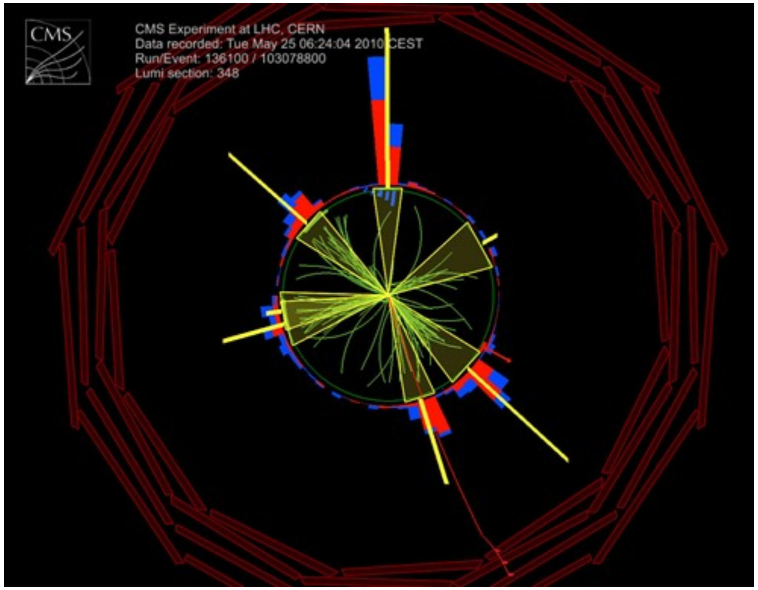
QCD Physics with CMS detector

Olga Kodolova, SINP MSU

(on behalf of CMS collaboration)



20th Lomonosov Conference on Elementary Particle Physics , 19-25 August, Moscow, Russian Federation

Outline

- **Motivation**
- **Soft physics**
- **Hard physics**
- **Summary**

Motivation

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

What is new at LHC:

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

Why we need to study:

- Important background for new territory in physics searches enormous cross section: QCD can hide many possible signals of new physics

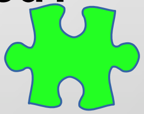
- QCD defines the hadronization process of partons whatever interaction mediator is in the hard production vertex

What we need to study:

- **parton structure,**
- **constrain the strong coupling**
- **all other pQCD theory components**
- **study non-perturbative effects**
- **tune Monte-Carlo generators**

How do we proceed?

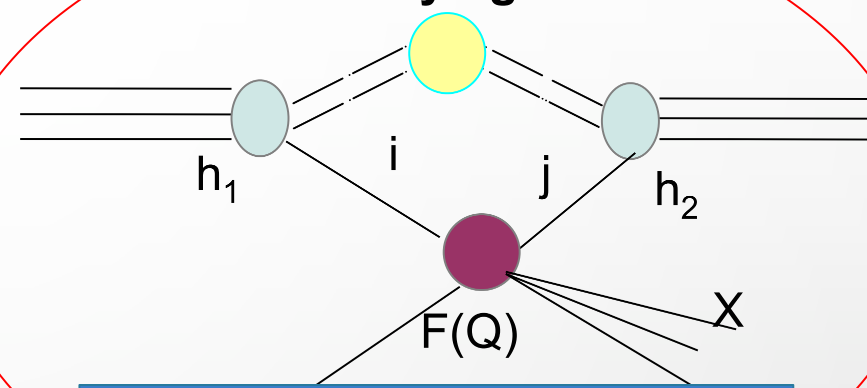
Collect puzzles!



QCD at hadron colliders

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

Soft underlying event



$p_1 = x_1 P_1$

$p_2 = x_2 P_2$

Hard interaction: production of the high-p_T objects

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)

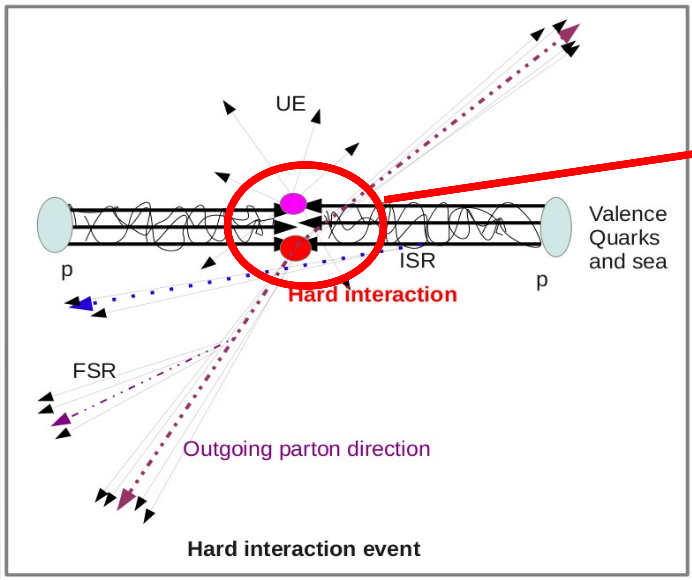
Partonic cross-section computed in pQCD

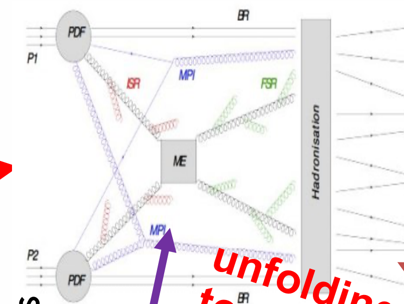
$$\hat{\sigma}_{ij} = \alpha_S^k \sum_n \left(\frac{\alpha_S}{\pi}\right)^n \sigma_{ij}^n$$

Soft interaction: production of the low-p_T hadrons

Fixed order pQCD

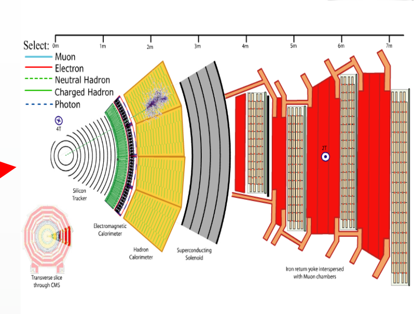
How do we proceed





particles

propagation towards particles level



unfolding towards particles level

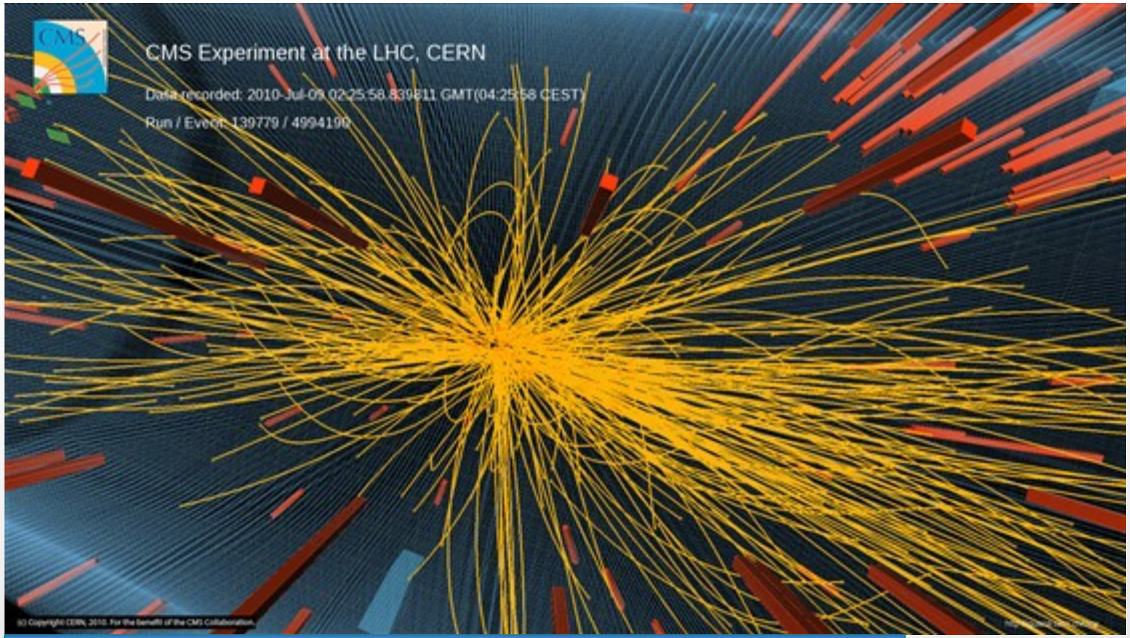
Reconstructed particles, reconstructed jets
Measured Cross-sections
Multiplicity
Rapidity
Momentum of Particles and Jets, missing E_T

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

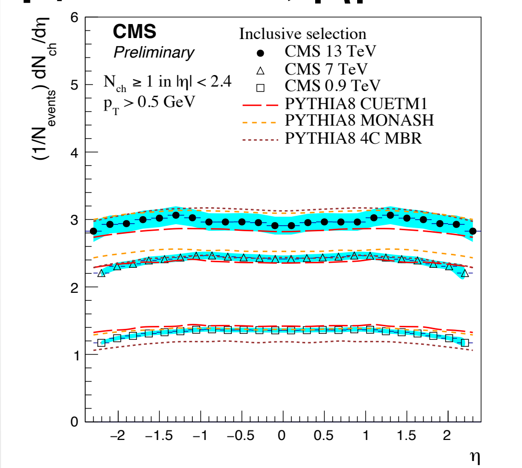


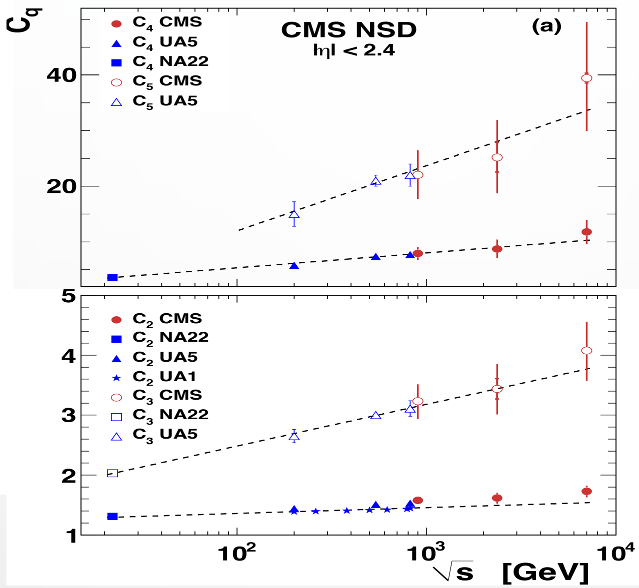
Charged particle multiplicity
Scaling, correlations
Underlying event

Charged particles

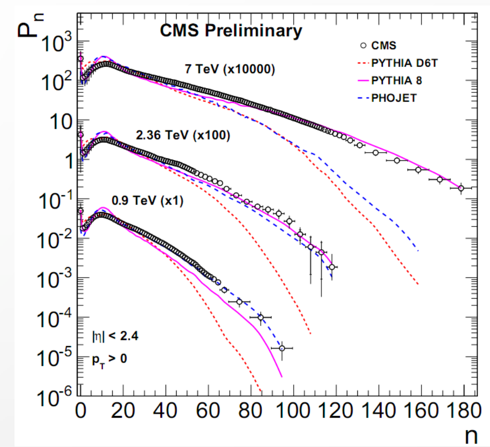
new input to the dynamics of soft hadronic interactions: interplay between soft and hard processes: no one MC describes data in all configurations

p_T>500 MeV, |η|<2.4

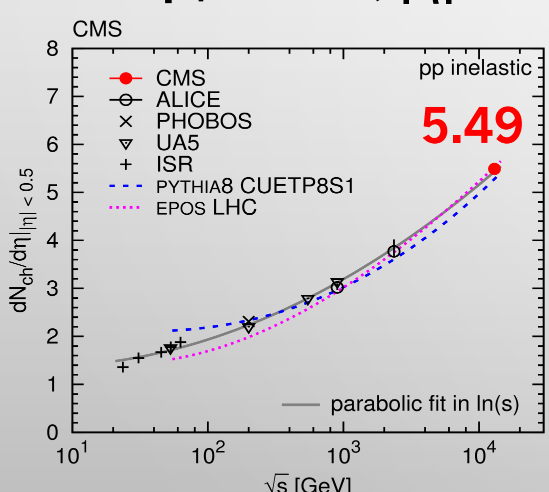




change of the slope at n~20

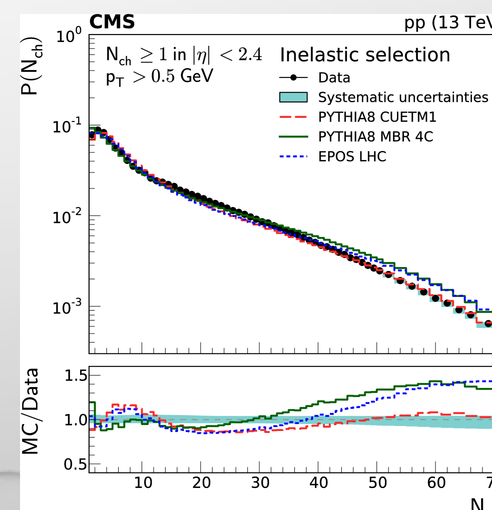


CMS: p_T>0 MeV, |η|<0.5

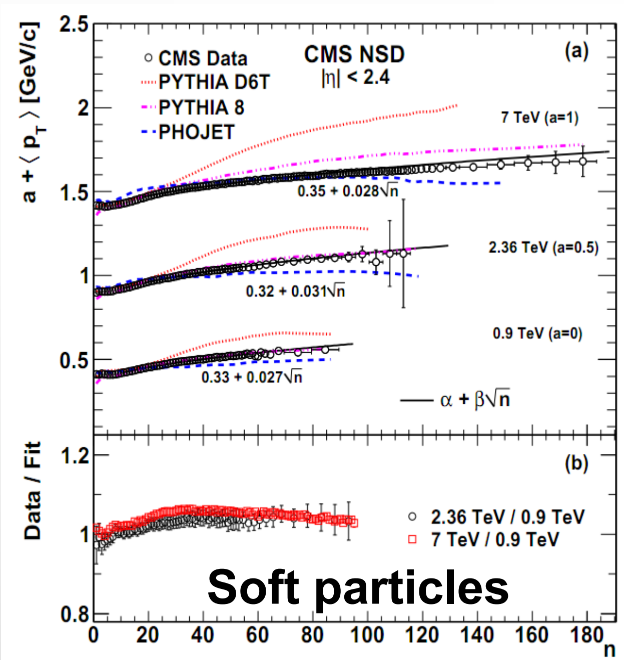


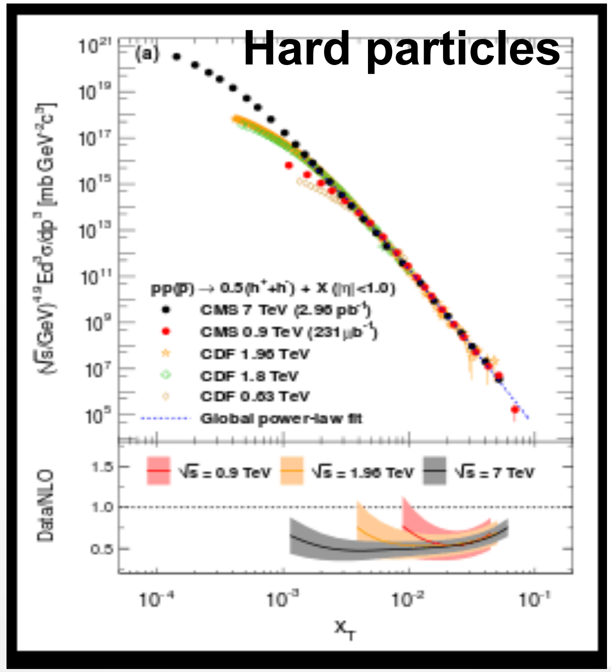
KNO (Koba-Nielsen-Olesen) scaling assumes the independence of C_q on the collision energy: violation in the range |η|<2.4

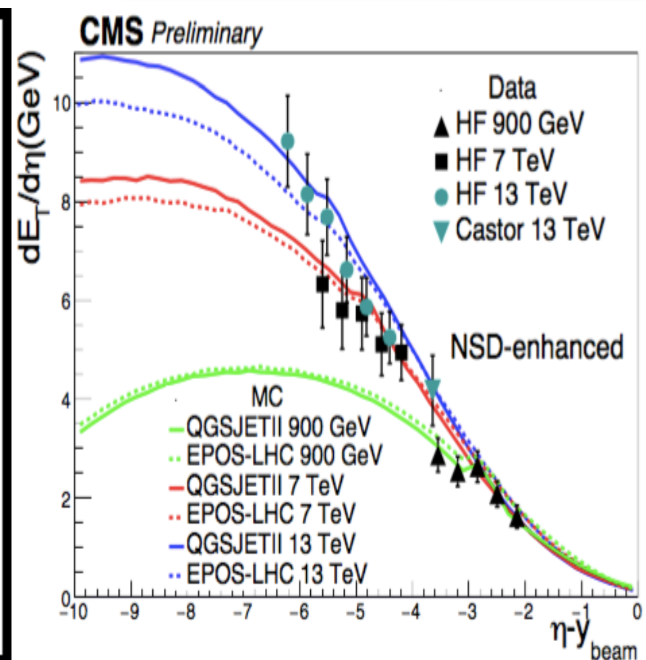
CMS-PAS-FSQ-15-008
Phys. Lett. B751 (2015) 143
JHEP 01 (2011) 079
EPJC 78 (2018) 697



p_T & x_T & limiting fragmentation







The rise of the $\langle p_T \rangle$ with multiplicity is energy independent

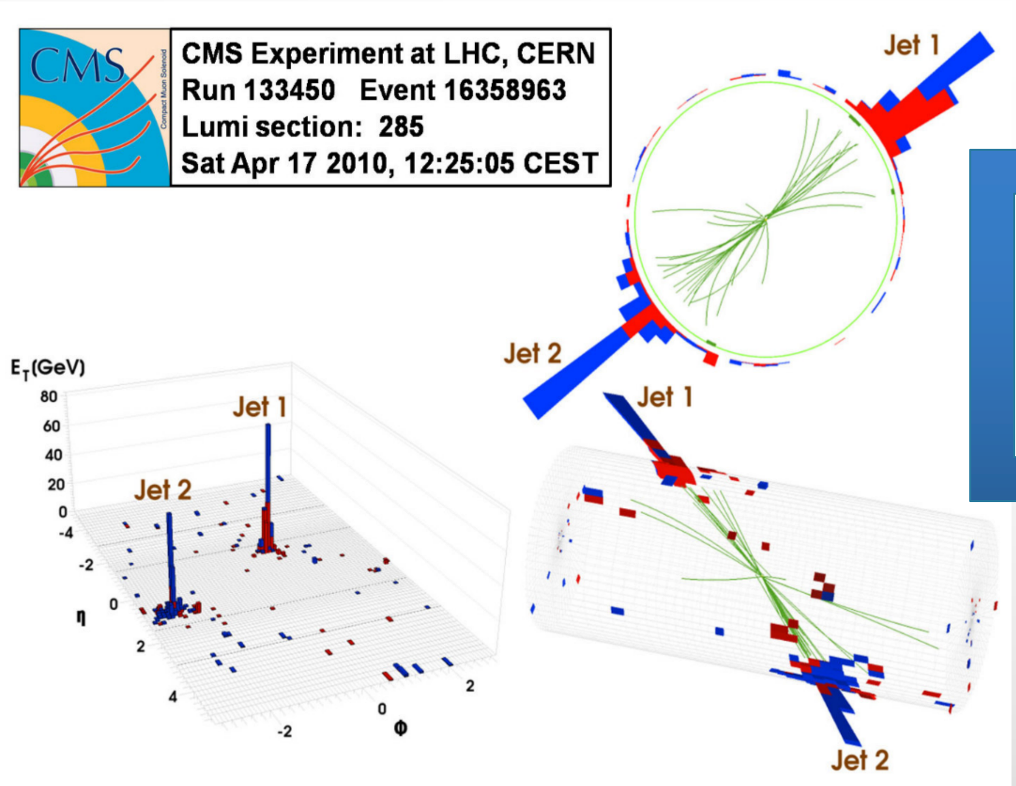
The CMS results are consistent with $x_T=2p_T/\sqrt{s}$ scaling (pQCD prediction) with exponent N=4.9 +- 0.1

Consistent with the hypothesis of limiting fragmentation: production of forward particles is independent on collision energy

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

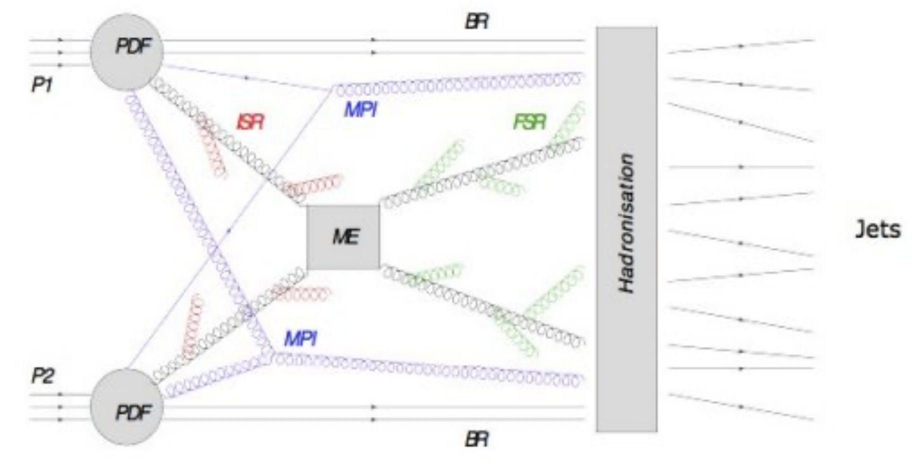
JHEP 08 (2011) 086
JHEP 01 (2011) 079
EPJC 79 (2019) 391

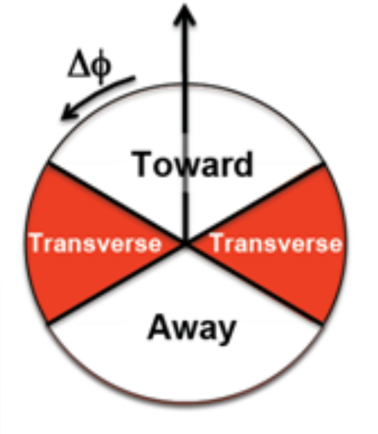
Hard interactions



PDFs and α_S measurement
- **DPS**
- **DGLAP vs BFKL**
- **Multijet correlations**

Underlying events





Everything in event that is not "triggered" interaction

Soft & semi-hard & hard

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

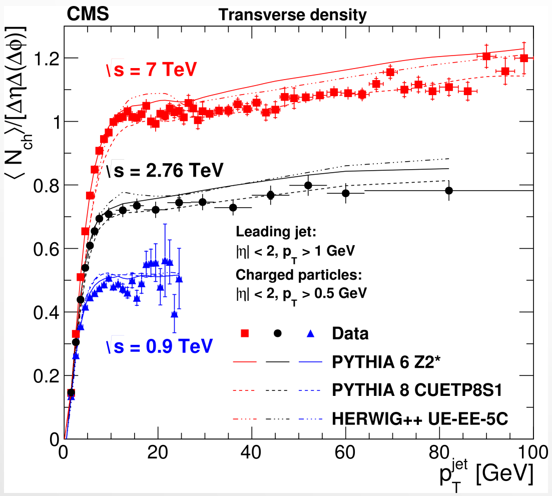
Initial (ISR) and final (FSR) state radiation

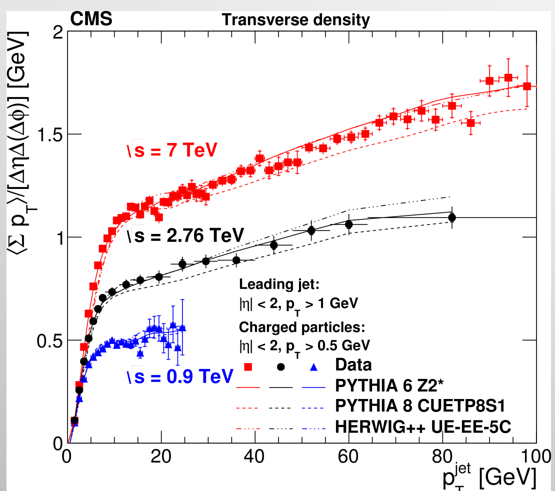
Multiple Parton Interactions (MPI). If higher pt interactions → Double Parton Scattering

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, Top events (new)

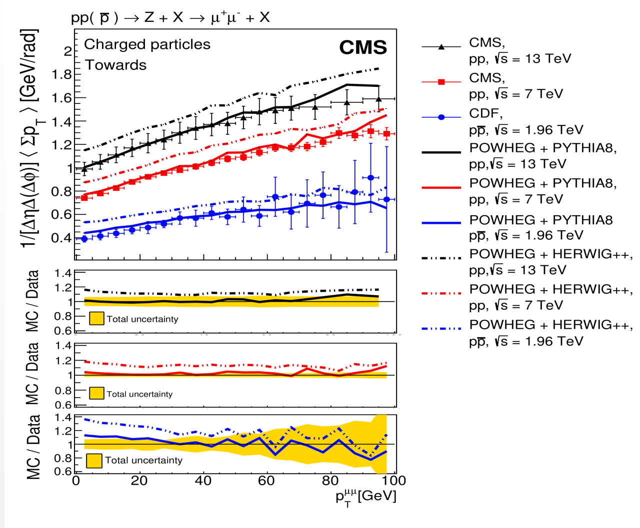
Underlying events

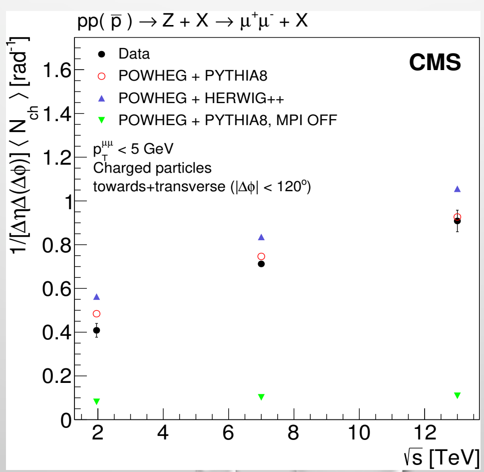
Tracker jets



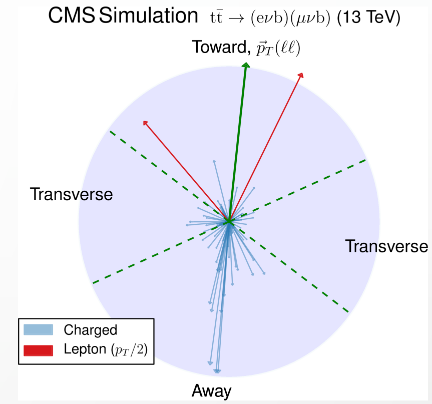


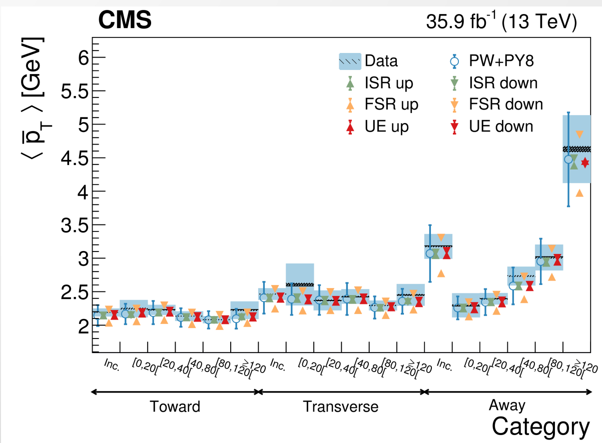
Z+jets





ttbar events



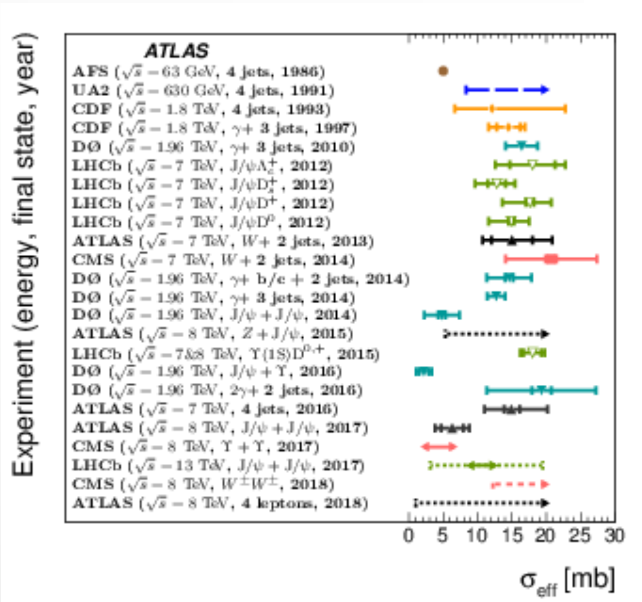


JHEP 07 (2018) 032
EPJC 79 (2019) 123
JHEP 09 (2015) 137

Double Parton scattering (DPS)

Two and more hard interactions within the same production vertex can happen.

DPS is characterized by $\sigma^{AB}_{DPS} = \frac{m}{2} \frac{\sigma^{A}_{SPS}\sigma^{B}_{SPS}}{\sigma_{eff}}$ $\quad \sigma_{eff} = \left[\int d^2 b \, (T(\mathbf{b}))^2 \right]^{-1}$



σ_{eff} **differs from 10 to 20 mb**

T(b) is the overlap function of two interacting hadrons

Why it is important:
increase of SM background for the searches.

Question:
is σ_{eff} independent on the process and interaction energy?

WW at 13 TeV(77 fb^{-1}):
σ_{DPS}=1.41+-0.28+--0.28 pb
Significance = 3.9
σ_{eff} = 12 +5 -2.9 mb

JHEP 02 (2018) 032
CMS-PAS-FSQ-16-009
CMS-PAS-SMP-18-015
JHEP 11 (2016) 110
Phys. Lett. 790 (2019) 595
CMS-PAS-SMP-20-009 subm to JHEP
CMS-PAS-SMP-20-007

4 jets events at 13 TeV:
A strong dependence of the extracted values of σeff on the model used to the describe the SPS contribution is observed.
ME NLO 2->2 or 2->3 gives 10 mb
ME LO 2->4 gives 15 mb
ME LO 2->2 gives 20 mb

PDFs and α_S

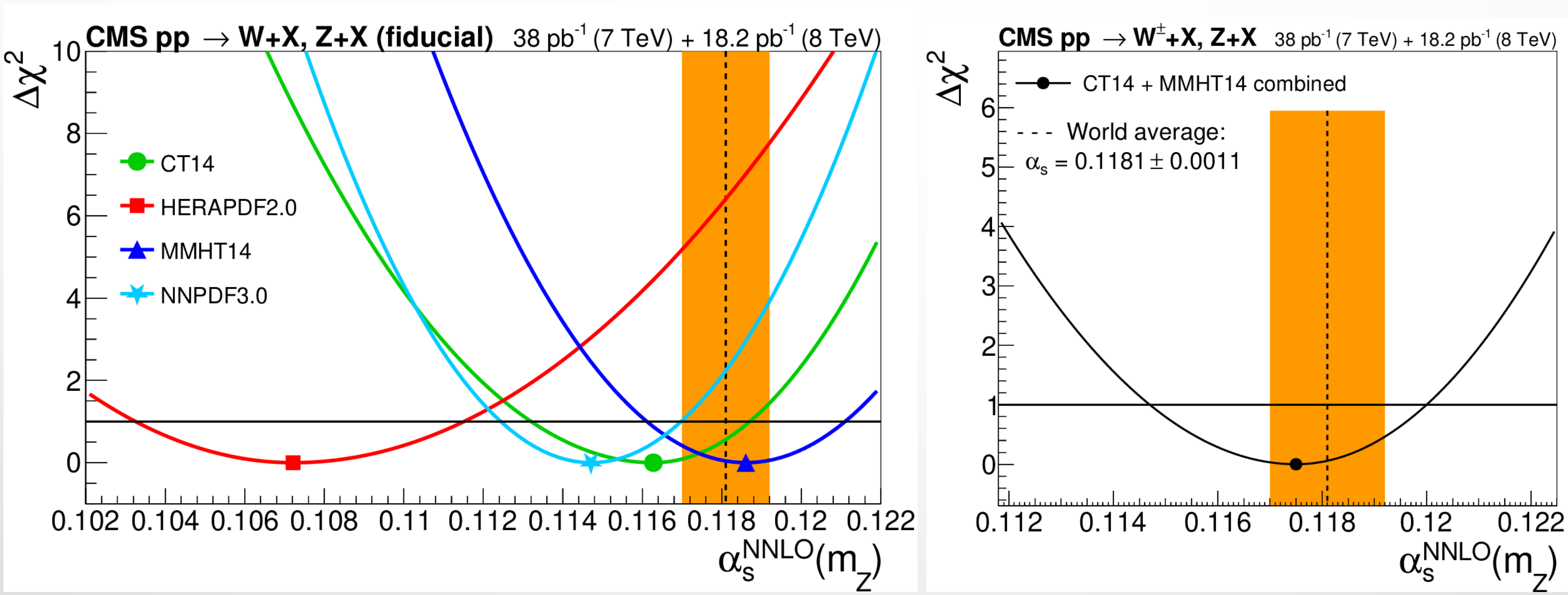
For the fixed pQCD order and definite PDF evolution (DGLAP, BFKL, CCFM,..):
A) Define PDFs at fixed α_S
B) Define α_S for the particulary PDF set which gives the best approximation of the Data by Theory
C) Combined PDFs and α_S fit

Process	Sensitivity
W mass measurement	Valence quarks
W,Z production	Quark flavor separation
W+c production	Strange quark
Drell-Yan, high mass	Sea quark, high-x, photon PDF
Drell-Yan low mass	Low-x, resummation
W,Z+jets	Gluon medium-x
Inclusive jets, multijets	Gluon and $\alpha_S(M_Z)$
Direct photon	Gluon medium, high-x
ttbar, single top	Gluon, $\alpha_S(M_Z)$

Differential production (single, double, triple), correlations, ratios, assymmetry

W+-, Z production and α_S

Sensitive to $\alpha_S(m_Z)$ due-to ISR, virtual gluon exchange, gq scattering (NLO, NNLO, …).
Calculate V-production cross-section at NNLO level for varying $\alpha_S(m_Z)$ and compare theoretical predictions to experimental data (12 samples with different decay modes).



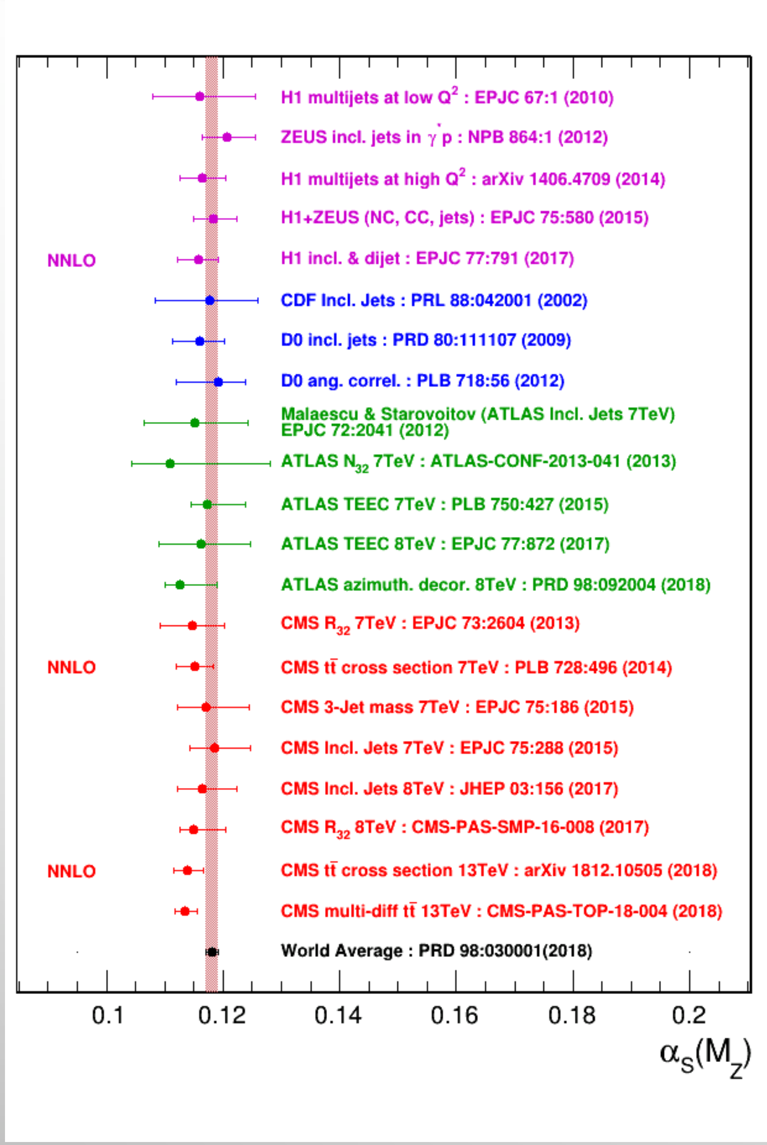
Cross-sections with CT14 and MMHT14 sets are the most sensitive to the underlying α_S value.
Robust and stable with respect to variations in the data and theoretical cross sections.
The result derived combining the CT14 and MMHT14 extractions:

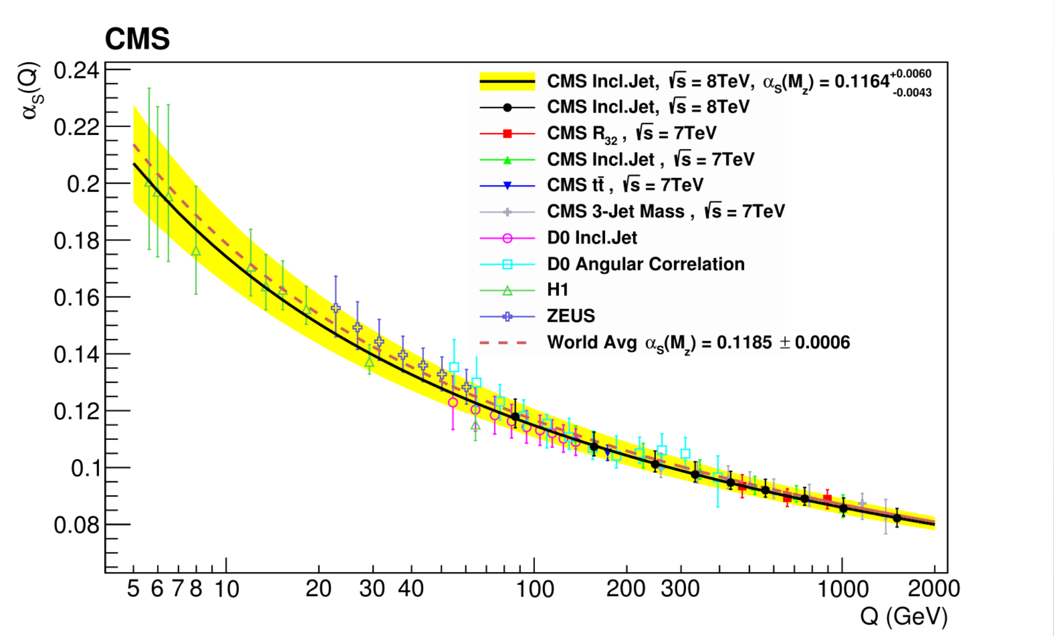
$\alpha_S(m_Z) = 0.1175{+0.0025}{-0.0028}$, has a ≈2.3%

This extracted value is fully compatible with the current $\alpha_S(m_Z)$ world average.

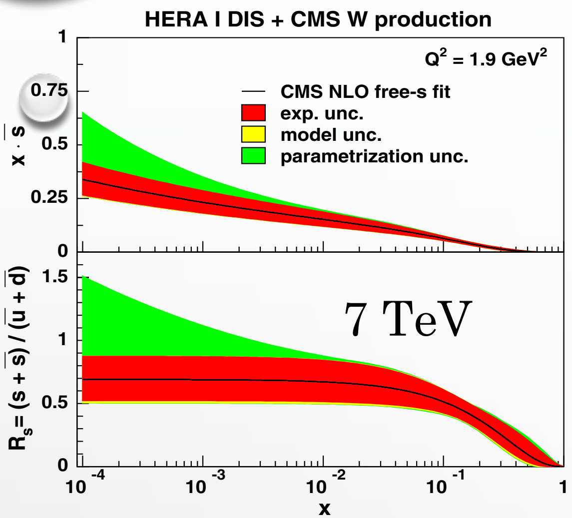
JHEP 06 (2020) 018

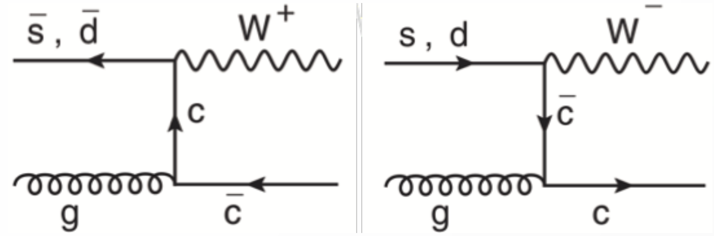
Summary on α_S





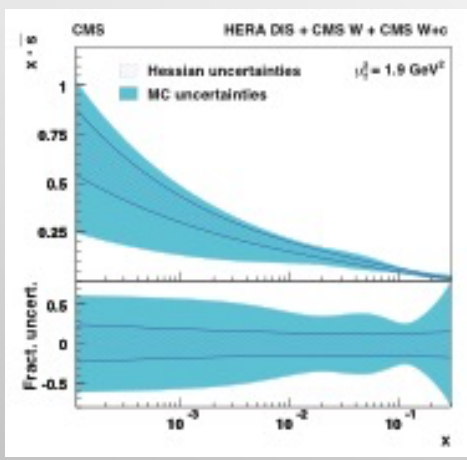
W+c: strange quark PDF

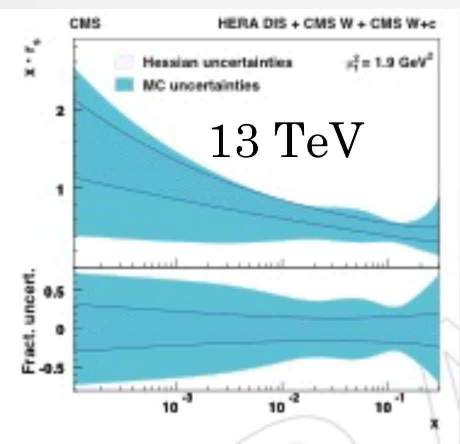


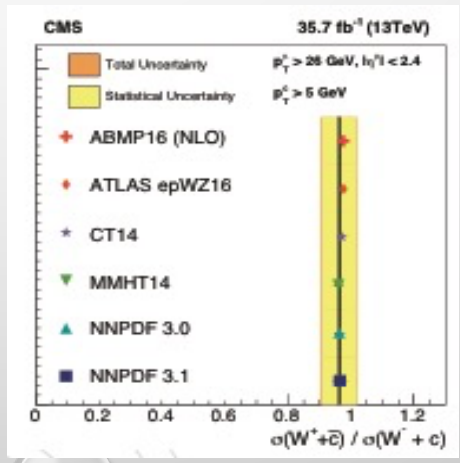


PDFs are probed at
$< x > \approx 0.007$
at the scale of W mass

13 TeV:
σ (W + c) = 1026 ± 31 (stat) ± 72 (syst) pb

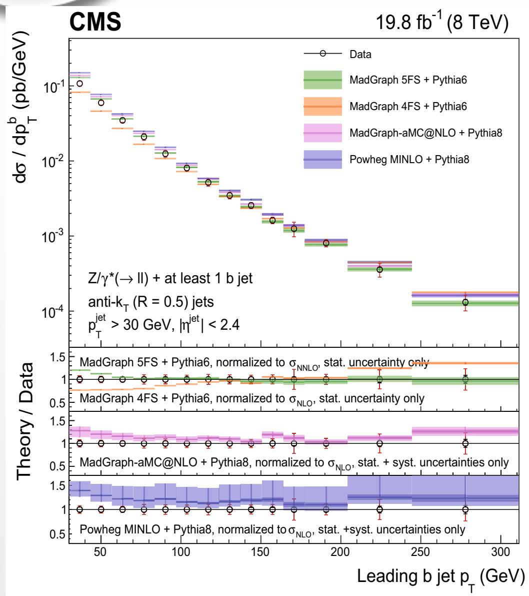






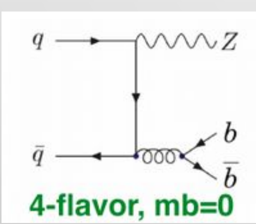
EPJC 77 (2017) 367
CMS-PAS-SMP-17-004
PRD 90 (2014) 032004

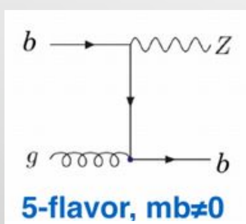
Z+c/Z+b: towards c- and b-quarks PDFs



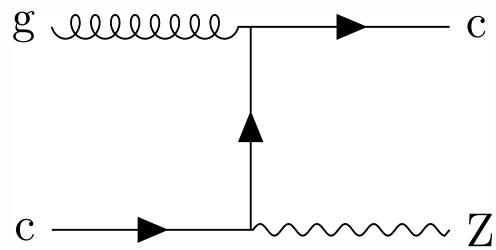
4-flavour vs 5 flavour?

uud vs uudQQbar

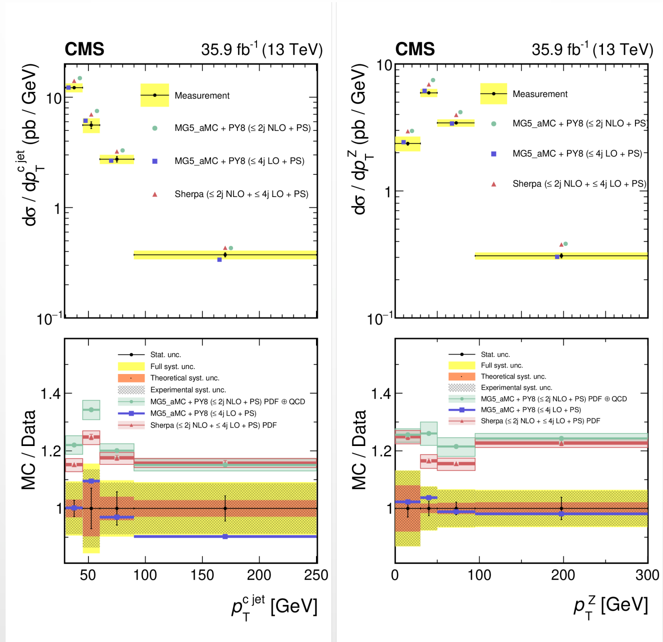




For Z+>=1b 4F schema fails to describe bjet vs p_T



One step before c-quark PDF extraction



Inclusive Z+c cross-section:

405.4 ± 5.6 (stat)

± 24.3 (exp)

± 3.7 (theo) pb

MadGraph5+MCatNLO:

524.9 ± 11.7 (theo) pb

MCatNLO and Sherpa overestimate Z+c cross-section at NLO and MCatNLO agreed with data at LO.

For Z+jets, NLO calculations has better agreement with data then LO -> PDF overestimate c-content?

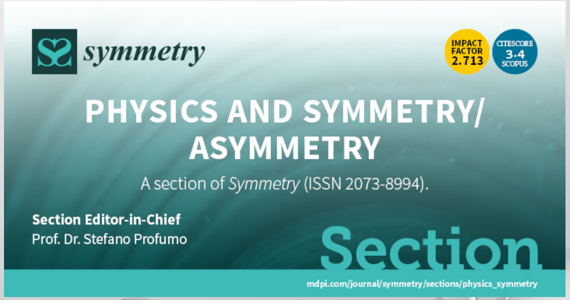
EPJC 77 (2017) 751
EPJC 78 (2018) 287
JHEP04 (2021) 109

Summary

- CMS measures both hard and soft QCD processes in various phase space regions and compare them with a wide range of LO , NLO and NNLO calculations
- CMS measurements are used for the combinations with other experiments in global fits and in Monte-Carlo Models tuning. Validation of the QCD predictions (scaling properties, particles spectra, strong coupling behavior, PDFs, evolution, etc) allows to further constrain and tune existing models.

More results can be found in CMS public web page:
http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html
http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ/index.html

Presentation is supported by the Journal Symmetry:



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Section Editor-in-Chief

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Department of Physics, University of California, Berkeley, CA, USA

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The "Physics and Symmetry" section covers topics, original research, and peer-reviewed articles related to the latest research and developments in any field of physics where symmetry plays a key role. This is a vast, highly interdisciplinary area, which runs the gamut from classical symmetries, to space-time symmetries, gauge symmetries, symmetry breaking, the origin of symmetry, etc. Areas of physics relevant to this section include mathematical physics, classical and quantum gravity, particles and fields, condensed matter systems, dynamical, disordered, and non-equilibrium systems, and biophysics.

In general, this section will be a platform for researchers to publish their scientific work, helping them to influence the scientific community as well as the general public.

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Deadline for manuscript submissions:
31 December 2021

Message from the Guest Editors

We are glad to announce the Special Issue "Symmetry: Feature Papers 2021" online. We aim to introduce a new insight into science development or cutting edge technology related to the physics and symmetry field, which will make a great contribution to the community. It covers topics, original research, and peer-reviewed articles related to the latest research and developments in any field of physics where symmetry plays a key role.

In general, this Special Issue will be a platform for researchers to publish their scientific work, helping them to influence the scientific community as well as the general public.

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Special Issue

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Message from the Editor-in-Chief

Symmetry is ultimately the most important concept in natural sciences. It is not surprising then that very basic and fundamental research achievements are related to symmetry. For instance, the Nobel Prize in Physics 1979 (Glashow, Salam, Weinberg) was received for a unified symmetry description of electromagnetic and weak interactions, while the Nobel Prize in Physics 2008 (Nambu, Kobayashi, Maskawa) was received for the discovery of the mechanism of spontaneous breaking of symmetry, including CP symmetry. Our journal is named *Symmetry* and it manifests its fundamental role in nature.

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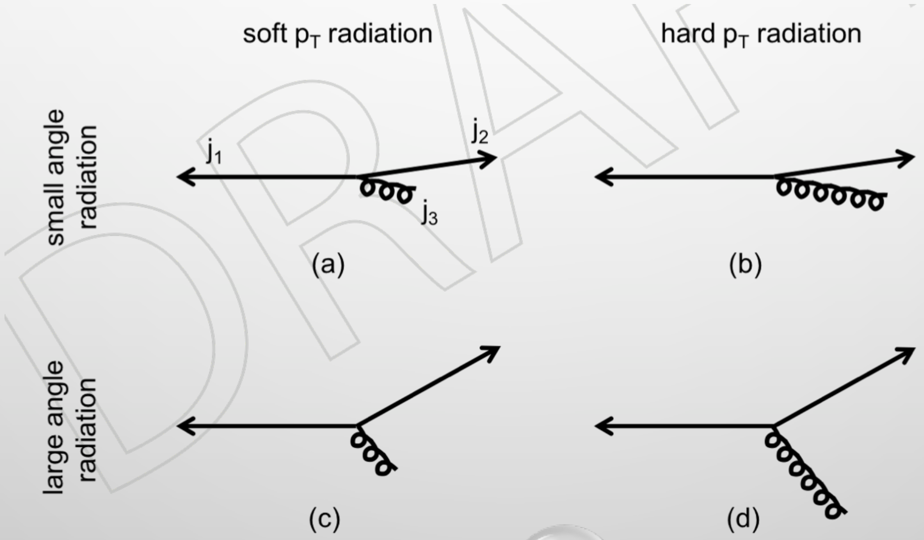
Back-up

Multi-jet correlations

Theoretical predictions are based on

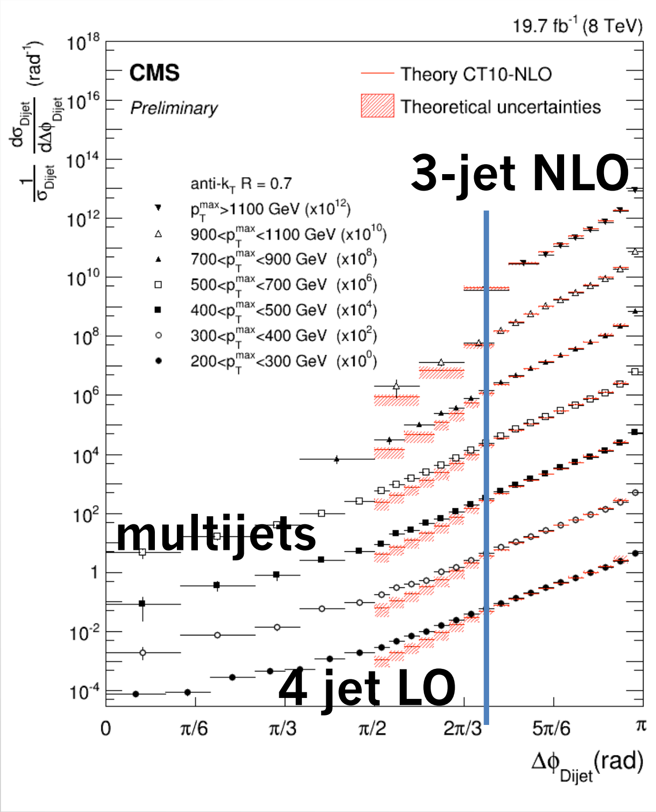
- Matrix element expansion and parton shower
- Multi-parton interactions and hadronization

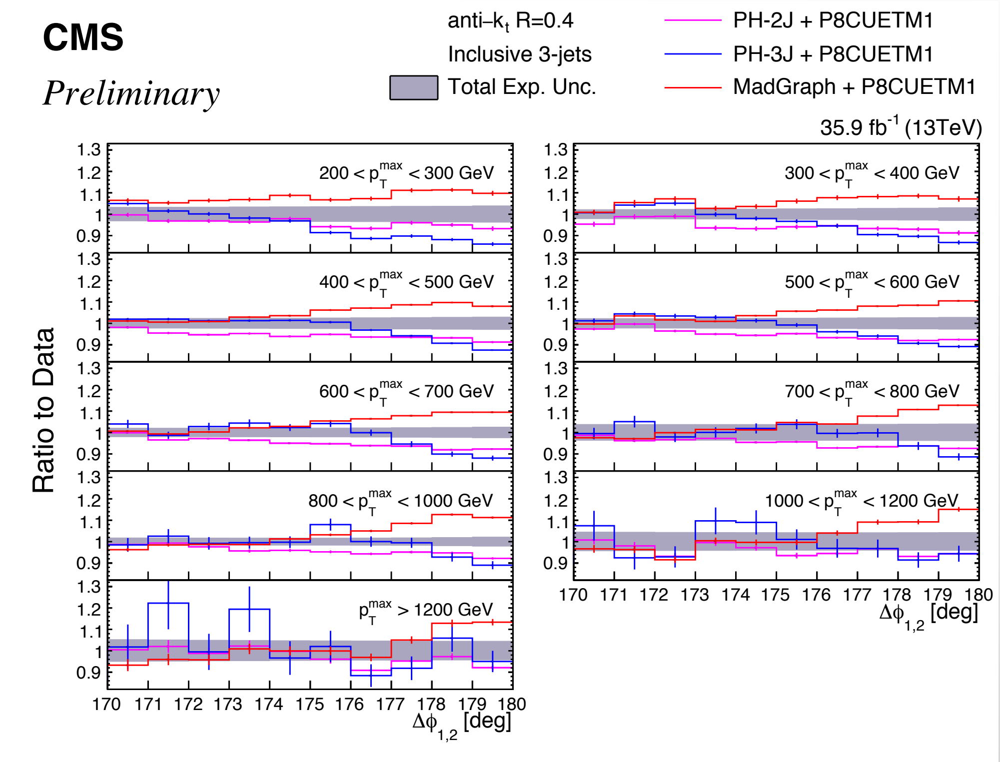


Azimuthal decorrelations

$\Delta\phi_{jj}$ in bins of p_{T1} for p_T>100 GeV, p_{T1}>200GeV, $|y_1|<2.5, |y_2|<2.5$

Back-to-back region of dijet correlations-sensitive probe of soft gluon radiation





Comparison is done with fixed-order pQCD (NLO) and with LO ME+PS

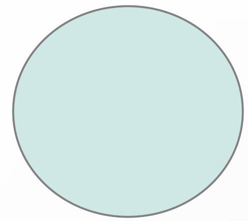
Deviations (~10%) are observed for all tested generators

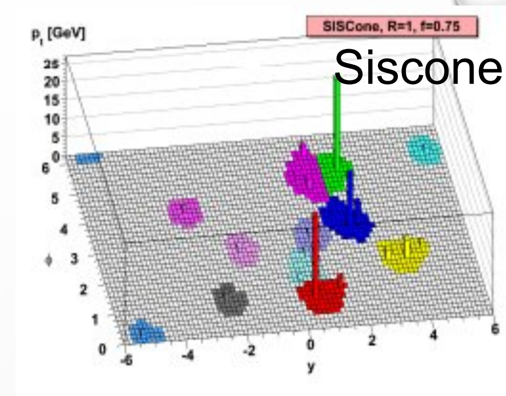
EPJC 76 (2016) 536
CMS-PAS-SMP-17-009

Jet clustering technique

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

Iterative cone



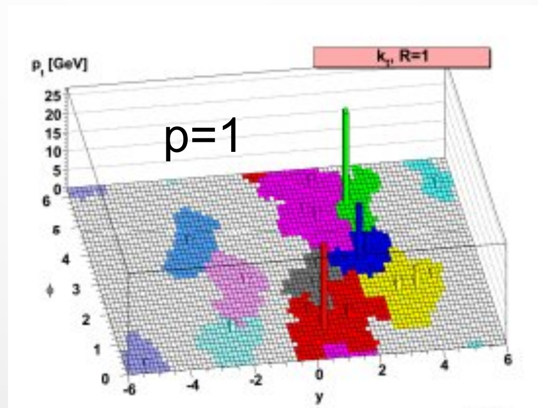


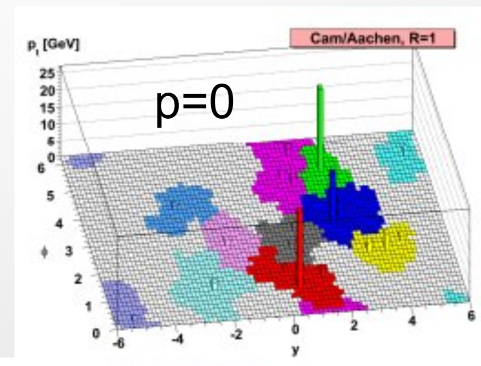
Successive recombination algorithms:

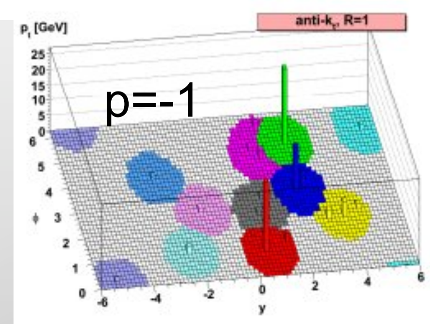
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\delta_{ij}^2}{R^2}$$

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

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

CMS uses R=0.5,0.7 in Run1
R=0.4,0.6 in Run2
ATLAS uses R=0.4,0.6 in Run1,2

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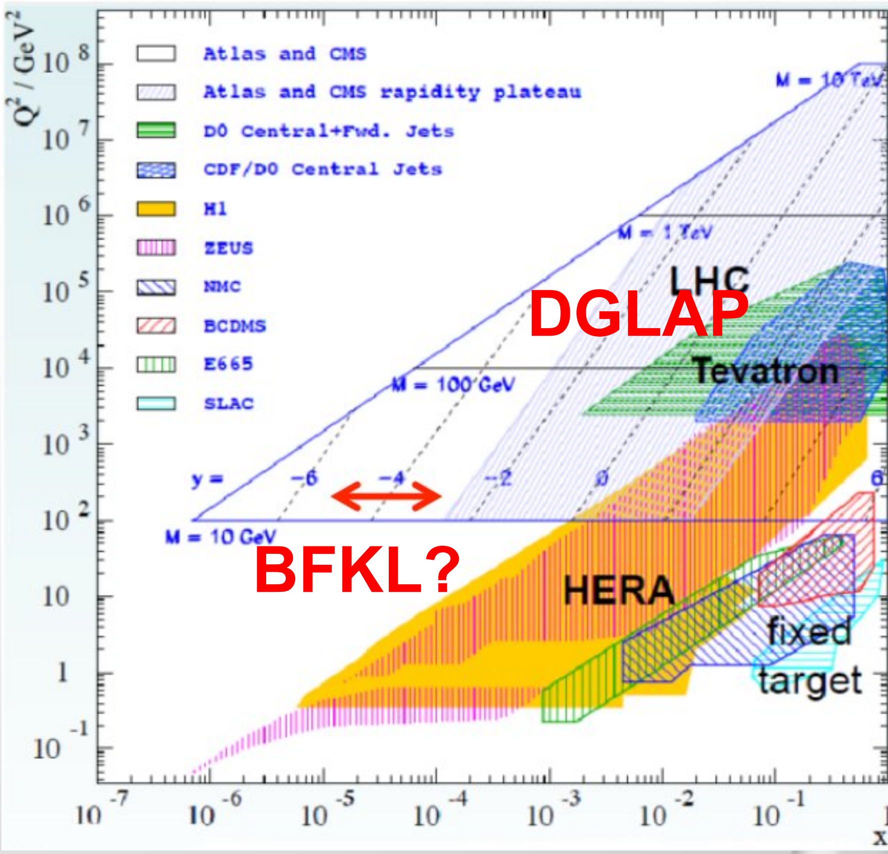
QCD Evolution equation

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.

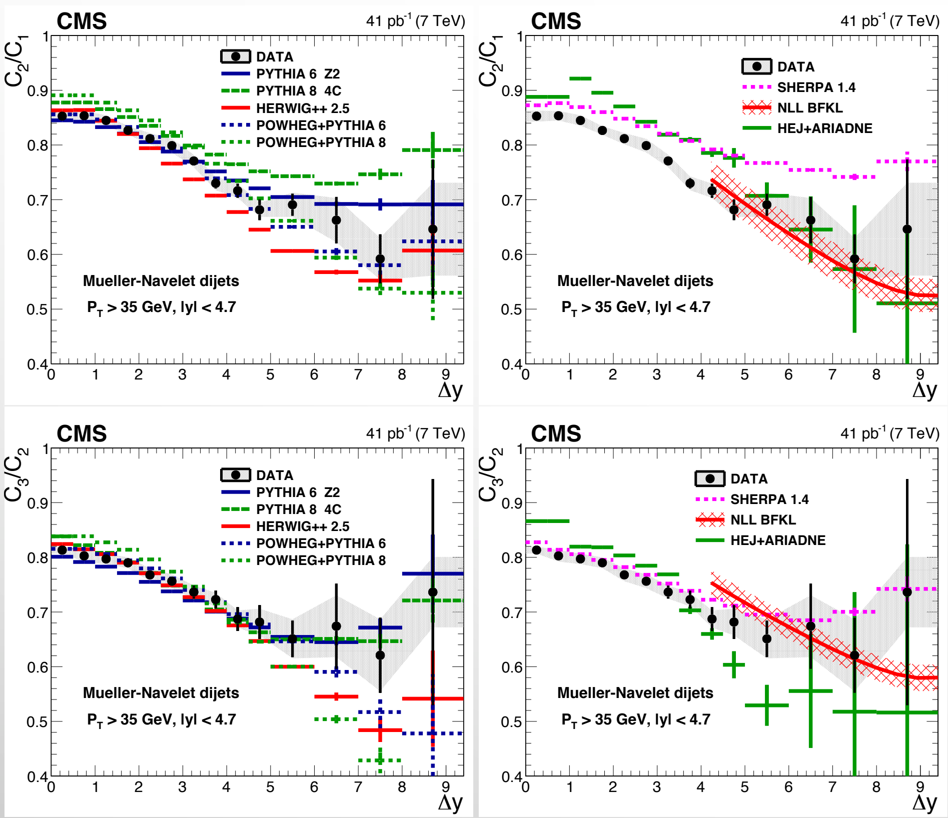
Need to develop alternative approaches:
- BFKL (expansion in terms of ln(1/x)).
- CCFM angular and energy ordering
- LDC (Linked dipole chain)
- …

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



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 (CMS) the angular distance is calculated: Δφ = φ1 – φ2



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

DGLAP generators start to be worse in high Δy description

Analytical BFKL calculations at NLL accuracy with an optimized renormalization schema provide reasonable description of data for the measured jet variables at Δy>4

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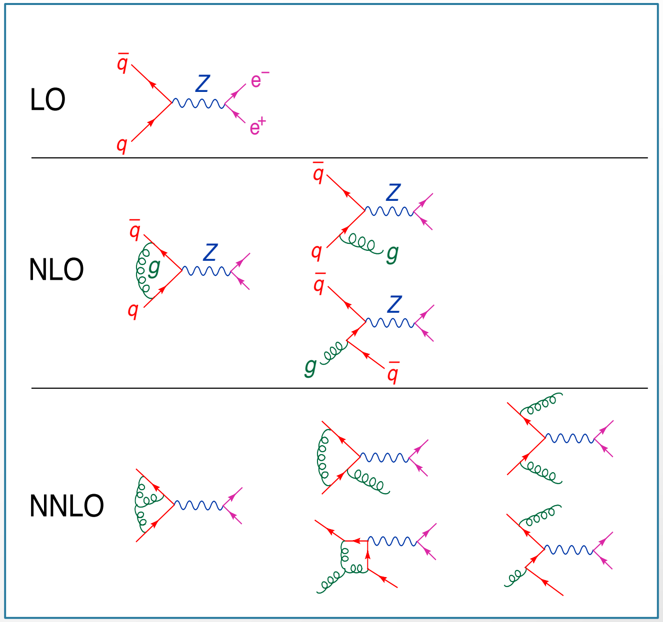
Perturbative QCD (pQCD)

pQCD prediction at fixed order calculation
Singularities (soft and collinear) are:

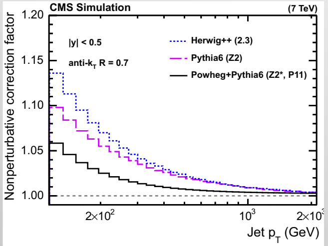
- ❑ **partially cancelled between real and virtual contributions,**
- ❑ **partially absorbed in PDFs and coupling renormalizations**



Finally, fixed order QCD calculations are matched with parton showers (PYTHIA or HERWIG) Monte-Carlo models which represent soft and collinear radiation patterns
OR in alternative approach non-perturbative and Electroweak corrections are applied as weights

NP corr PS corr EWK corr

pQCD X



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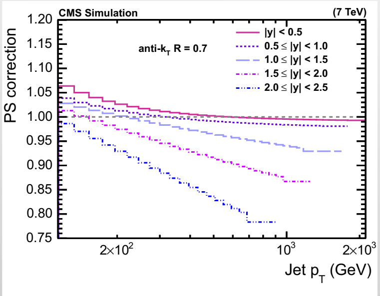

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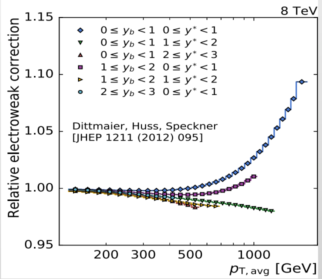
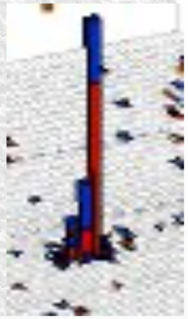


http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-13054.pdf

Jet reconstruction in detector

Calorimeter jets (CaloJets):
Jet clustered from Calorimeter Towers (CMS,ATLAS) Or TopoClusters (ATLAS)
CaloMET

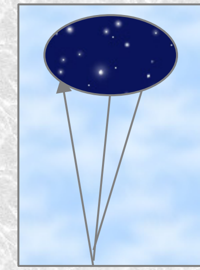


Anti-Kt clustering algorithm is applied to the different objects

Tracker jets (TrackJets):
Jet clustered from Tracks

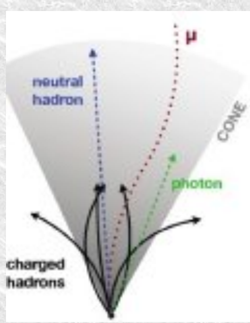
Subdetectors: Tracker

(ATLAS,CMS)



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 CMS



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

CMS