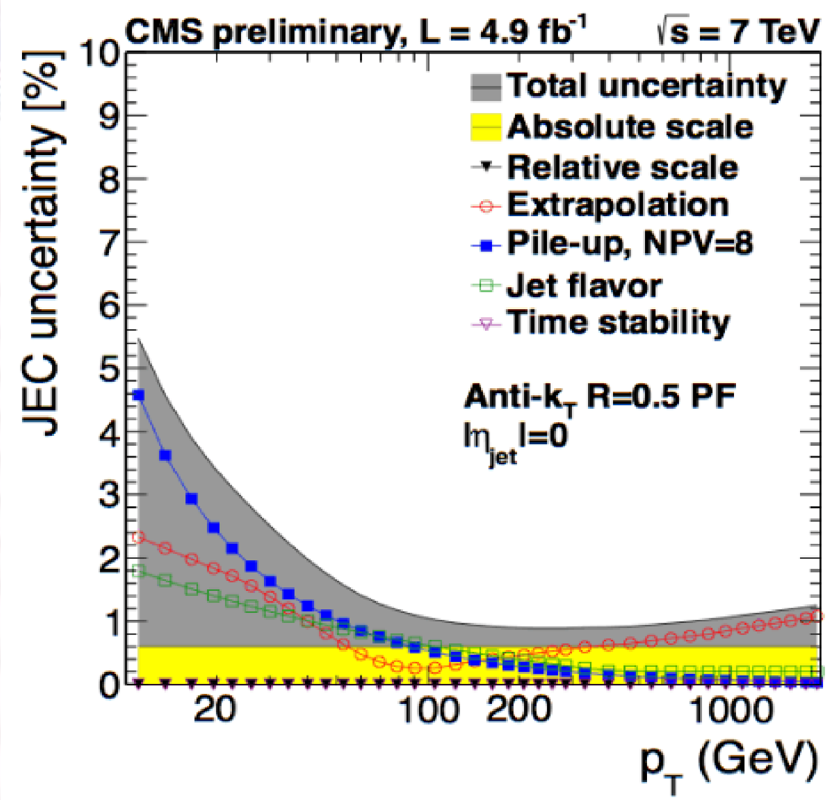
All subdetectors Participate in reconstruction

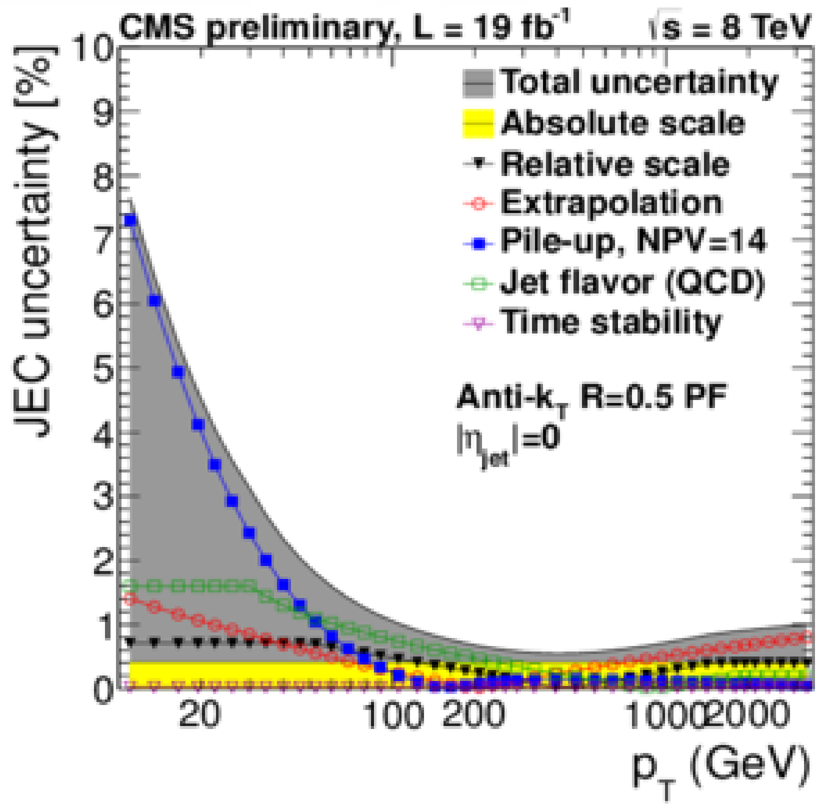
The residual jet energy corrections is applied on top of all algorithms

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



Jet energy scale





Sources of the jet energy scale distortion

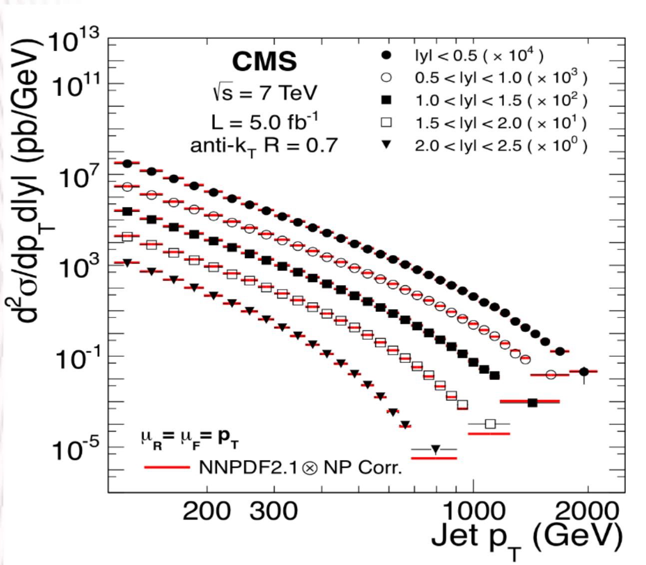
- ❖ **Calorimeter response**
- ❖ **Magnetic field**
- ❖ **Electronic noise**
- ❖ **calorimeter thresholds**
- ❖ **Dead materials and cracks**
- ❖ **Longitudinal leakage**
- ❖ **Shower size, out of cone loss**
- ❖ **pileup contribution**

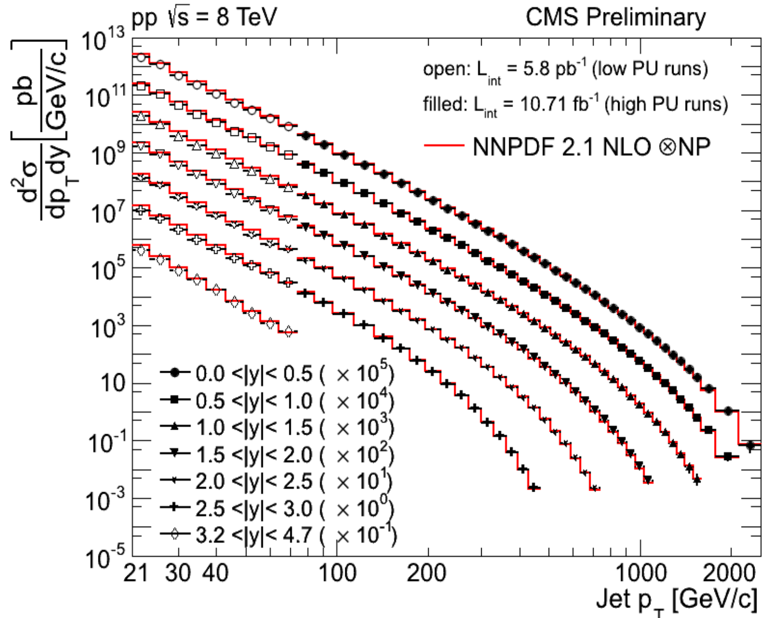
JINST 6 P11002 (2011)
CMS DP-2012-006
CMS-DP-2013-033

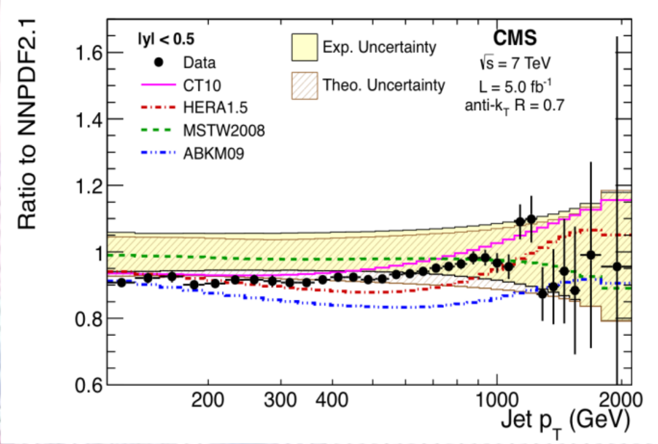
Inclusive jet production

Fundamental test of QCD

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{e \times L_{int}} \frac{N_{jets}}{\Delta p_T \Delta |y|}$$





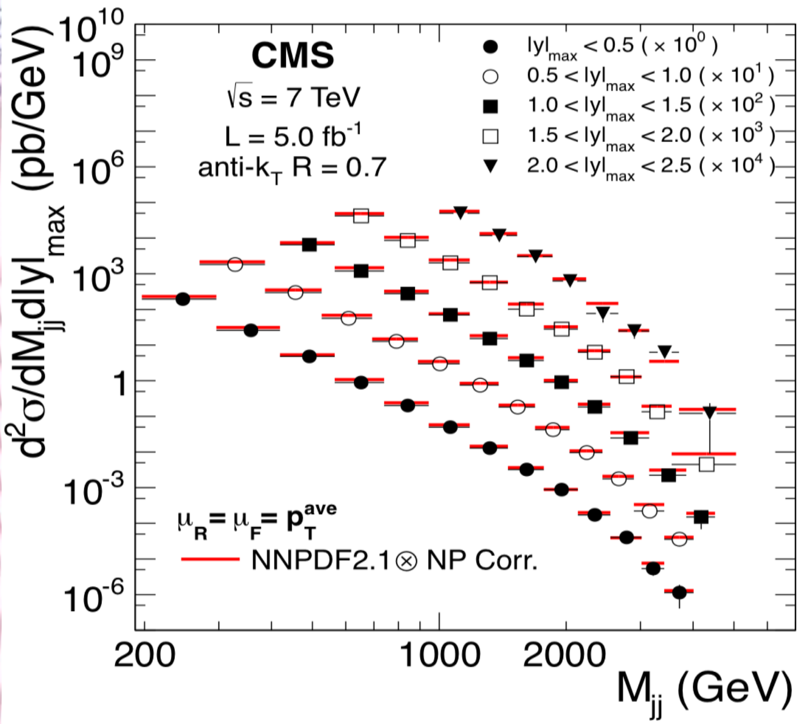


Discriminate PDFs to some extent, in particular, gluon PDF at high x

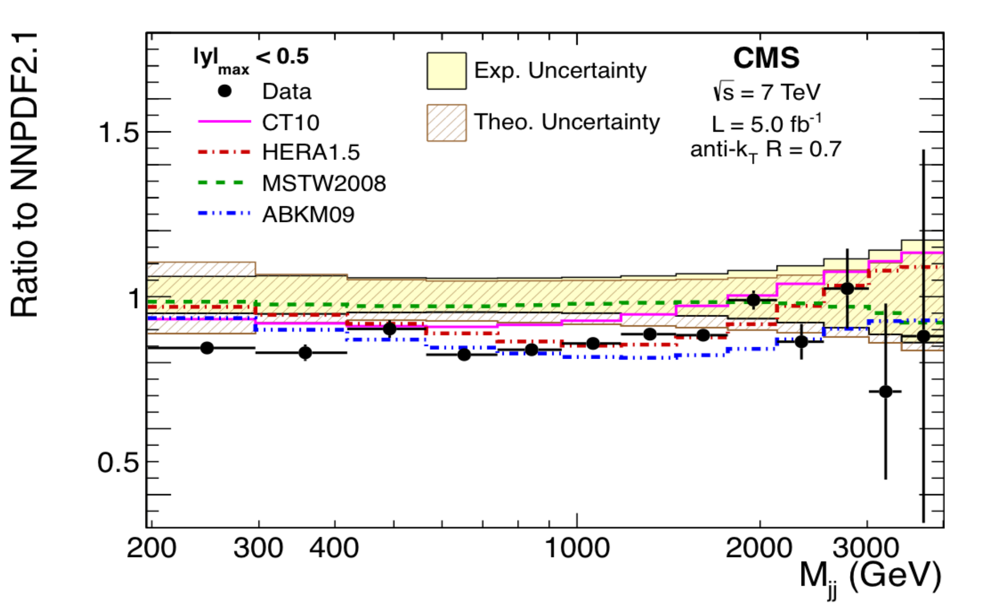
The extraction of the strong coupling α_S

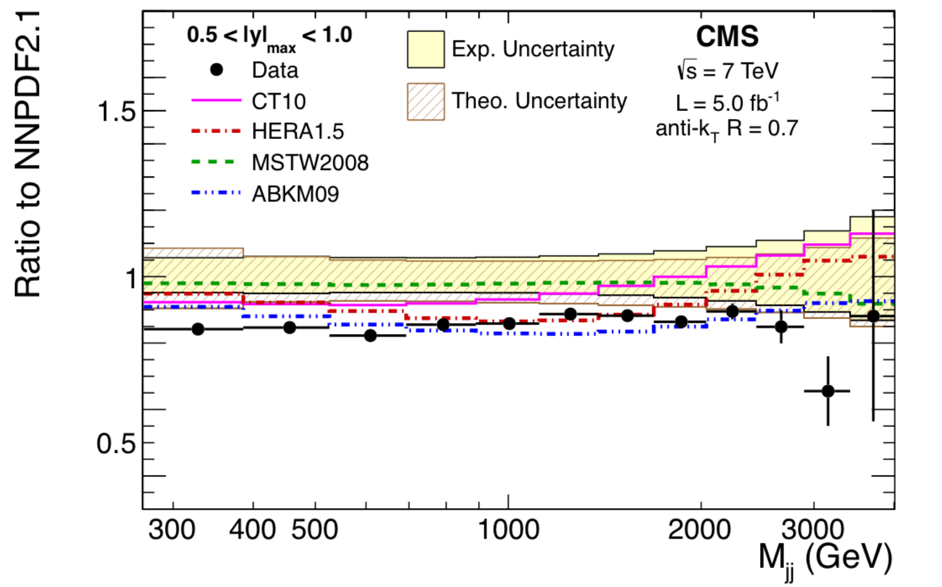
Phys. Rev. D 87 (2013) 112002
CMS-PAS-SMP-12-012
CMS-PAS-FSQ-12-031

Di-jet production



7 TeV





NLO QCD (NLOJet++) + NP corrections

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

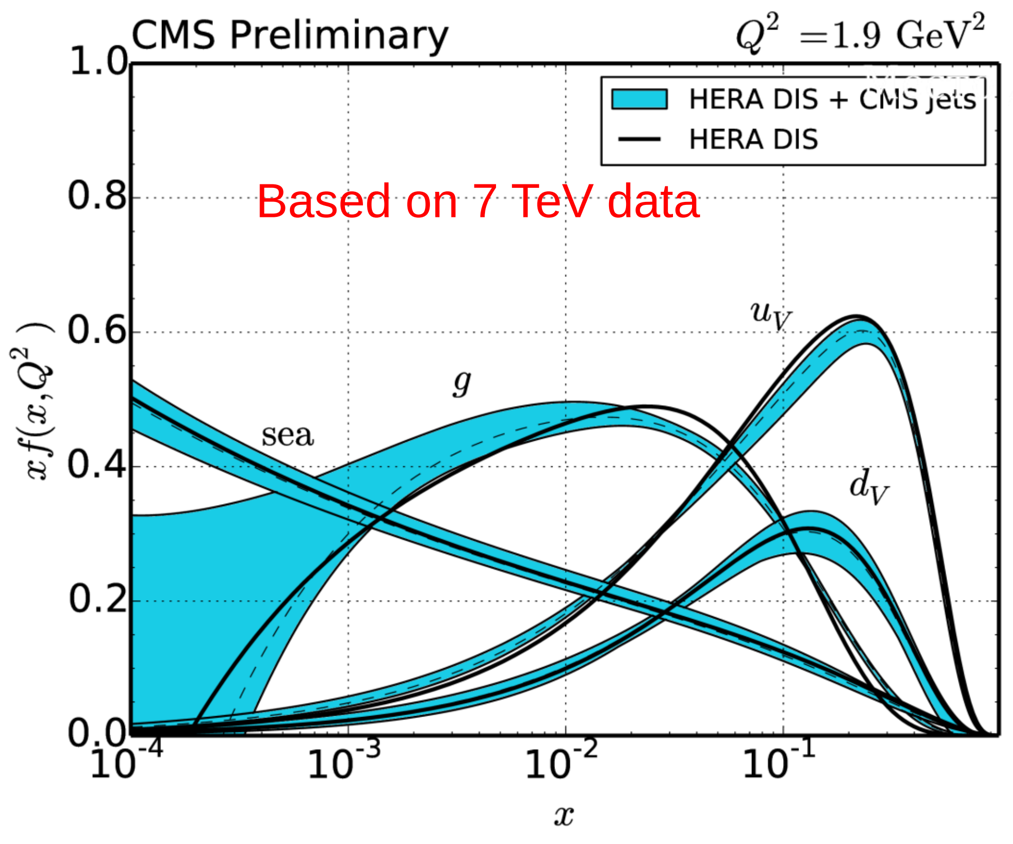
Consistent with NLO calculations within uncertainties, gives the constraint to PDFs.

Phys. Rev. D 87 (2013) 112002

PDF and α_s extraction from inclusive jets spectra

Combined fit of HERA DIS and CMS inclusive jets data is performed using DGLAP evolution at NLO with two options:

- **with fixed $\alpha_s(M_Z)$=0.1176**
- **simultaneous fit of PDFs and α_s**



The correlation between g-pdf and cross-section is observed in the central region and for q-pdf In forward region:

- **Significant improvement of gluon pdf at high-x**
- **Slight change of d_{val} quark distribution**

$\alpha_s(M_Z)$ is extracted for each PDF set and from simultaneous fit of PDFs and α_s

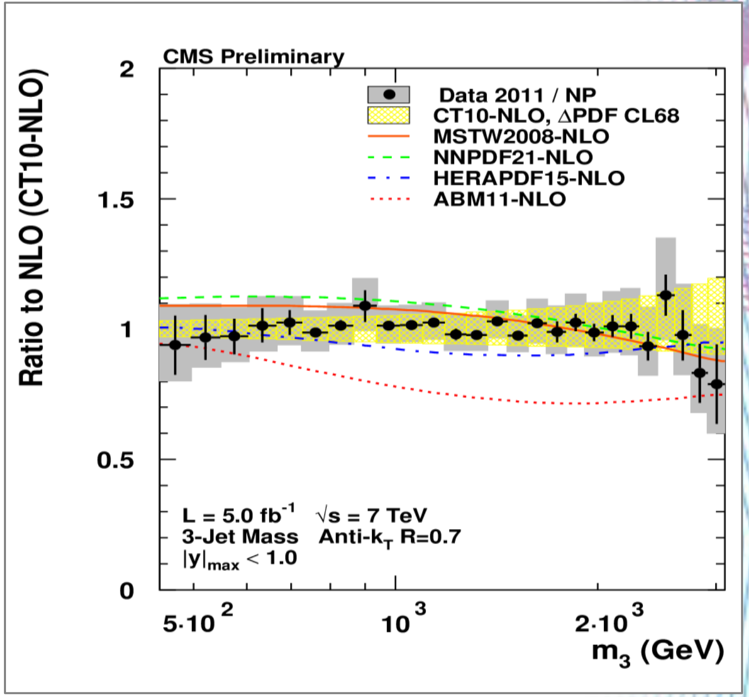
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_S^2$$

CMS-PAS-SMP-12-028

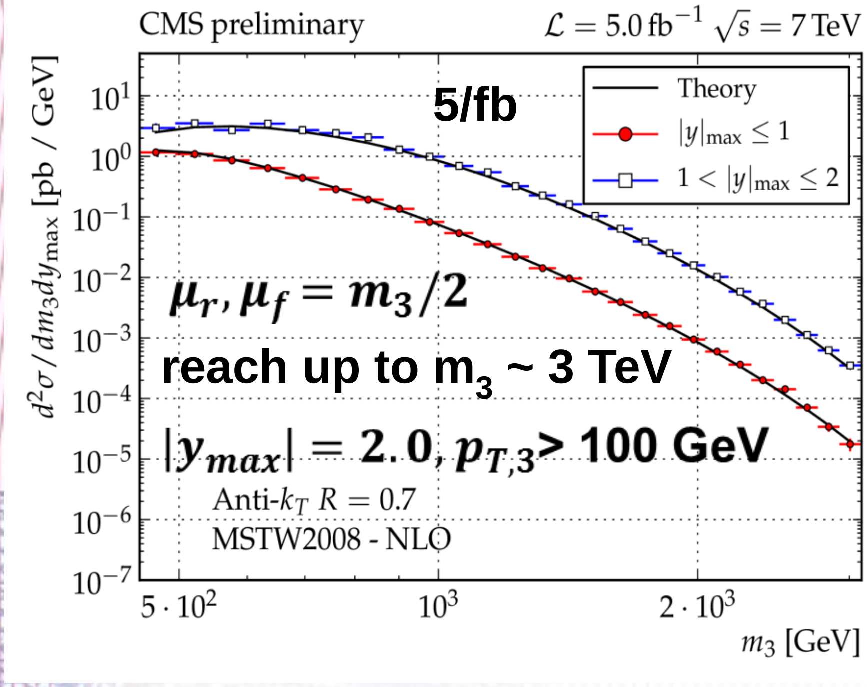
Multijet production (3 jets)

sensitivity to PDFs and α_S

$m_3^2 = (p1+p2+p3)^2$, $|y_{max}|=\max(|y_1|,|y_2|,|y_3|)$, $Q=m_3/2$



Agreement with pQCD @ NLO x NP
Most PDF sets compatible with data



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$\mu_r, \mu_f = m_3/2$

reach up to m_3 ~ 3 TeV

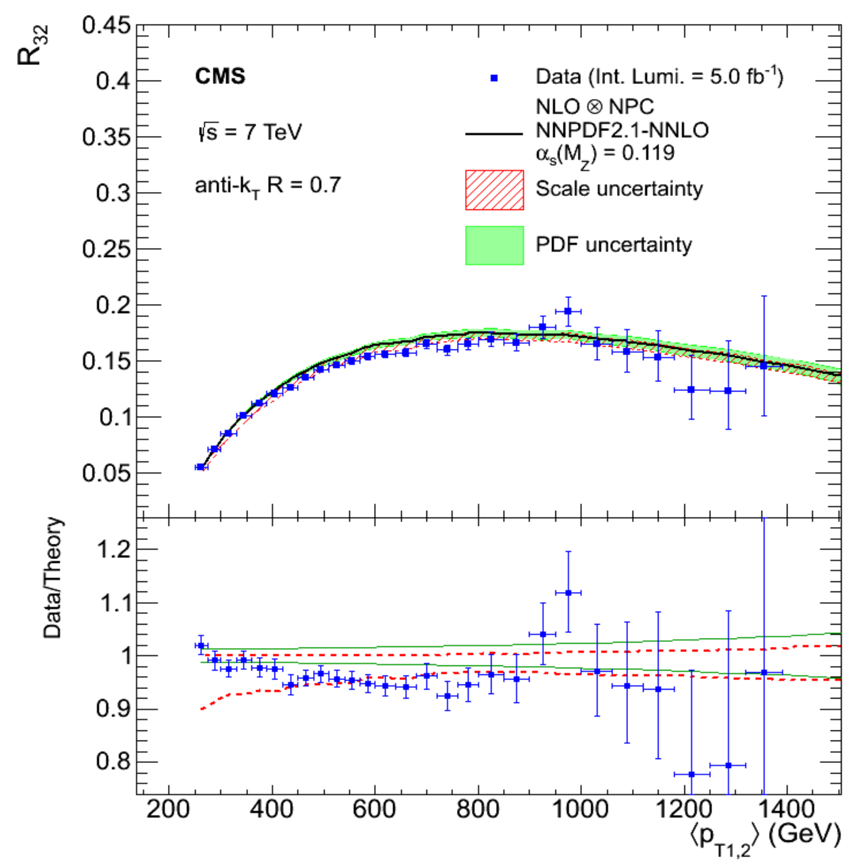
$|y_{max}| = 2.0$, $p_{T,3}$ > 100 GeV

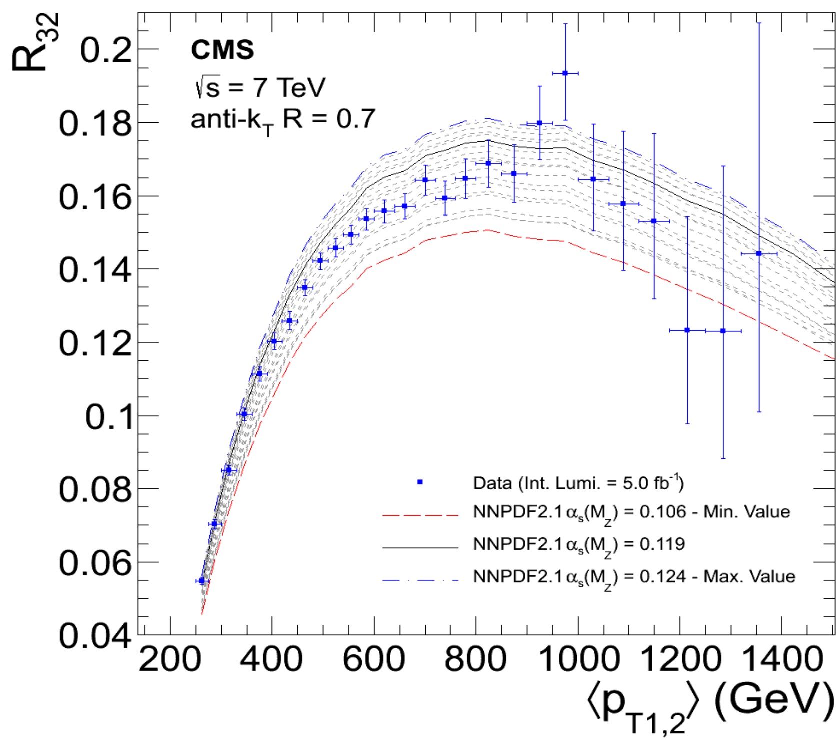
$$\frac{d^2\sigma}{dm_3\,dy_{max}} \propto \alpha_S^3$$

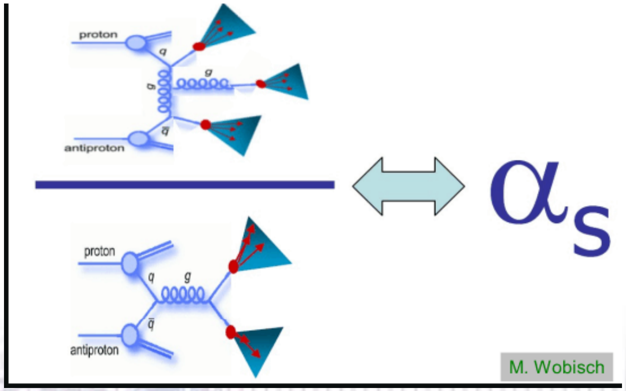
Deviations observed with NLO + ABM11 PDF

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

3-jet over 2-jet cross section ratio







Cross-section ratio R32:

- inclusive 3-jet over 2-jet production is sensitive to α_S

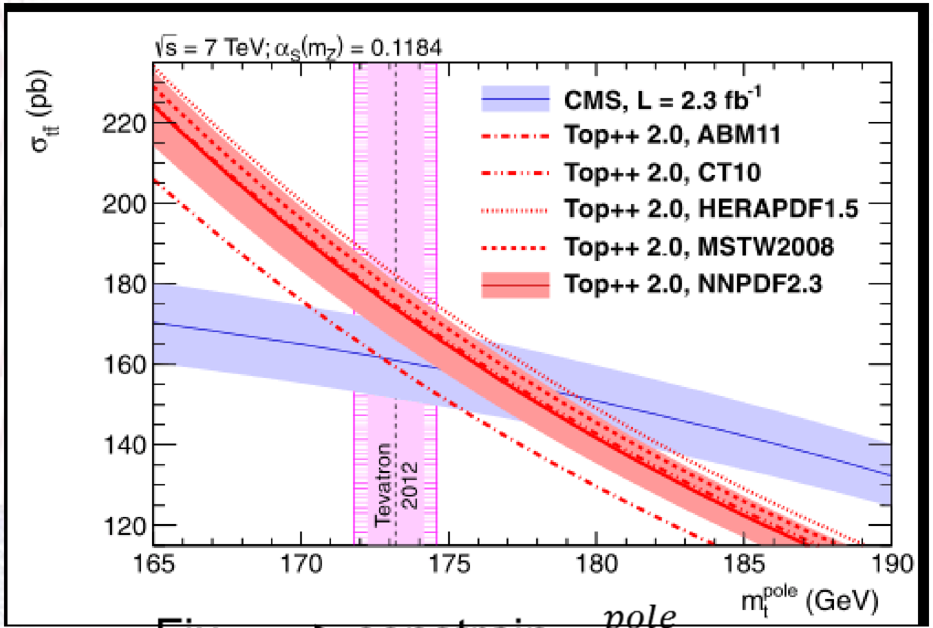
Multiple alternative phase-space options

- depending on the cut imposed on the 3rd jet p_T

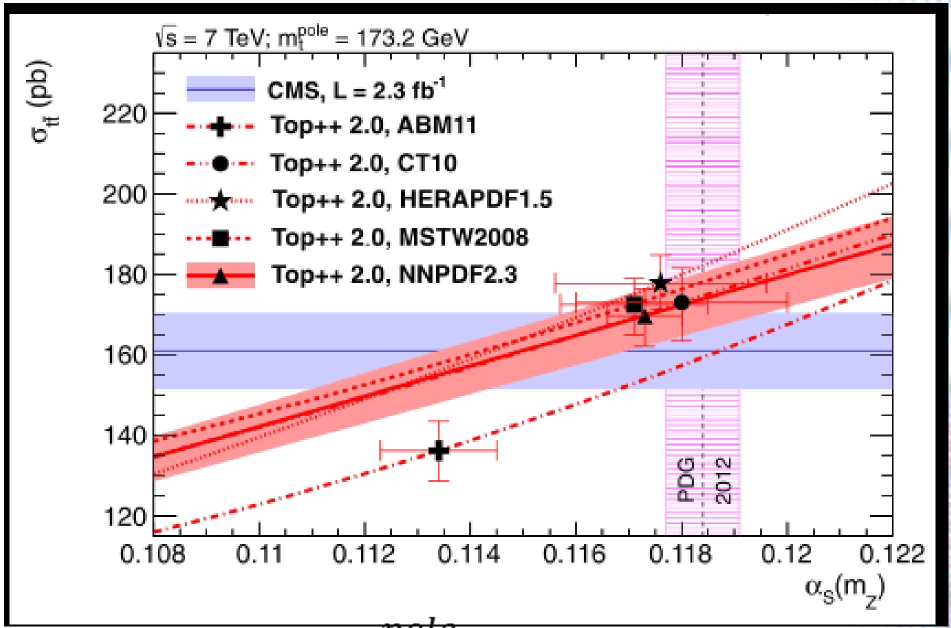
CMS-PAS-QCD-11-003
arXiv:1304.7498

α_s fit with top-pair production

Top pairs production is sensitive to $m_t^{pole}, \alpha_S, g(x, \mu_f^2)$. Fits are performed with fixing one of the PDF sets.



Fix α_S -> constrain m_t^{pole}



Fix m_t^{pole} -> constrain α_S

CMS, PLB 728, 496 (2013)
JHEP 11, 067 (2012)

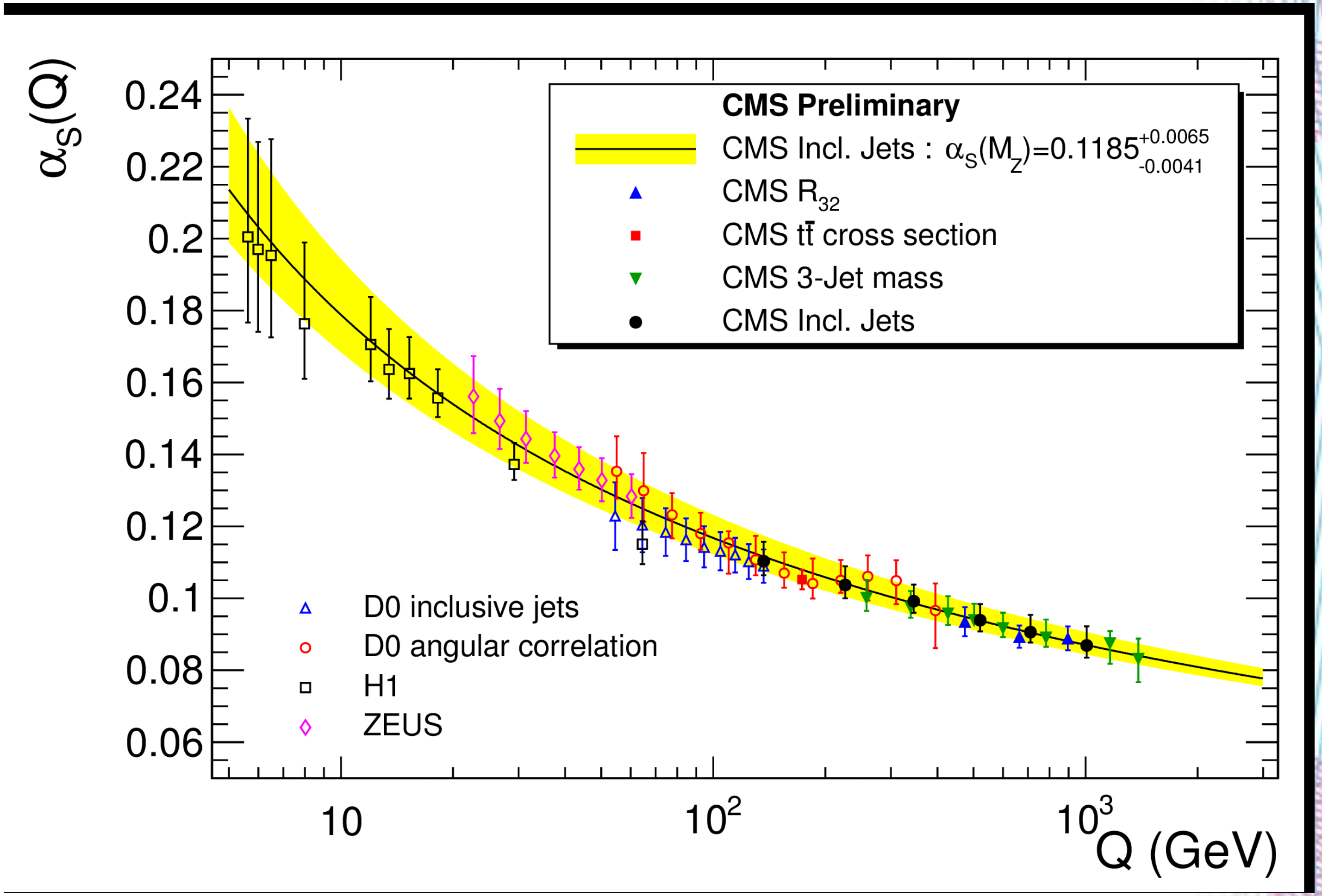
α_s extraction from data

LHC at 7 TeV and 8 TeV enables measurements up to 2 TeV

Theory at NLO and NNLO (tt cross-sections) plus the additional electroweak corrections

Typical uncertainty:

- Experimental 1-2%
- PDF 1-2%
- Scale 4-5%
- Non-perturbative effects <1%
- Other theory uncertainties ?



CMS-PAS-SMP-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
- CMS measurements are used for the combinations with other experiments in global fits and in Monte-Carlo Models tuning. The overall coverage of the phase space reaches 2 TeV

The data are, in general, in broad agreement with the perturbative predictions. However, some discrepancies are observed.

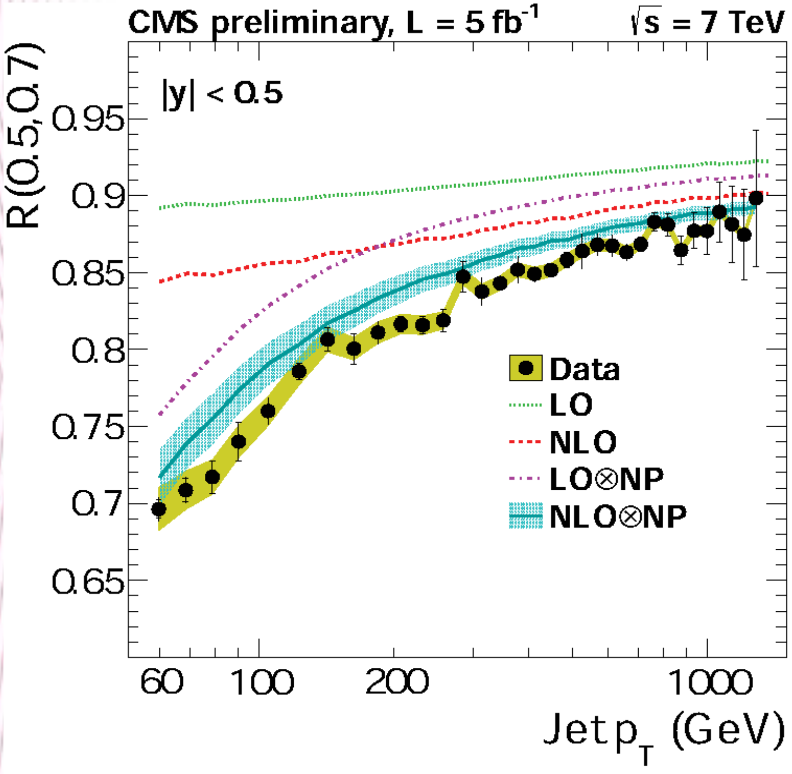
More results can be found in back-up slides and in CMS public web pages.

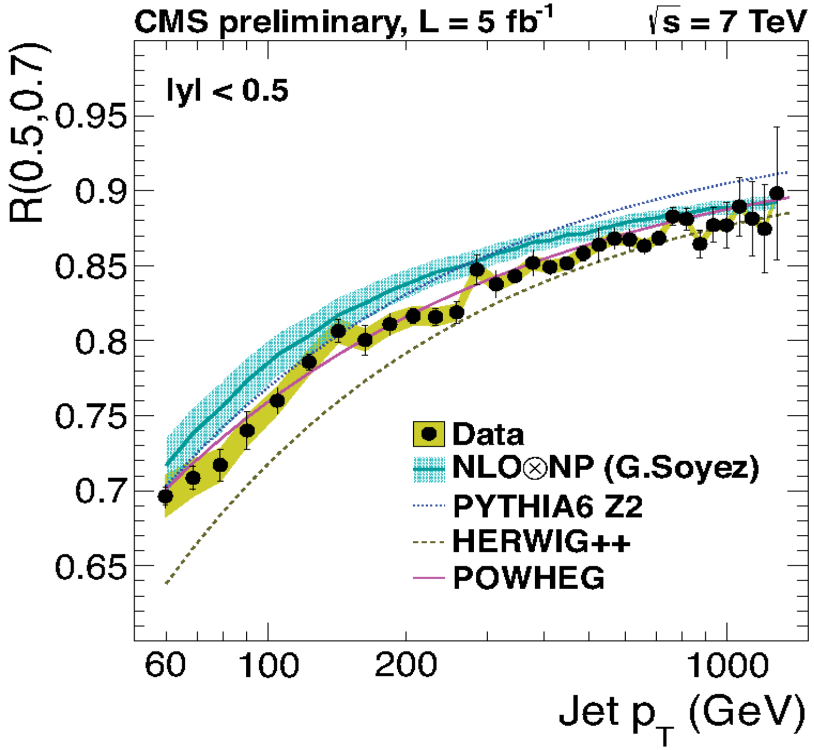
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

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

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





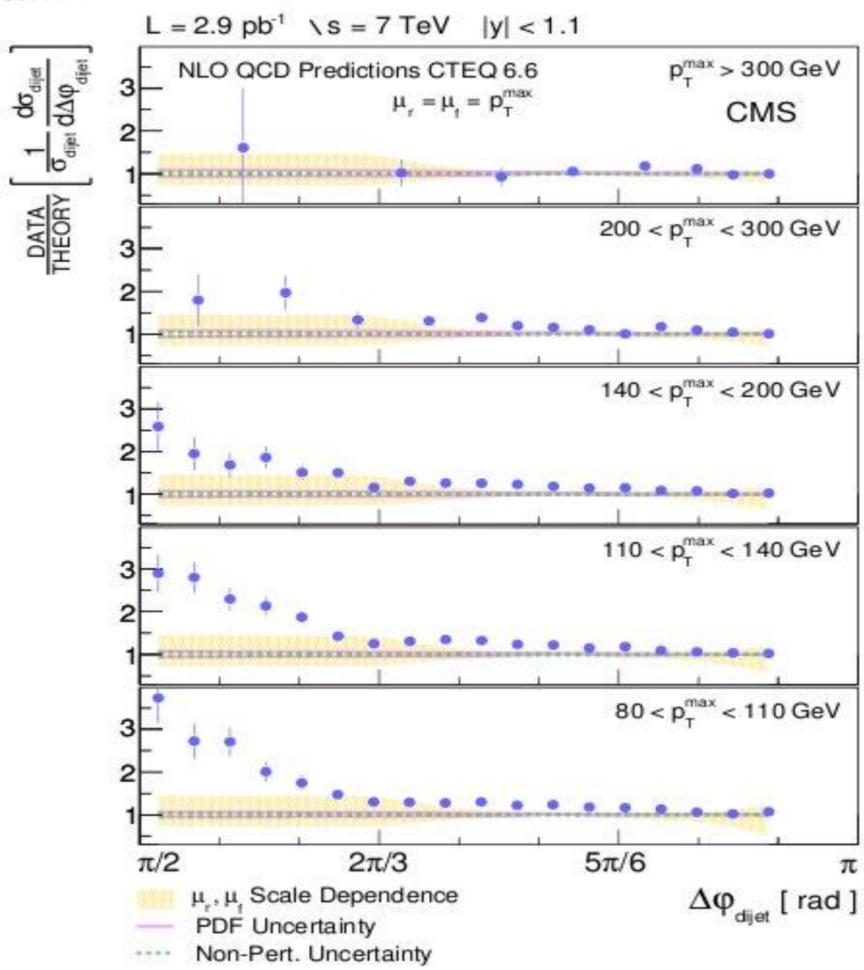
Several systematic uncertainties cancel in ratio
The ratio gradually increases towards unity with increasing Jet-p_T.
Powheg (NLO+PS) prediction has the describes the data best

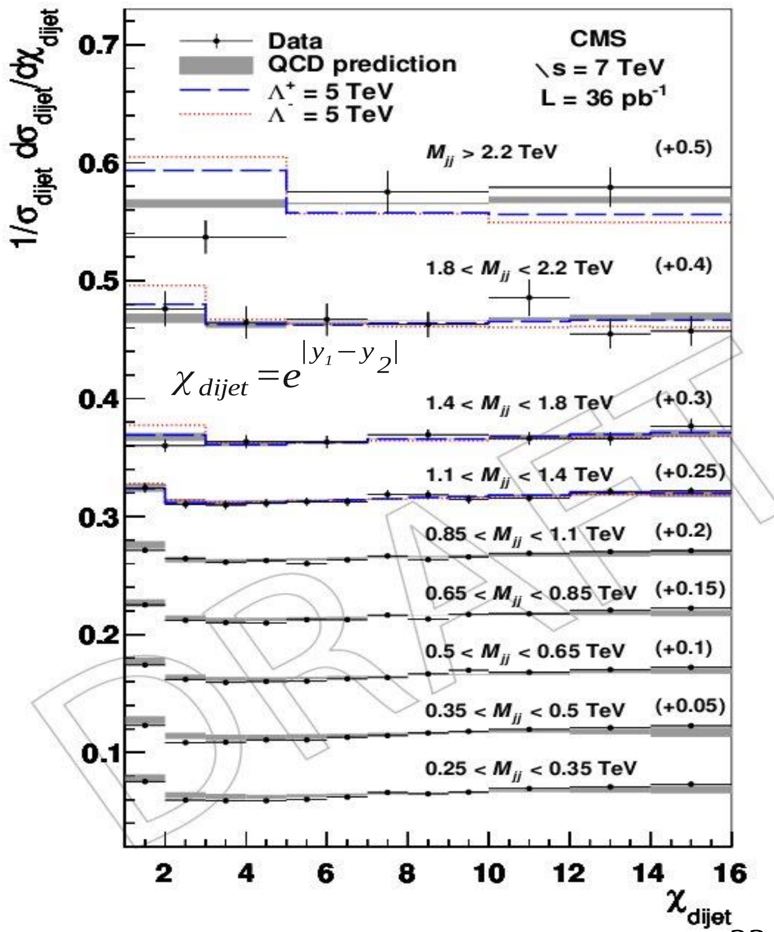
CMS-PAS-SMP-13-002

Dijet production: Δϕ,Δη

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





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

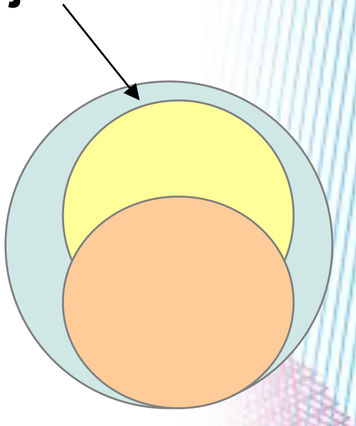
Phys. Rev. Lett. 106 (2011) 201804
Phys. Rev. Lett. 106 (2011) 122003

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

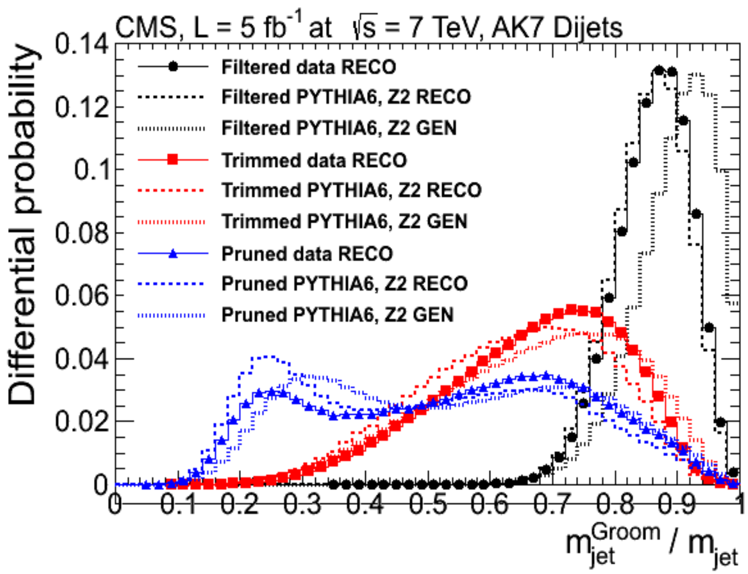
Filtering:
recluster jet with CA with R=0.3, take the 3 highest subjets, re-estimate the 4-vector of jet from 3 subjets

Trimming:
Ignores particles falling below dynamic threshold
Recluster with kT with Rsub (0.2) and keep subjets with pT sub > fcut x λhard; fcut = 0.03

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

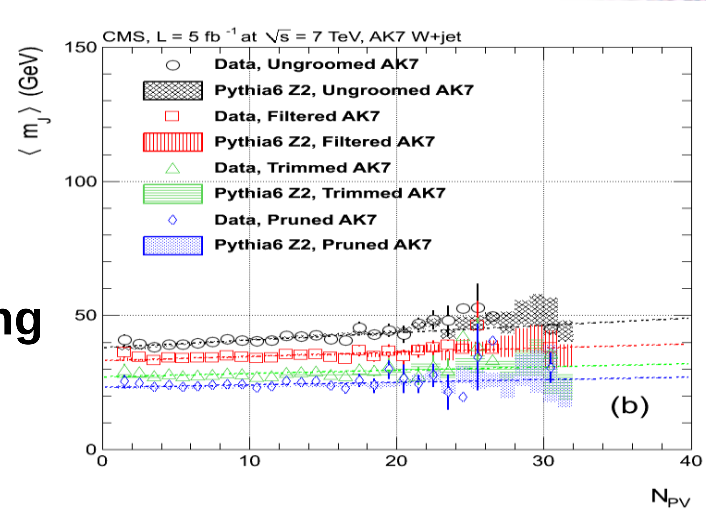
JHEP05(2013)090

Dijet Mass and Jet substructure

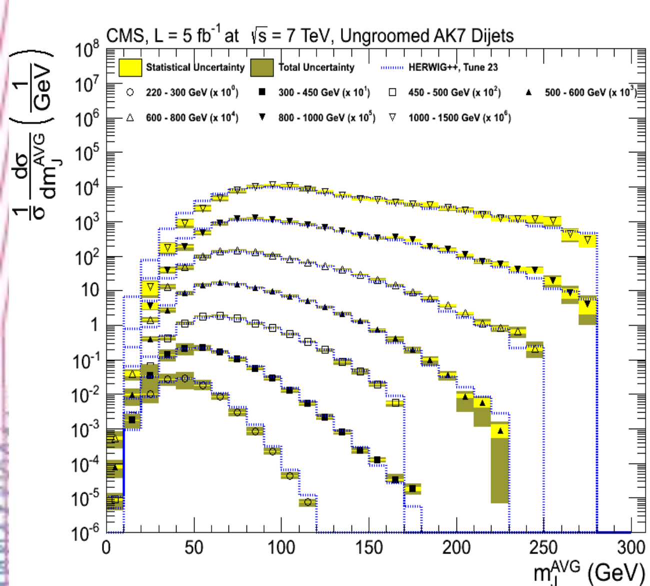


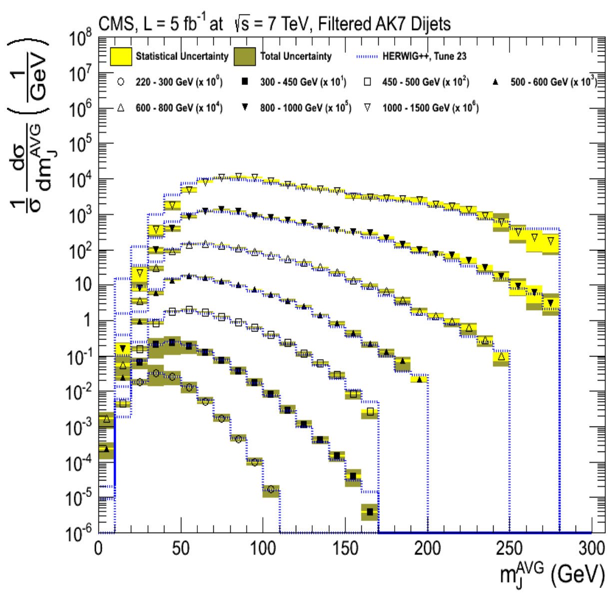
Pruning algorithm
Is the most aggressive

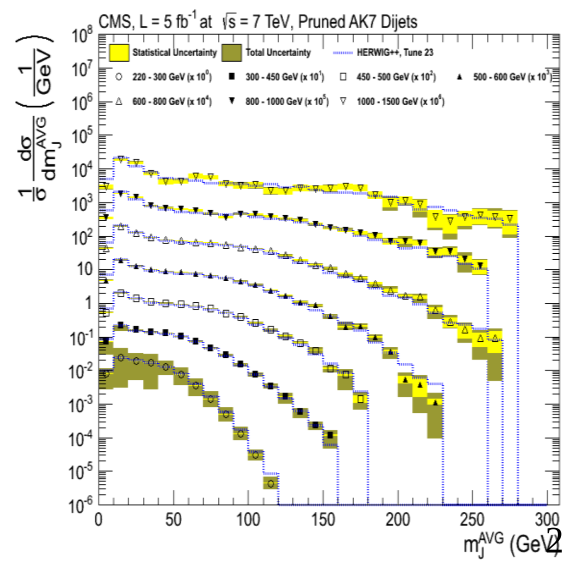
Groomed jets are stable
w.r.t pileup – favorize the use
With high-lumi runs



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

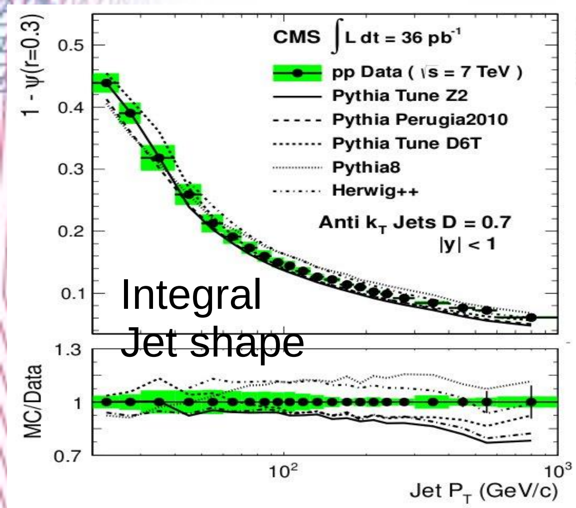


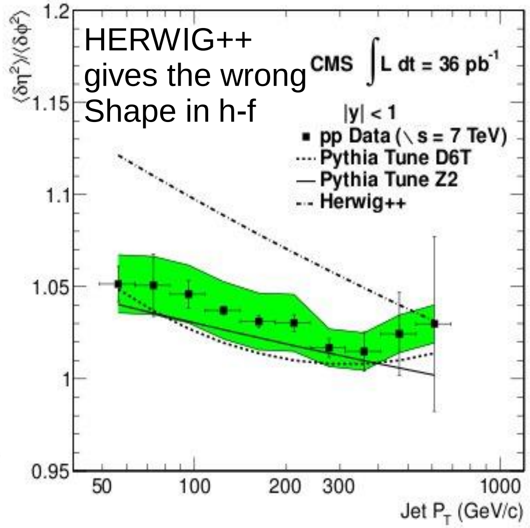




JHEP05(2013)090

Jets properties: charged particles multiplicity, shape



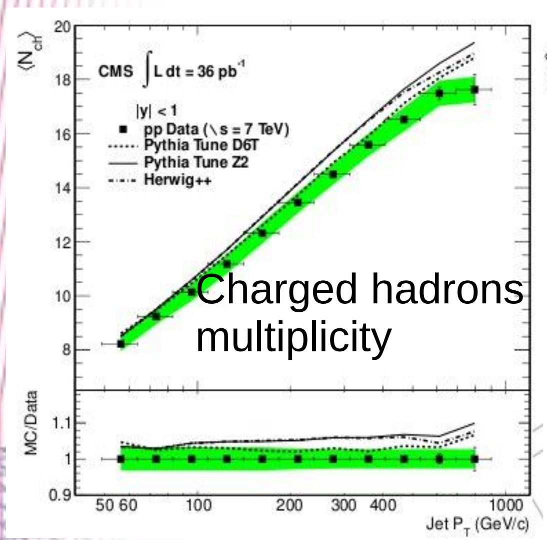


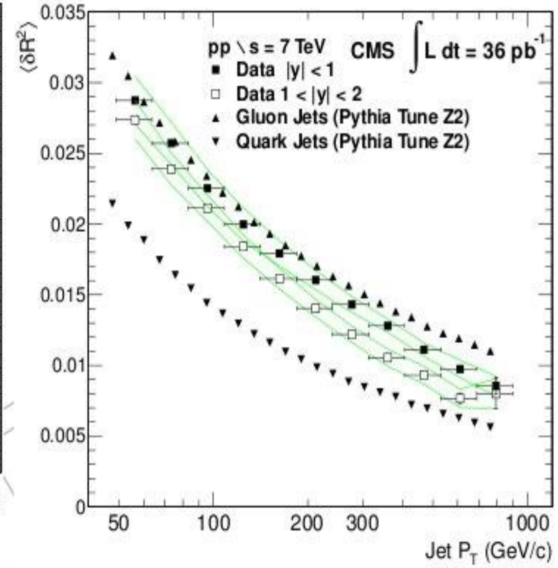
$$\langle \delta R_2 \rangle (p_T) = \langle \delta \varphi_2 \rangle (p_T) + \langle \delta \eta_2 \rangle (p_T)$$

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

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|

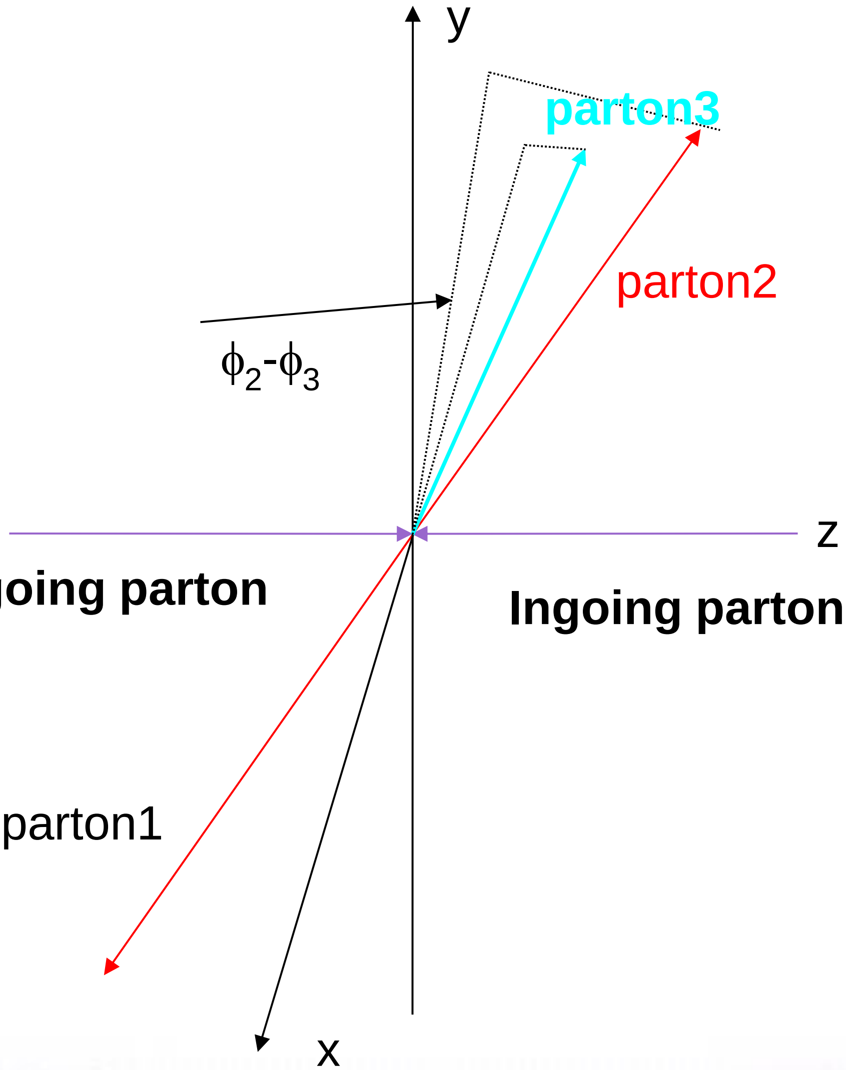
Agreement with predicted increase in the fraction of quark-induced jets at higher jet p_T and |y|

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

JHEP06(2012)160

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. $\beta \to 0$ or $\beta \to \pi$

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

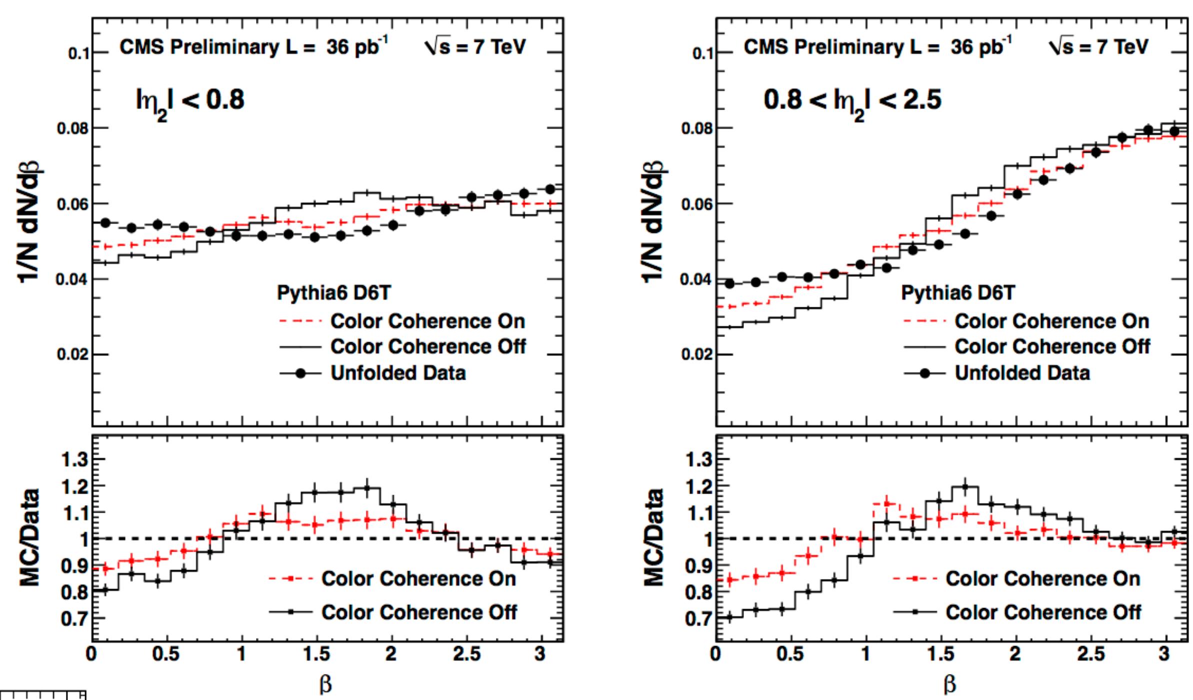
CMS-PAS-SMP-12-010

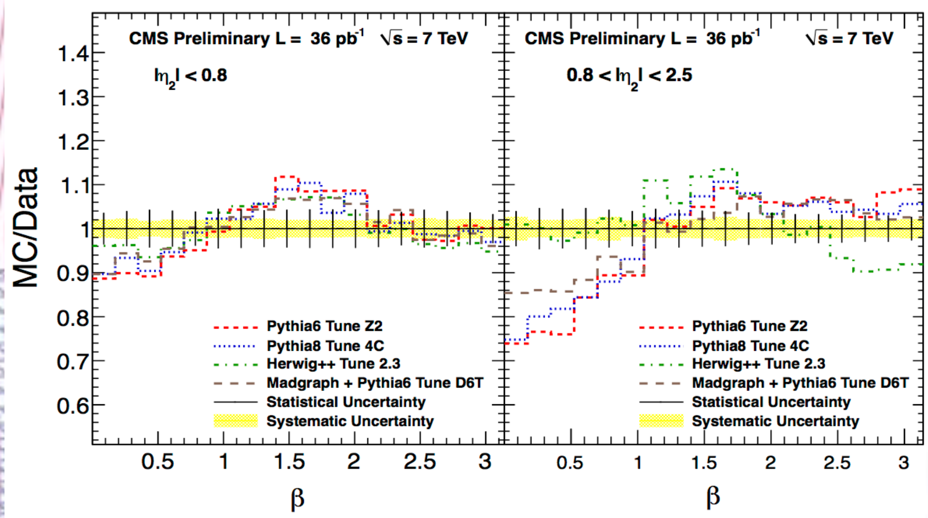
Color coherence

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

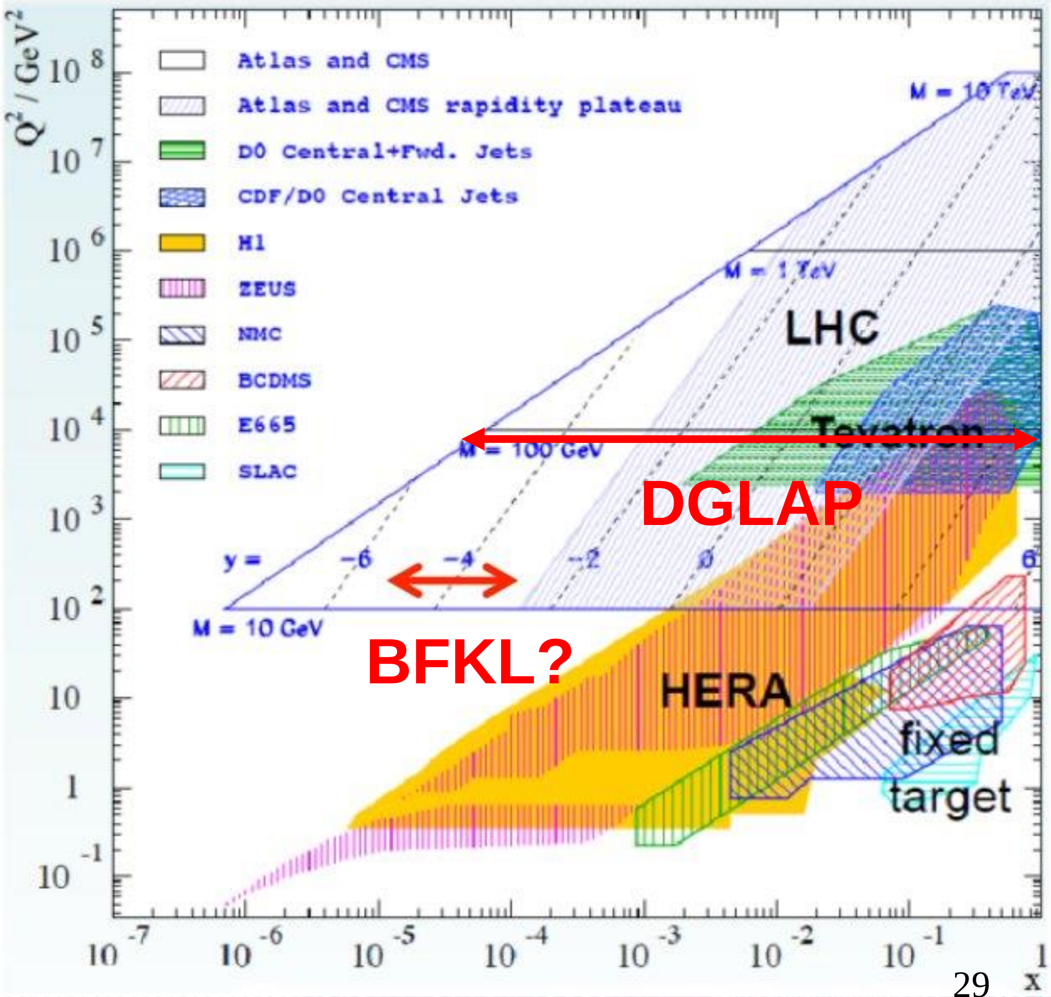
CMS-PAS-SMP-12-010

Small-x QCD

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

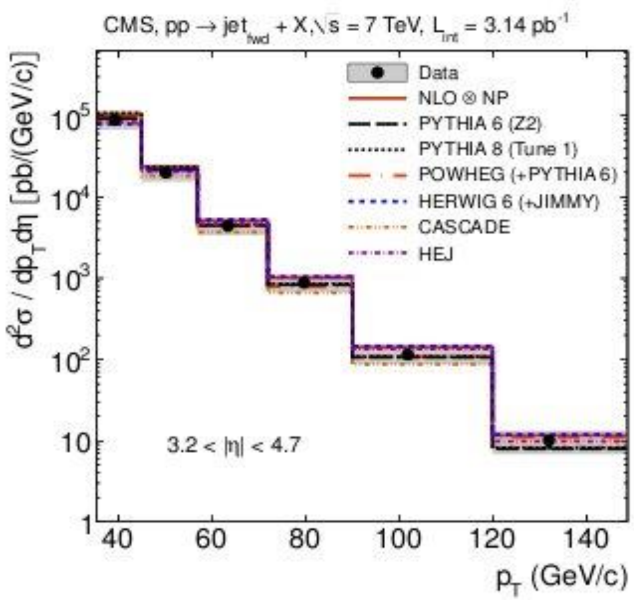
In small-x region standard approach to NLO QCD perturbative calculations. DGLAP (expansion in terms of power of $a_S \ln(Q^2)$) is predicted to be not sufficient. An alternative approach is BFKL (expansion in terms of ln(1/x)).

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



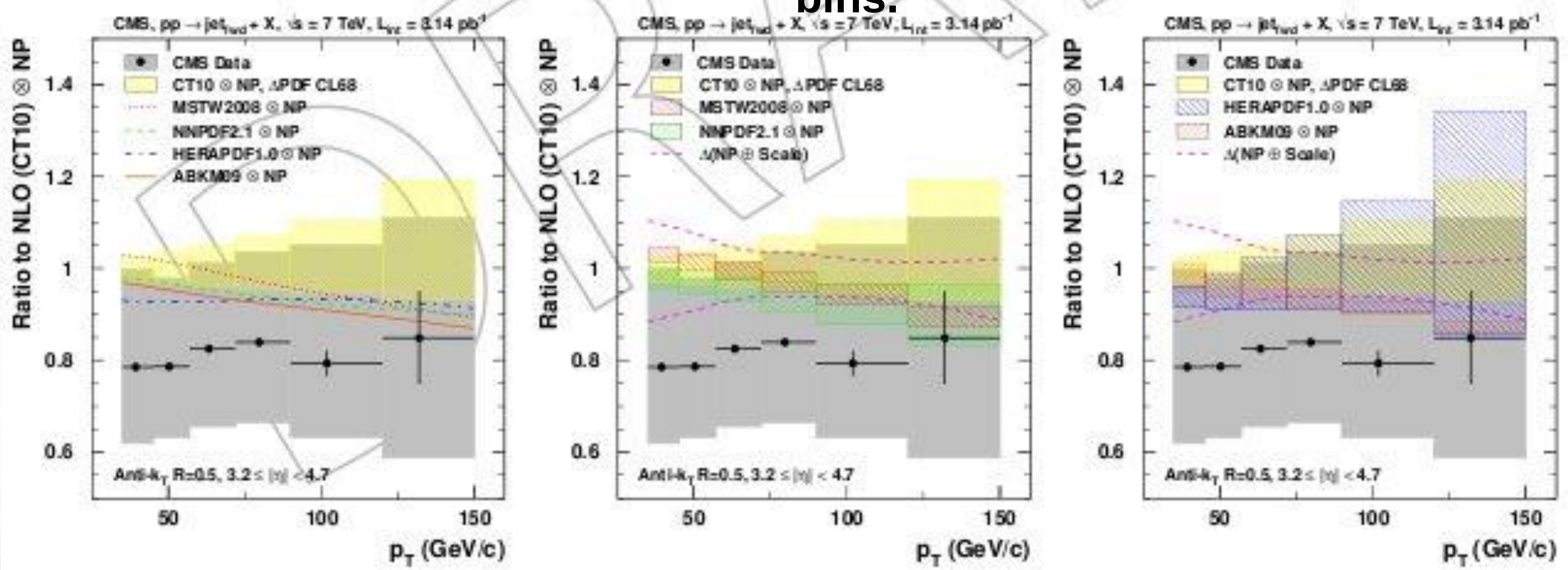
Inclusive forward jets production

Jet 3<|η|<5



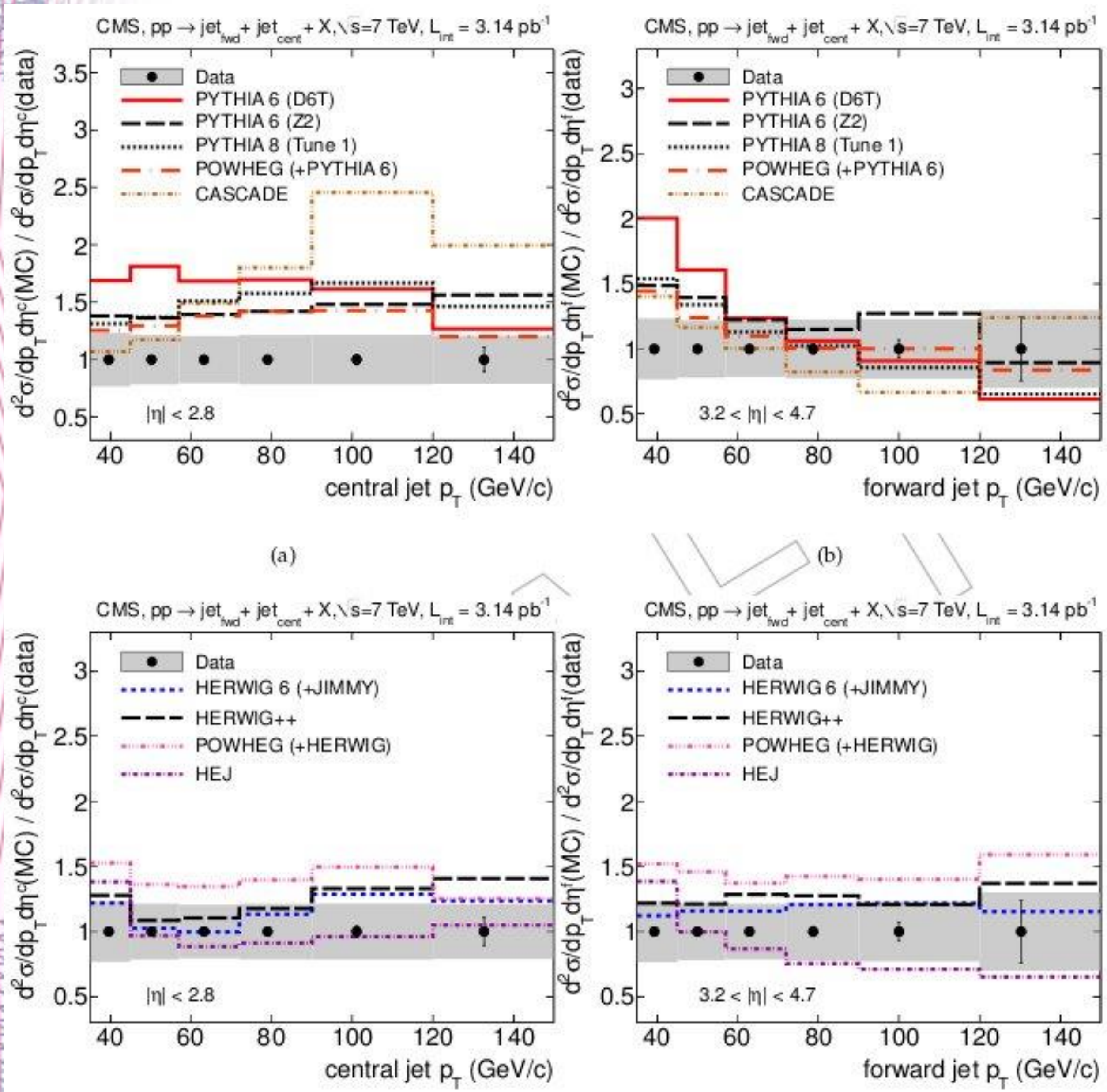
1. DGLAP evolution + parton showering (PYTHIA6/8, HERWIG 6) with the different UE tunes
   DGLAP with angular ordered shower (HERWIG++ 2.3)
2. NLO (POWHEG)+PYTHIA6 or HERWIG 6
3. NLO (NLOJET++)+NP corrections
4. CCFM/BFKL evolution (CASCADE,HEJ) + uPDF

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

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

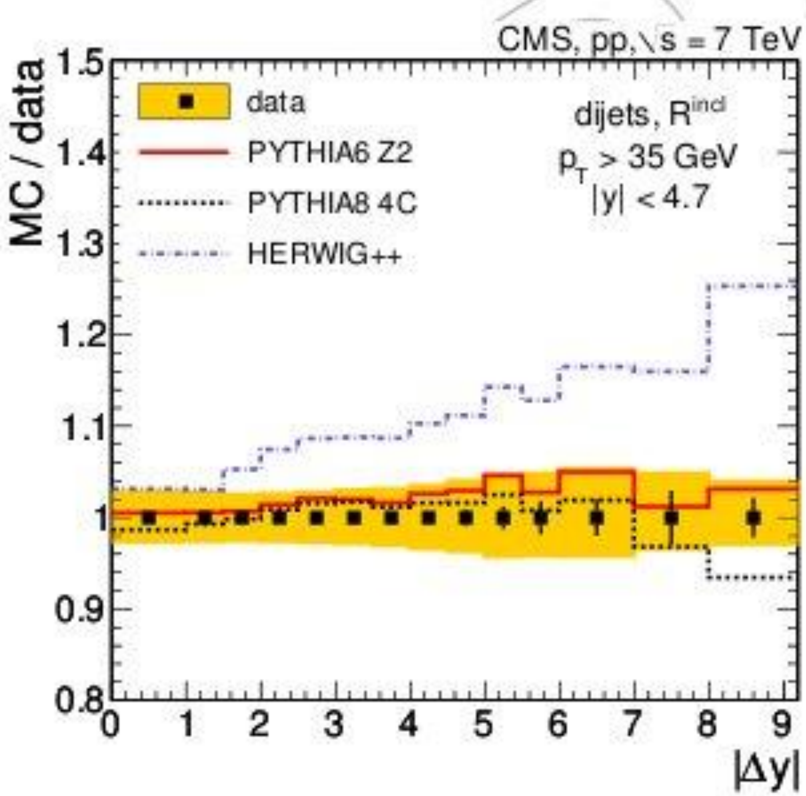
JHEP06(2012)036

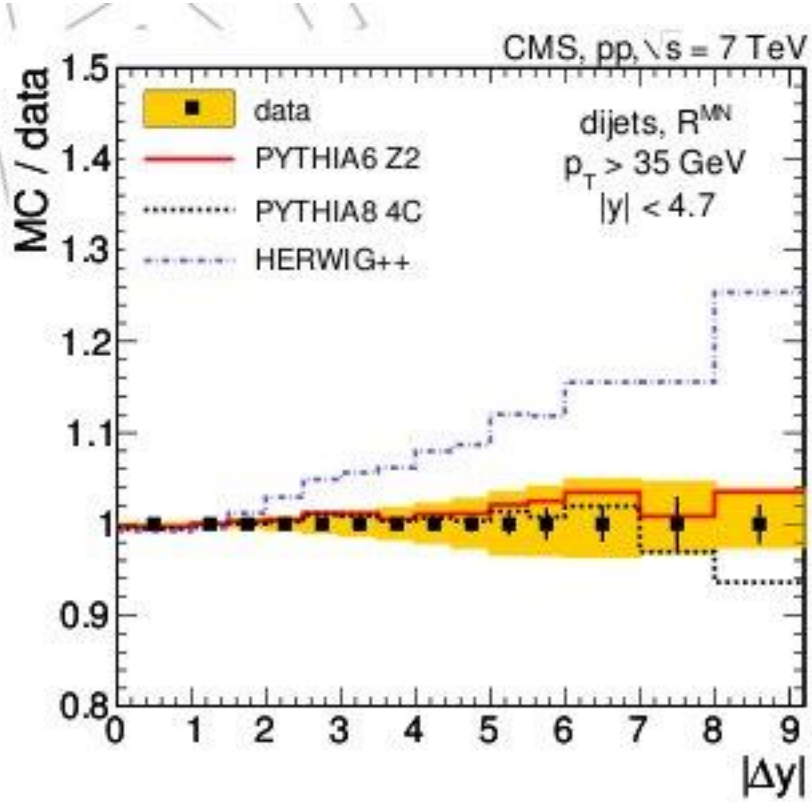
Dijet production vs Δy separation

$R_{inc} = \sigma(N_{jet}>=2)/\sigma(N_{jet}=2)$
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.





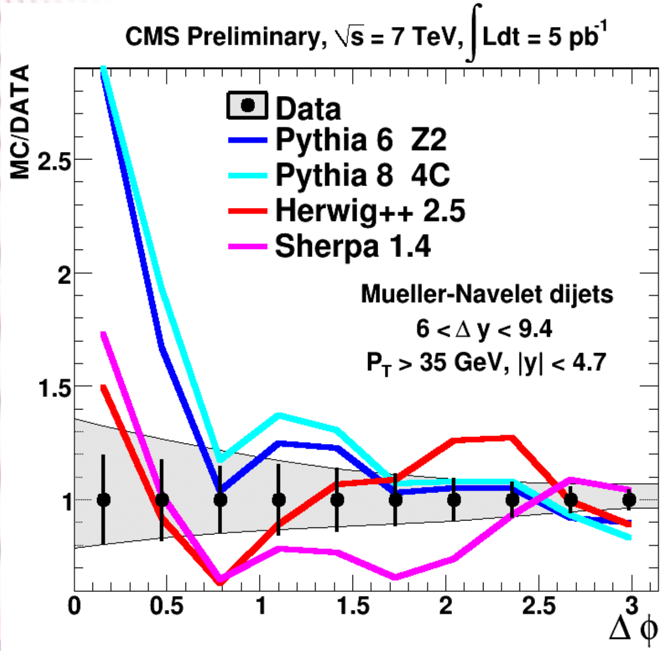
Eur.Phys.J.C(2012)72:2216

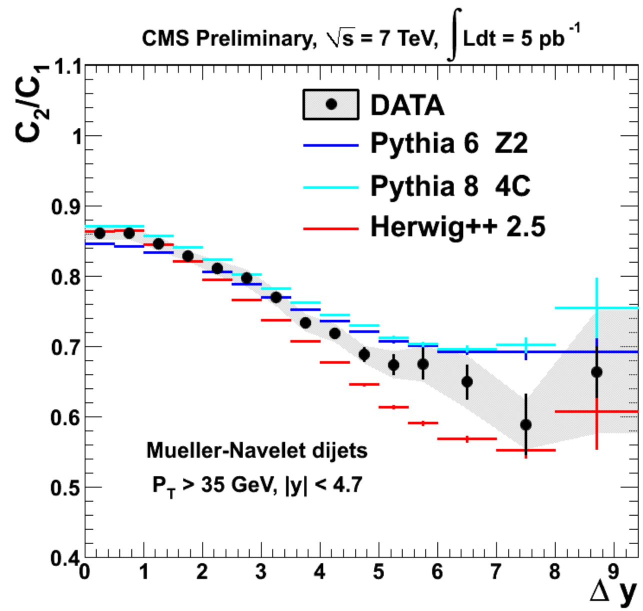
Angular correlations of jets

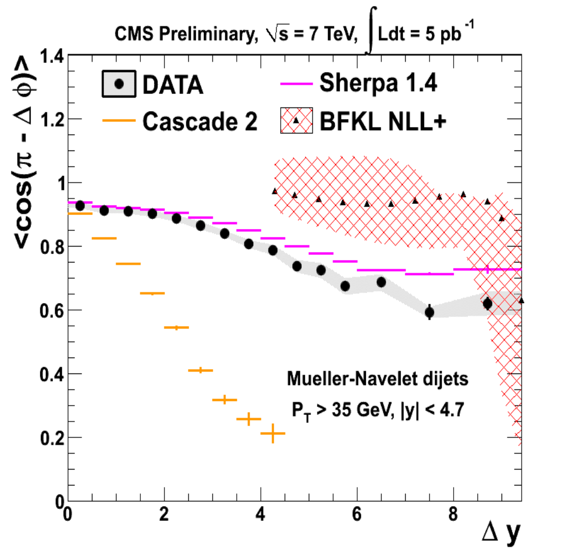
- Events with at least two jets passing cuts: p_T>35 GeV in |η|<4.7.
- For a pair of jets with the largest Δη (Mueller-Navelet dijet) the angular distance is calculated: Δφ = φ1 – φ2
- We study Δφ distributions for different Δη, and correlation factors C1, C2, C3

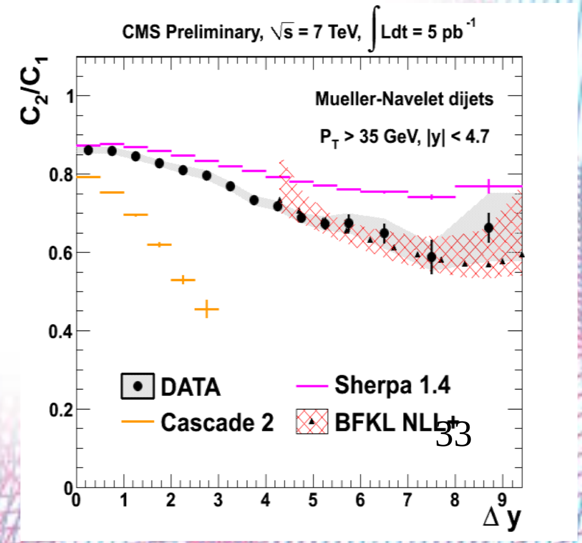
and its ratios C_2/C_1, C_3/C_2

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





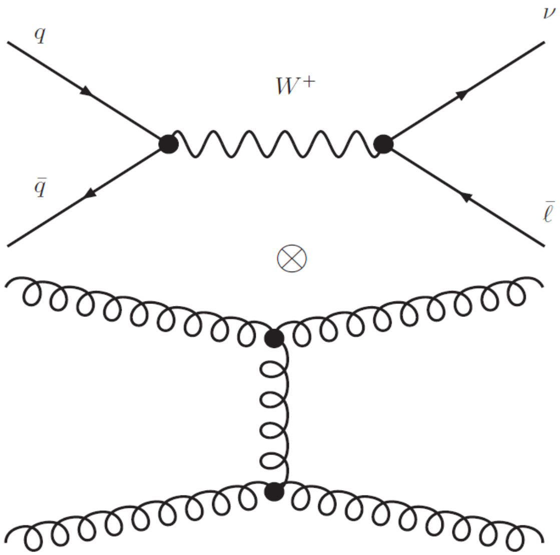




DGLAP generators starts to be worse in high Δy description
BFKL/CCFM generators do not provide good description of data in full Δη range.
Large unc. of NLL BFKL calculations.

CMS-PAS-FSQ-12-002

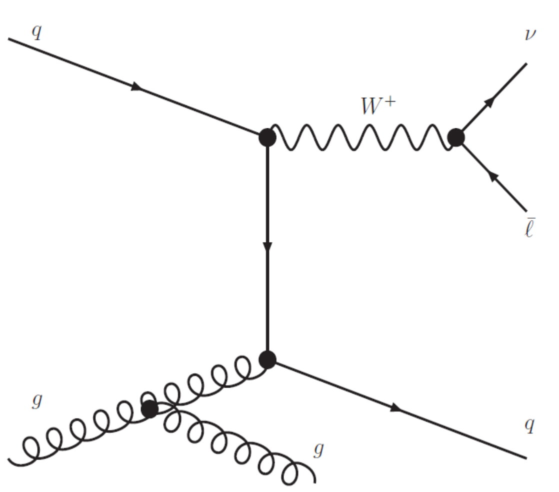
Double parton scattering



Double parton scattering

The measure of the size of DPS contribution

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

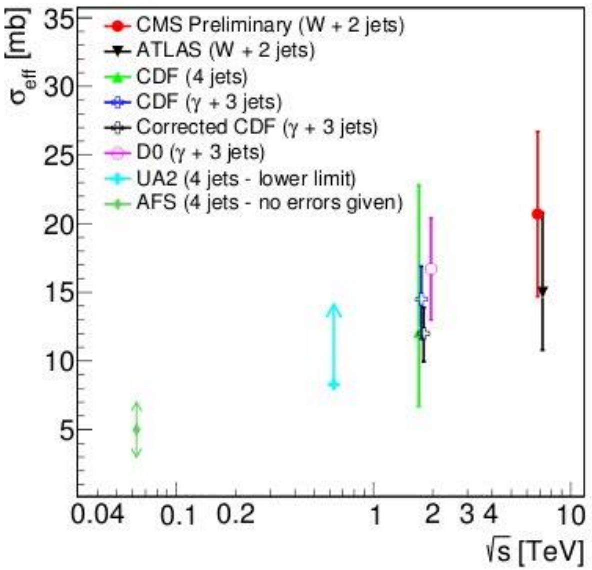


Single parton scattering

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

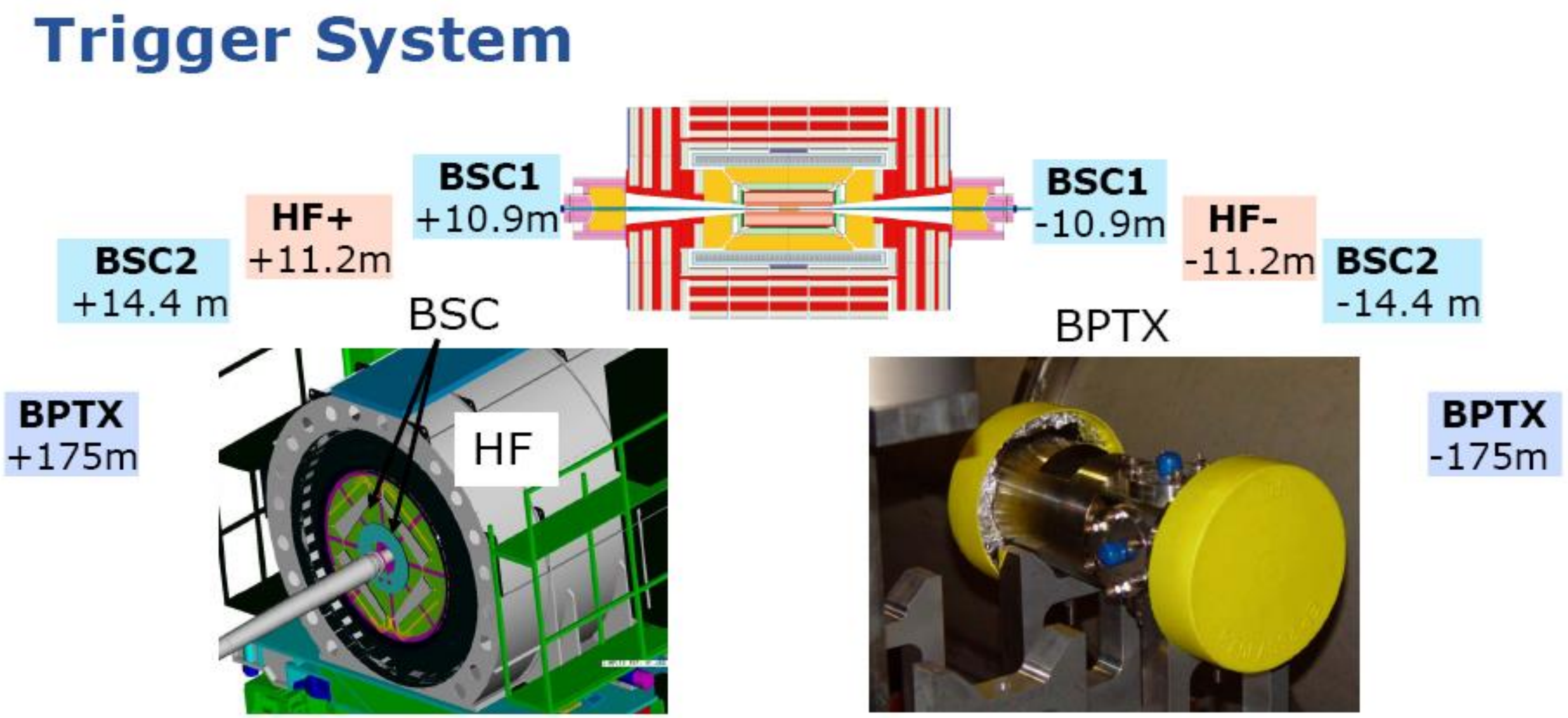
$$\delta p_T = \frac{p_T(j1,j2)}{\left(p_T(j1) + p_T(j2)\right)}$$

Azimuthal angle between W and dijet vector



CMS-PAS-FSQ-12-028

MinBias (MB) events selection



Trigger :

Beam crossover

Activities in forward calorimeters & scintillators

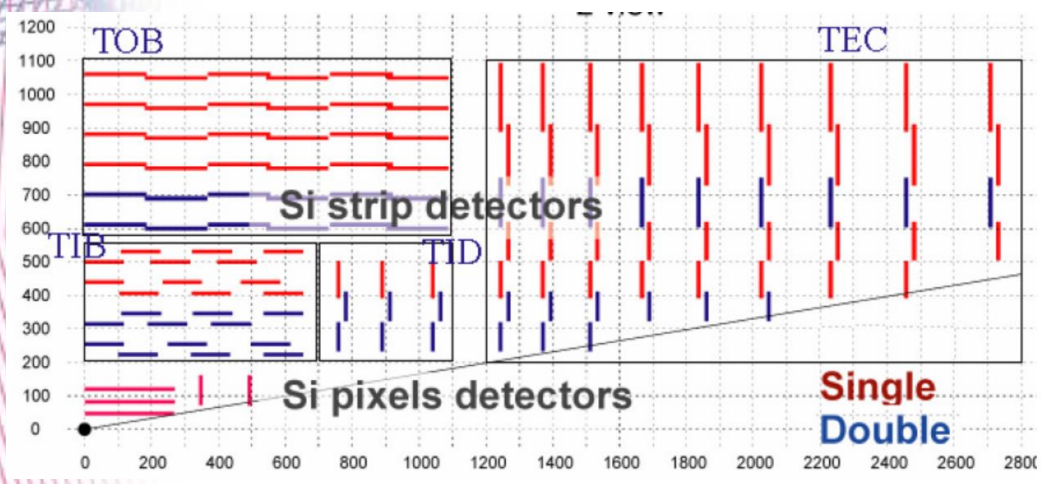
Offline event selection :

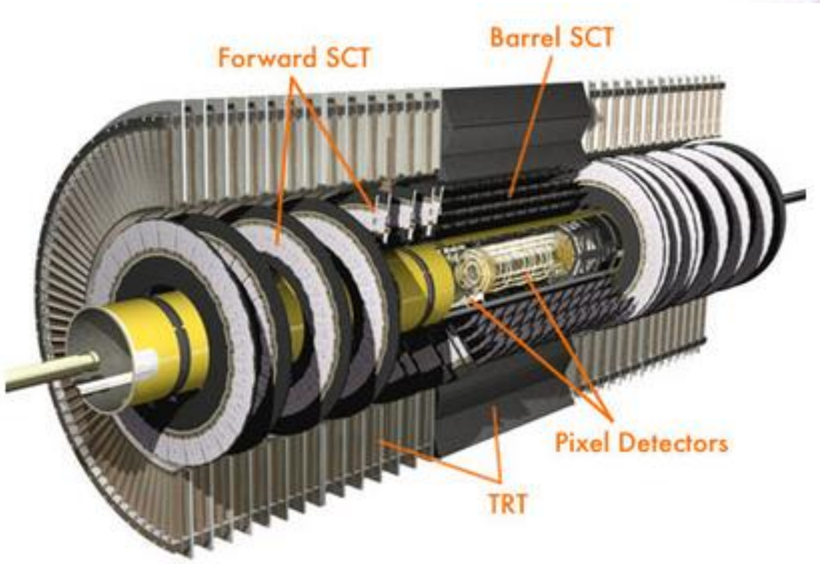
rejection of the beam halo & beam background

selection of main primary vertex

some diffraction rejection cuts if needed

Charged particles reconstruction





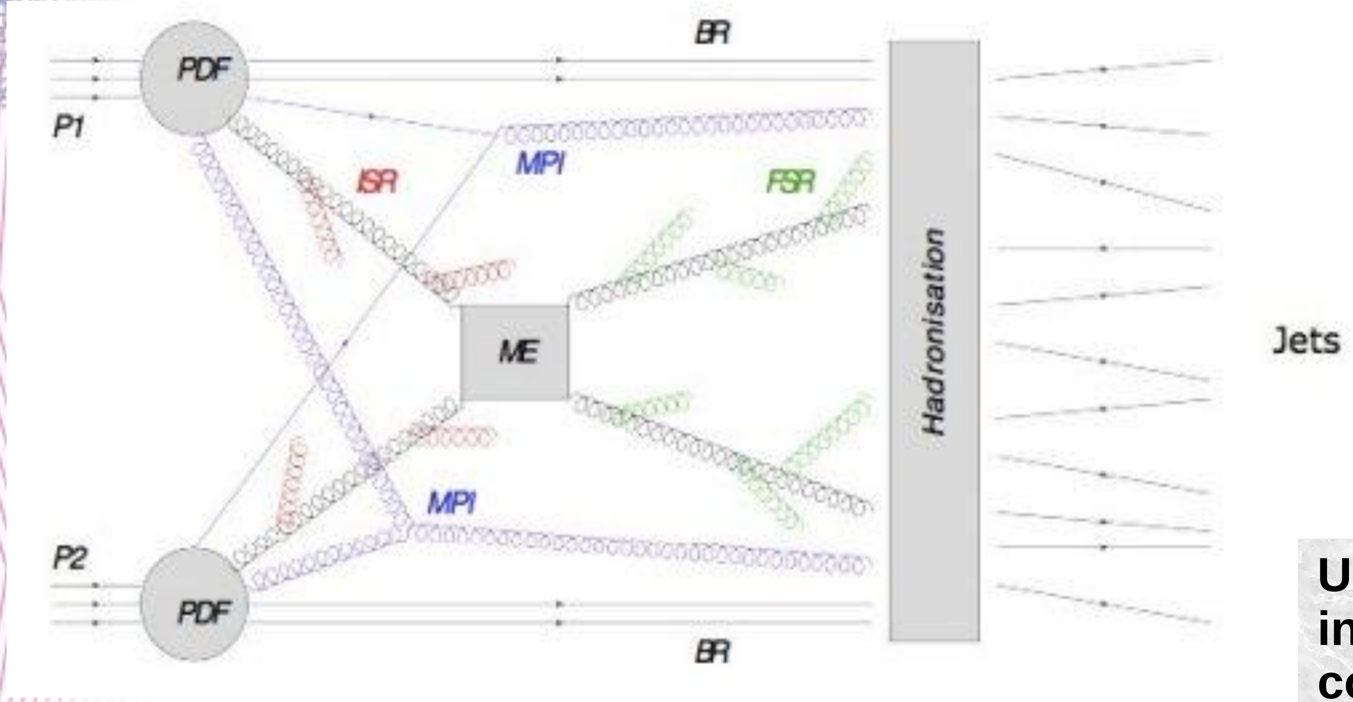
Acceptance $|\eta|<2.5$

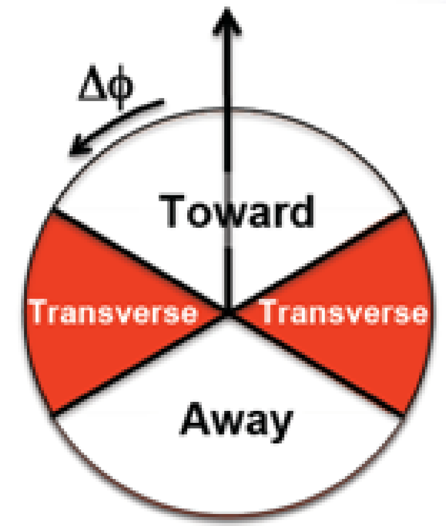
Standard tracking down to 100 MeV

Dedicated low pt tracking used for some measurements

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

Underlying event





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

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)

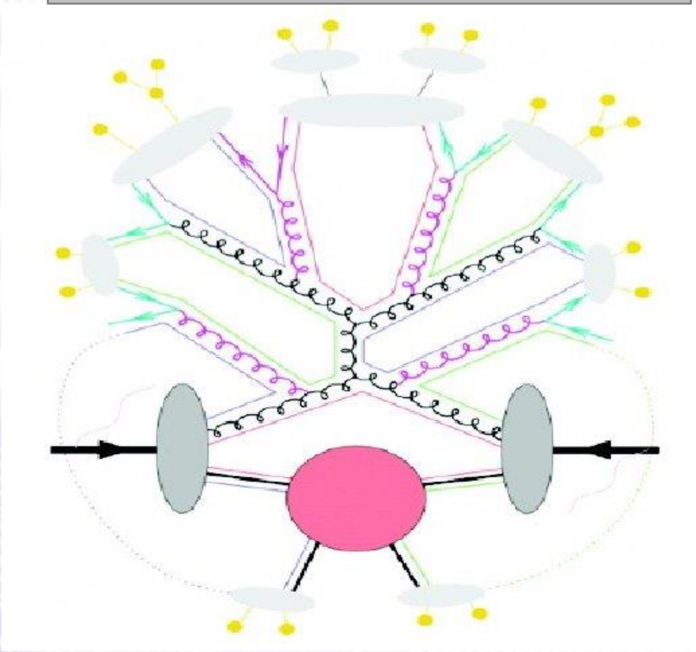
Drell-Yan events

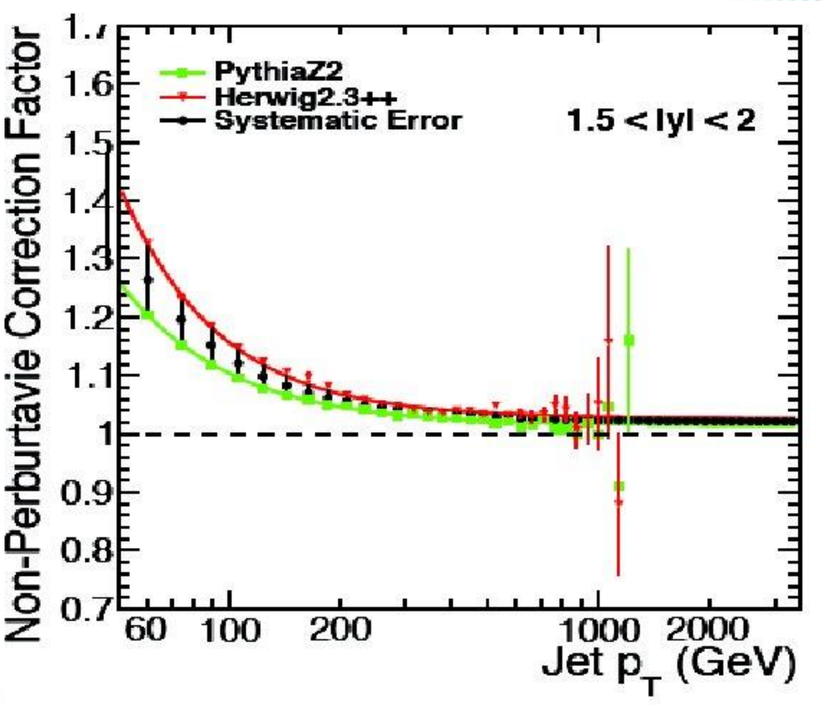
Two notes towards jet production measurement

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

Detector

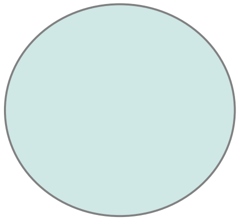


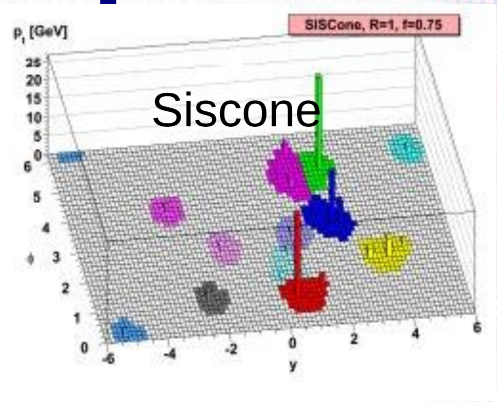


Jet clustering techniques

Fixed cone algorithms:
- **Iterative Cone (CMS) / JetClu (ATLAS)**
- **Midpoint algorithm (CDF/D0)**
- **Seedless Infrared Safe Cone (SISCone)**

Iterative cone



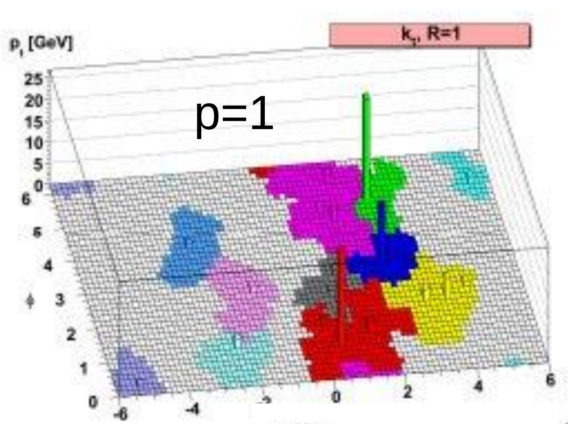


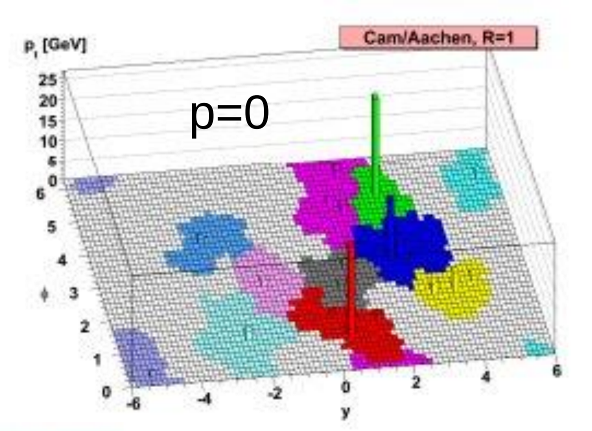
Successive recombination algorithms:

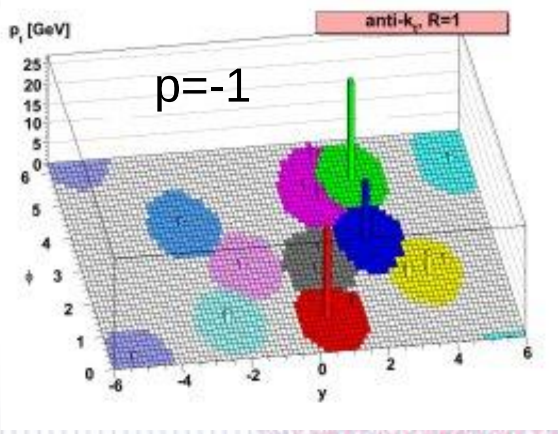
$$d_{ij} = min\left(k_{ti}^{2p}, k_{tj}^{2p}\right)\frac{\delta_{ij}^{2}}{R^{2}}$$

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

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



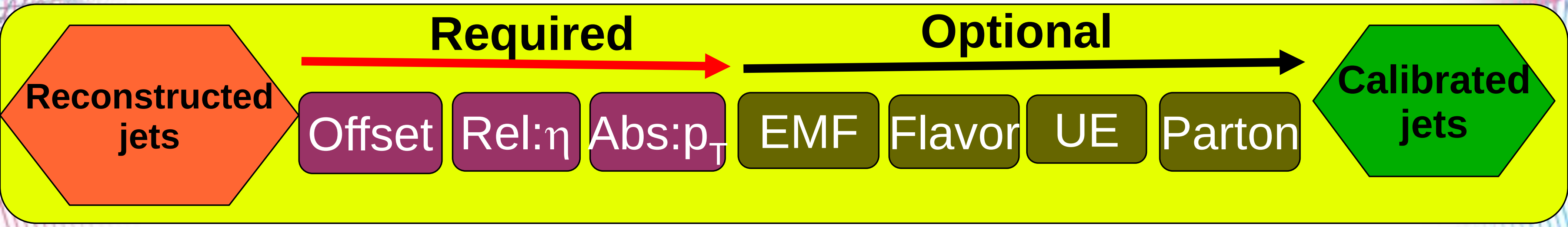




p=1 ->k_T jet algorithm
p=0 ->CA jet algorithm
p=-1 ->"Anti-k_T" jet algorithm

JHEP04(2008)063

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)

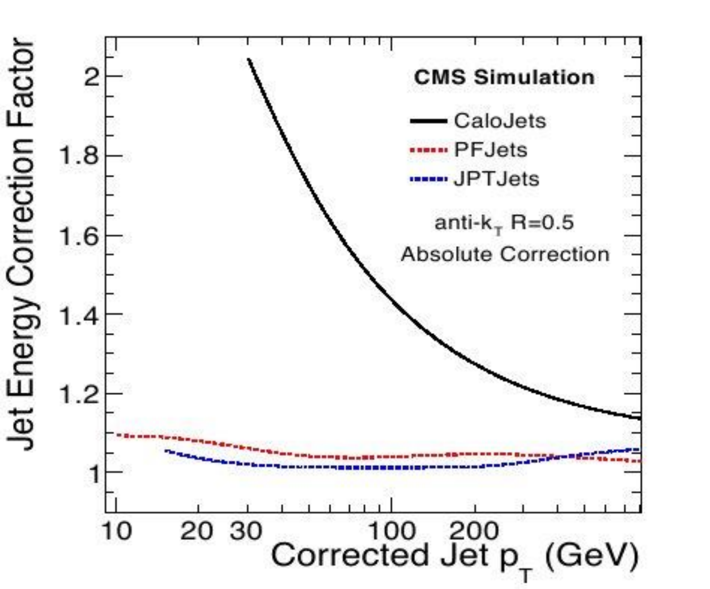
"Residual" - remove the residual difference between JES in MC and Data

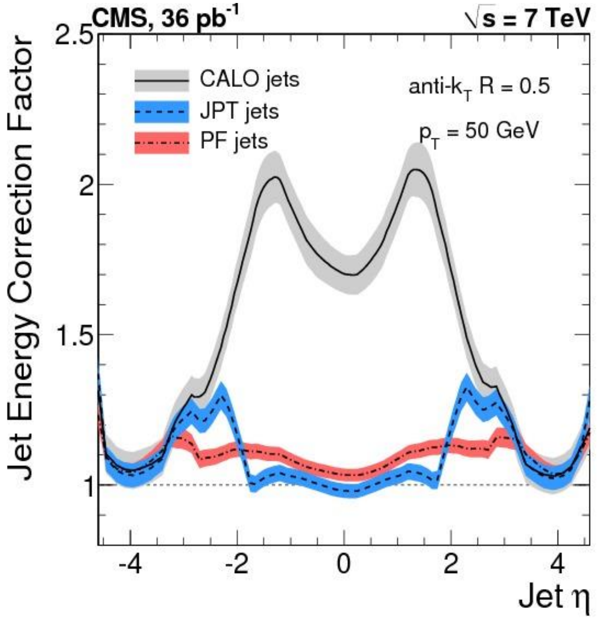
Two sources of the correction:
Monte-Carlo simulations
In-situ measurements with physics process

We correct for:

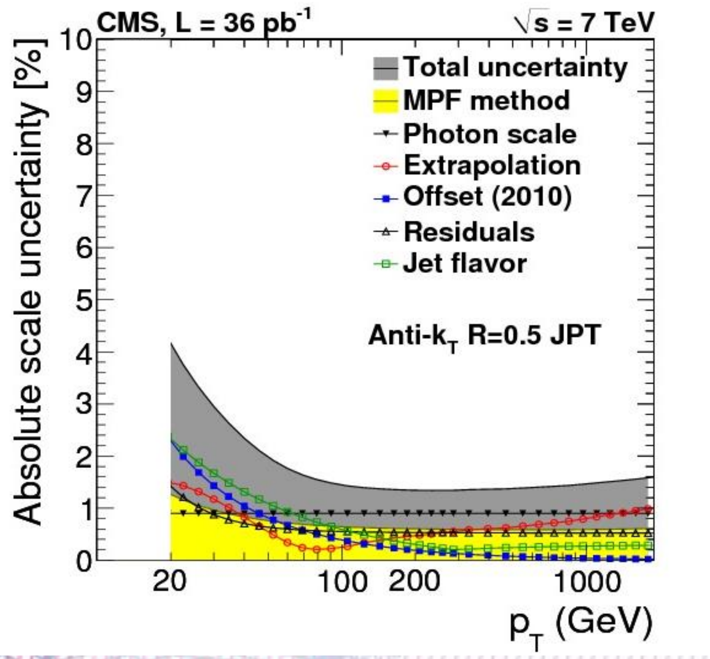
- **Calorimeter response**
- **Magnetic field**
- **Electronic noise/tower thresholds**
- **Dead materials and cracks**
- **Longitudinal leakage**
- **Shower size, out of cone loss**

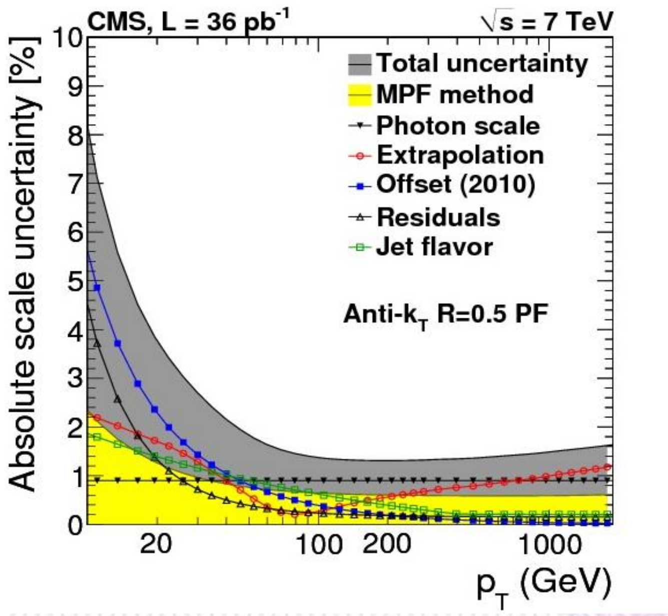
Jet performance





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

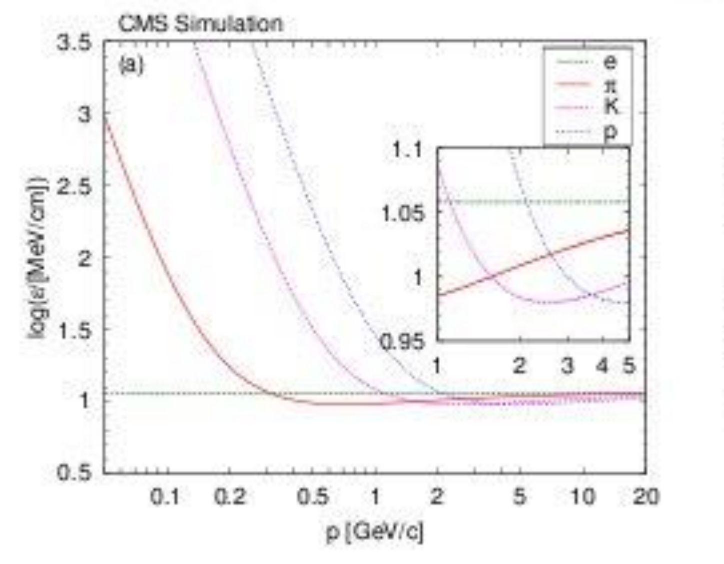


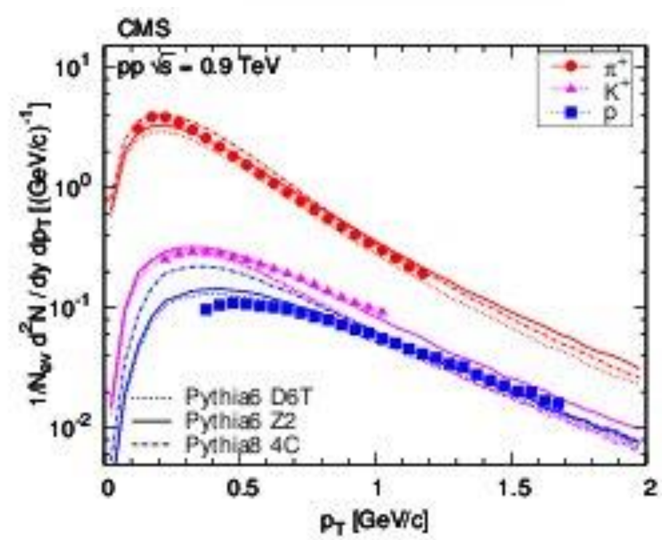


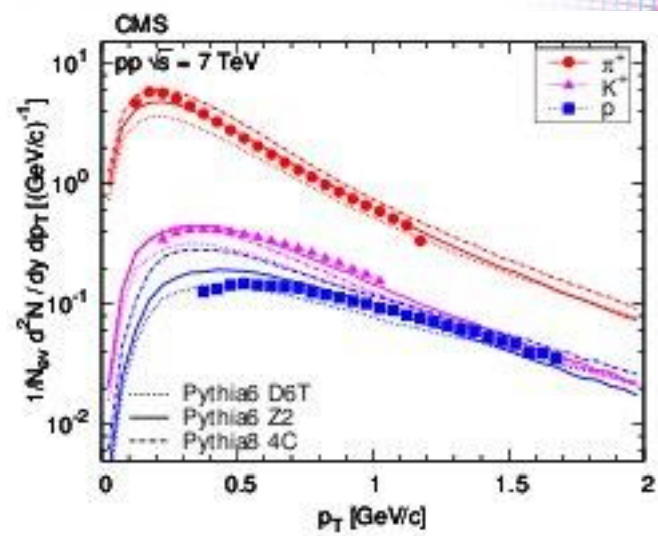
The better we know response function the more exact measurements deconvolution we can perform

JINST 6 P11002 (2011)

Identified particle spectra

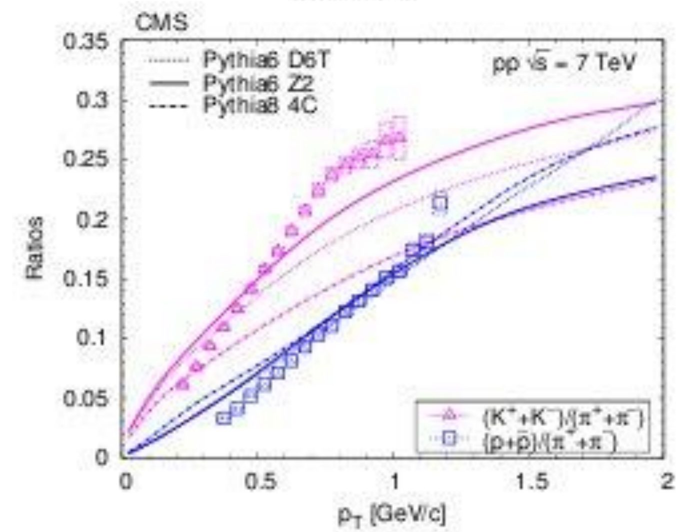


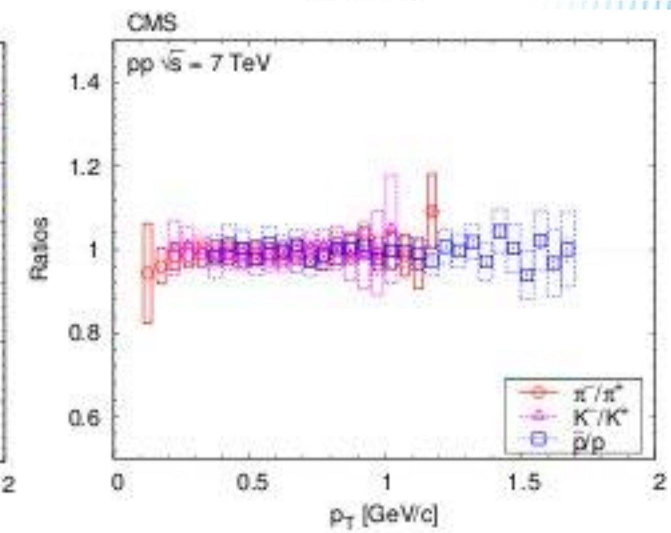




Identified via dE/dx in the silicon layer of the tracker and Number of hits per track, Track quality in eta-pt bins: combined fit.

Charged hadrons: pions, kaons protons in pt 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

Underlying event

JHEP 09 (2011) 109
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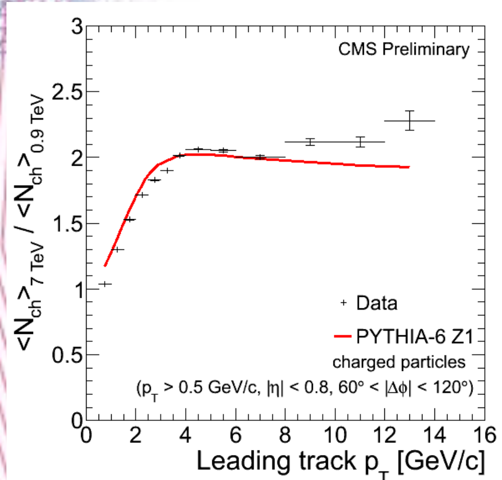
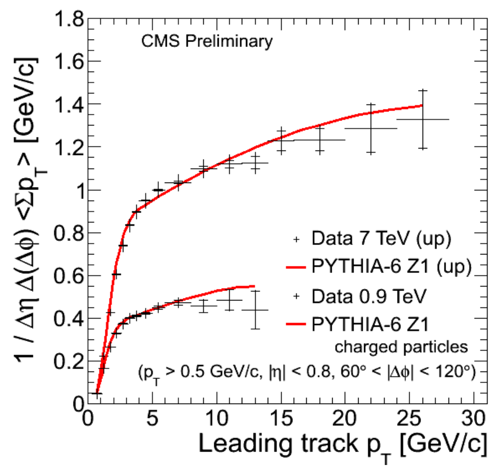
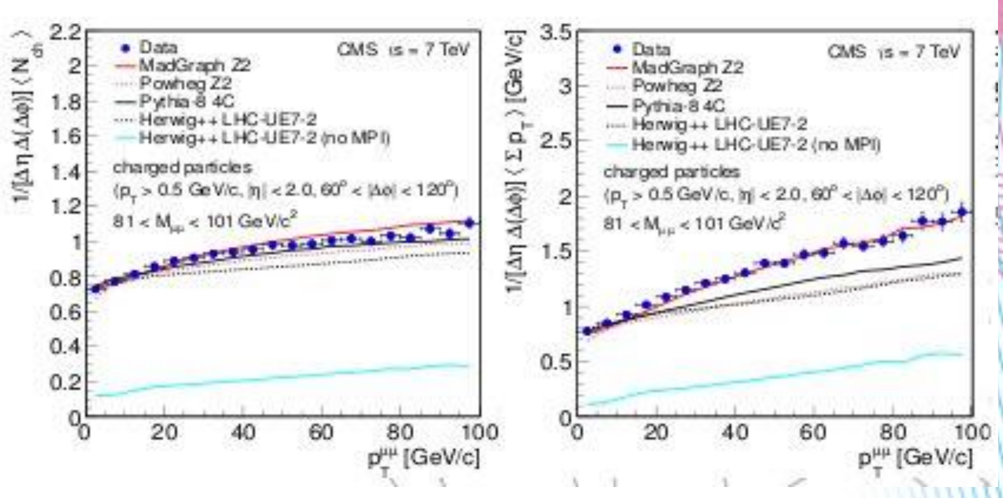
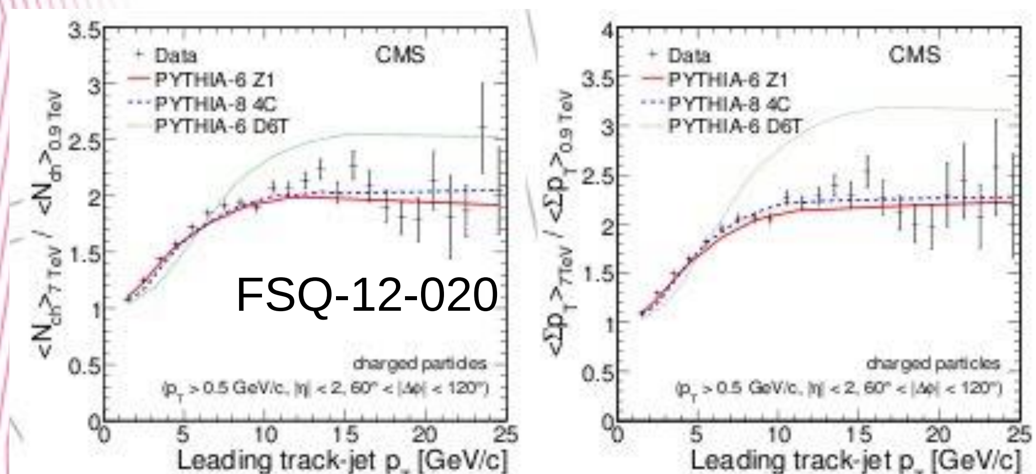


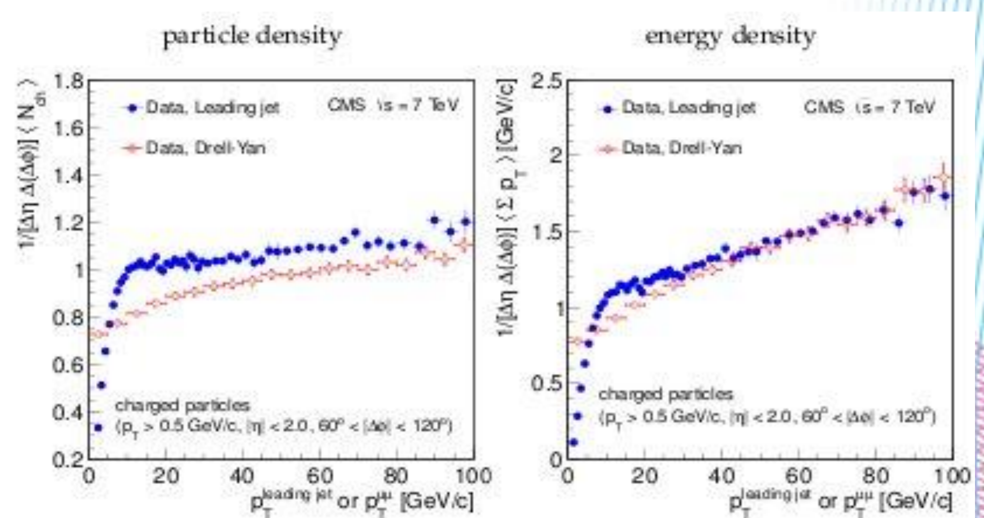




UE in DY events



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: