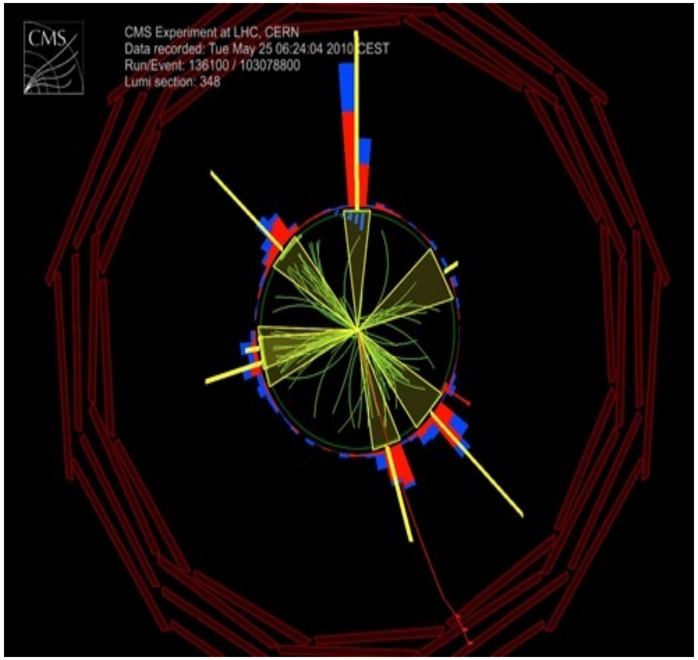
QCD Physics with CMS detector



Olga Kodolova, SINP MSU

(on behalf of CMS collaboration)

CHEP-Yerevan-2023, Yerevan, Armenia, 11-15 September, 2023

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:

- **Although QCD is the basic theory of strong interactions its parameters are still not well known.**
- **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:

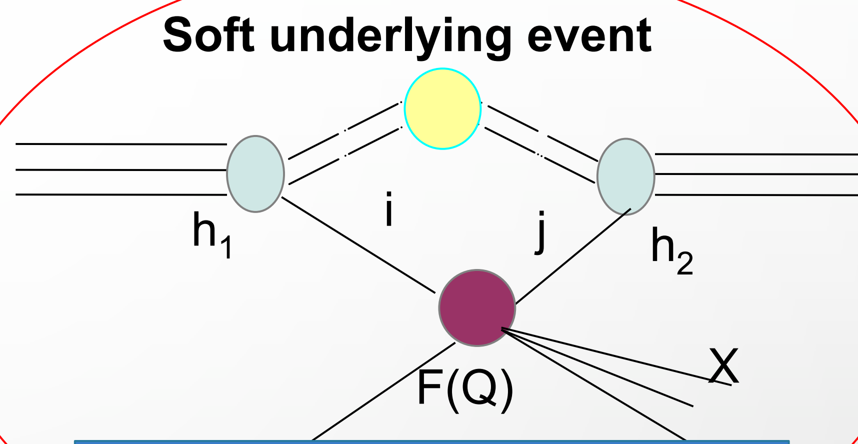
- **proton structure,**
- **constrain the strong coupling**
- **pQCD theory components**
- **study non-perturbative effects**
- **tune Monte-Carlo generators**

How do we proceed?

Collect puzzles!

QCD at hadron colliders

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



$p_1 = x_1 P_1$

$p_2 = x_2 P_2$

Hard interaction: production of the high-p_T objects

Factorization property

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

Parton distribution function (PDF)

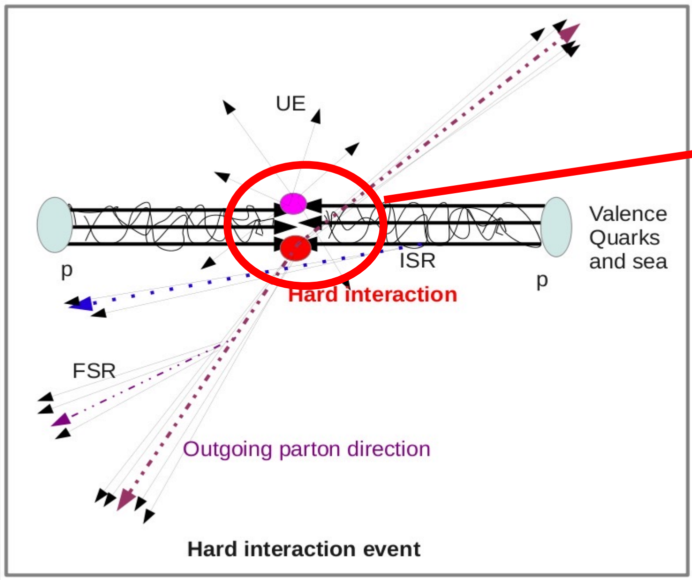
Partonic cross-section computed in pQCD

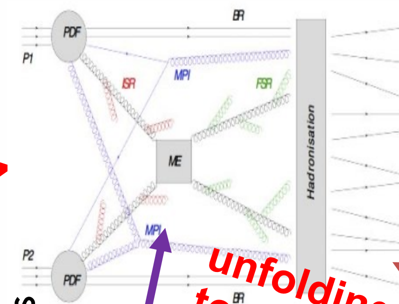
$$\hat{\sigma}_{ij} = \alpha_S^k \sum_n \left(\frac{\alpha_S}{\pi}\right)^n \sigma_{ij}^n$$

Fixed order pQCD

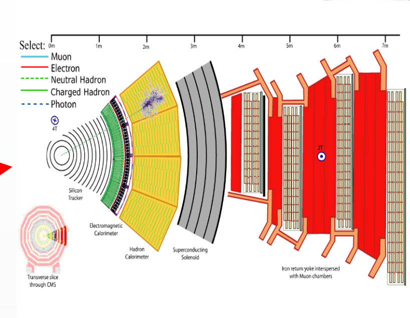
Soft interaction: production of the low-p_T hadrons

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

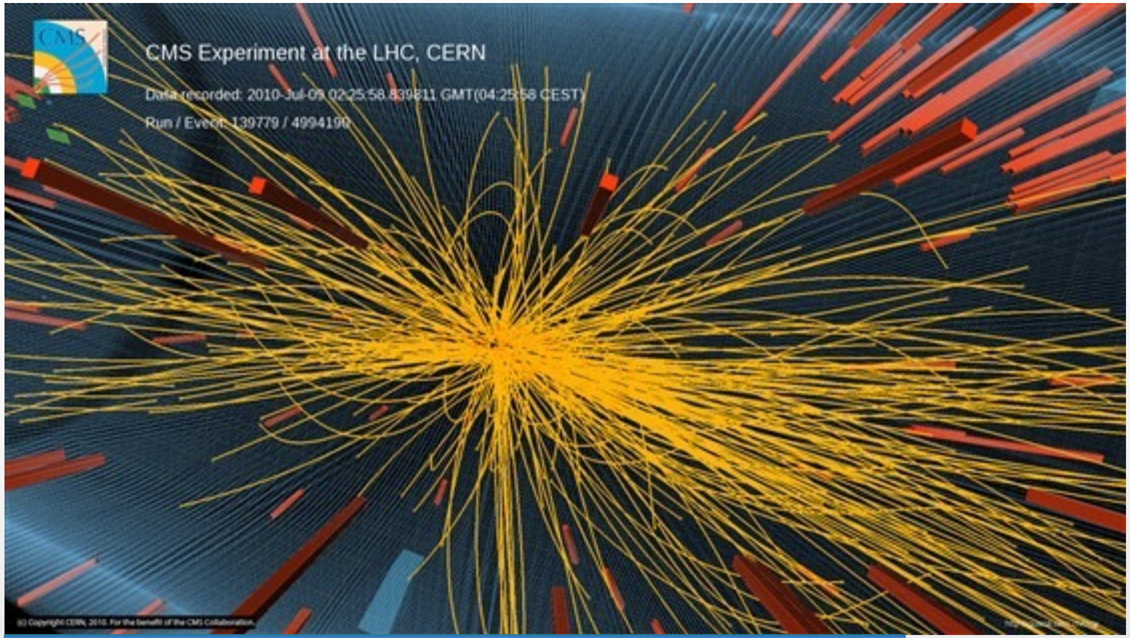
↕

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

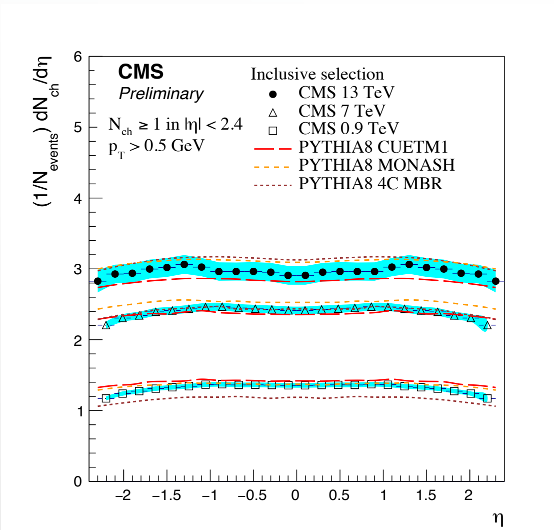


Charged particle multiplicity
Scaling, correlations
Underlying event

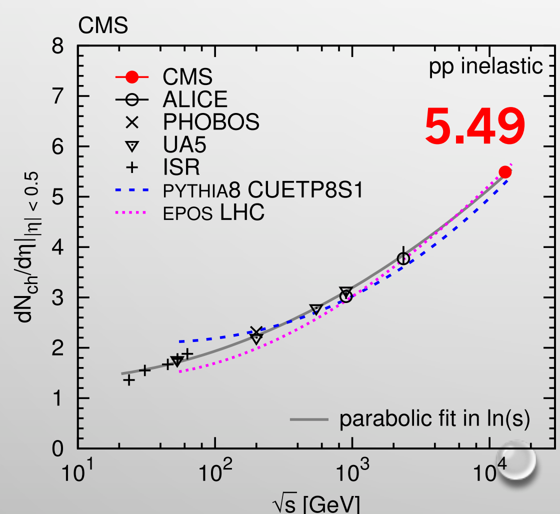
Charged particles

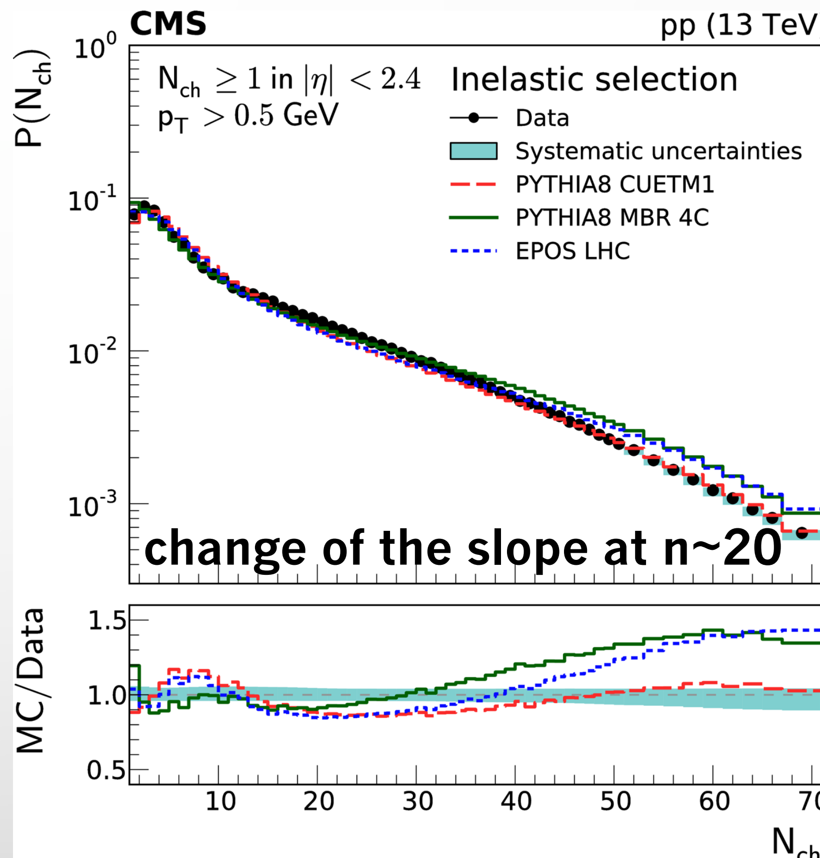
new input to the dynamics of soft hadronic interactions: interplay between soft and hard processes: no one MC describes data in all configurations

p_T>500 MeV, |η|<2.4



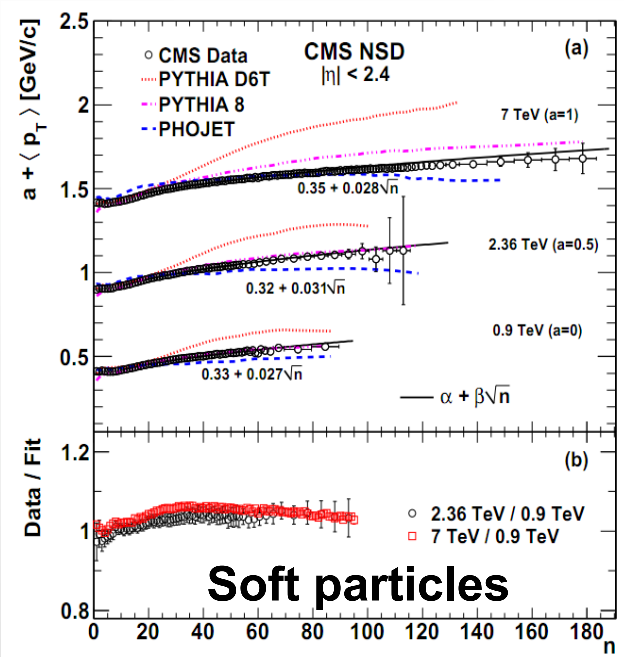
p_T>0 MeV, |η|<0.5

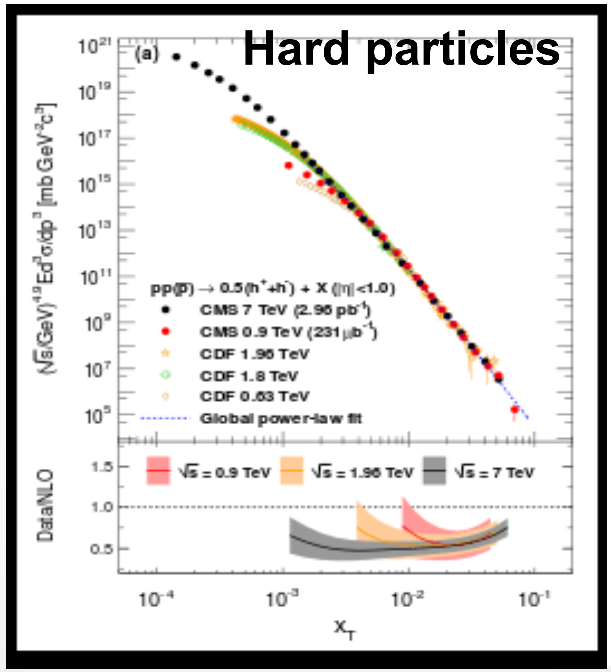


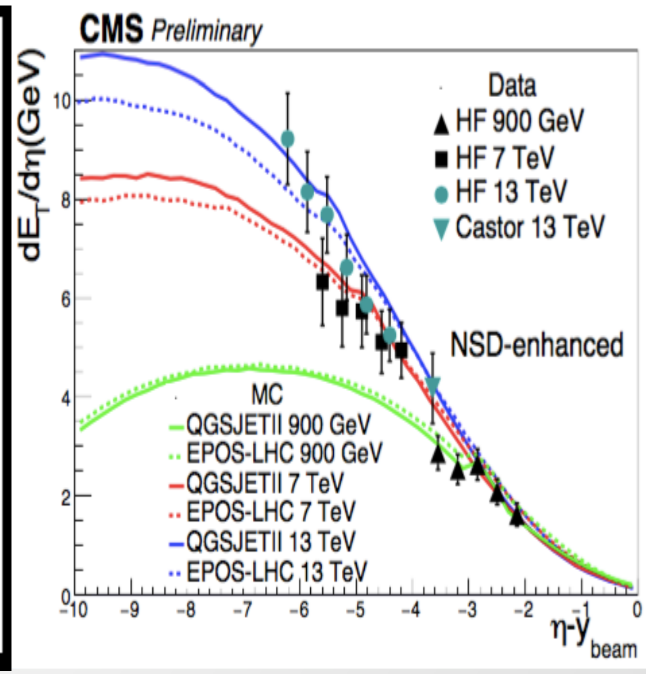


CMS-PAS-FSQ-15-008
EPJC 78 (2018) 697
JHEP 01 (2011) 079

p_T & x_T & limiting fragmentation







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

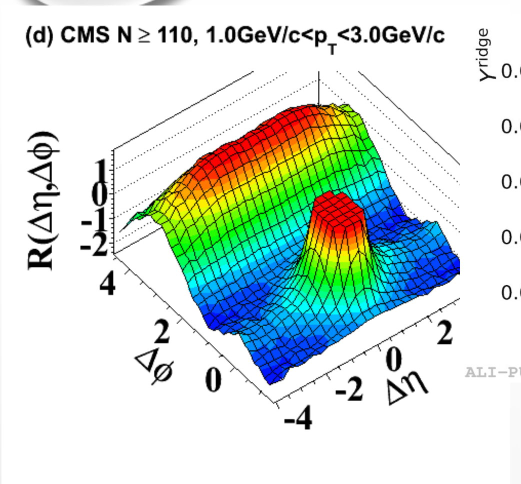
The CMS results are consistent with $x_T=2p_T/\sqrt{s}$ scaling (pQCD prediction) with exponent N=4.9 +- 0.1

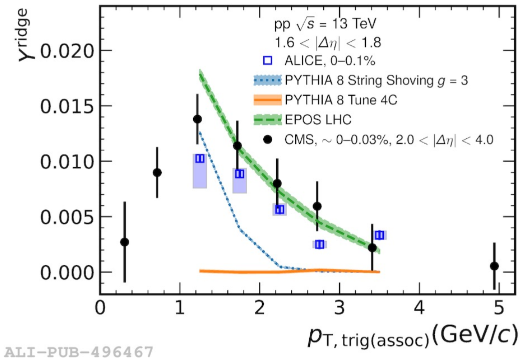
Consistent with the hypothesis of limiting fragmentation: production of forward particles is independent on collision energy

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

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

Long-range correlations





Qualitatively described effect:

PYTHIA8 string shoving:

interacting strings

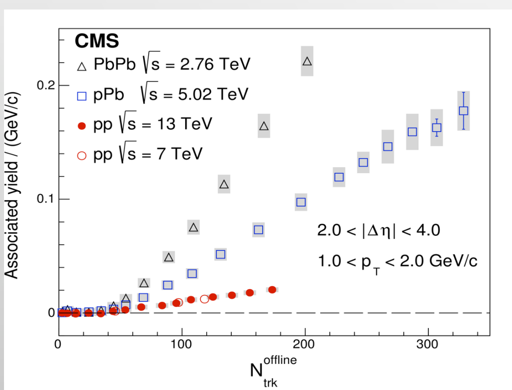
EPOS LHC:

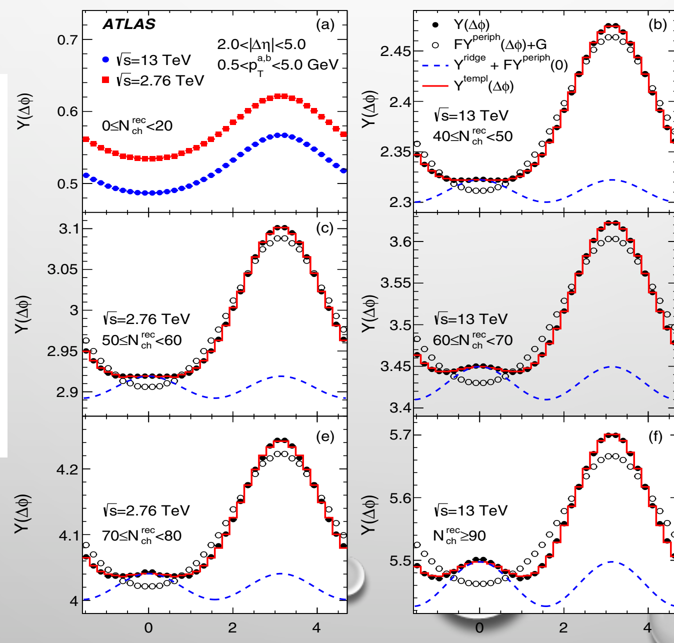
hydrodynamical evolution

Of high-density core (formed by color String fields)

Agreement with ATLAS and ALICE

Ridge at Δϕ~0 and large Δη at high multiplicity in pp events at intermediate p_T





Superposition the low multiplicity yield and modulation as cos(2Δϕ). Extracted $V_{2,2}$ exhibit factorization.

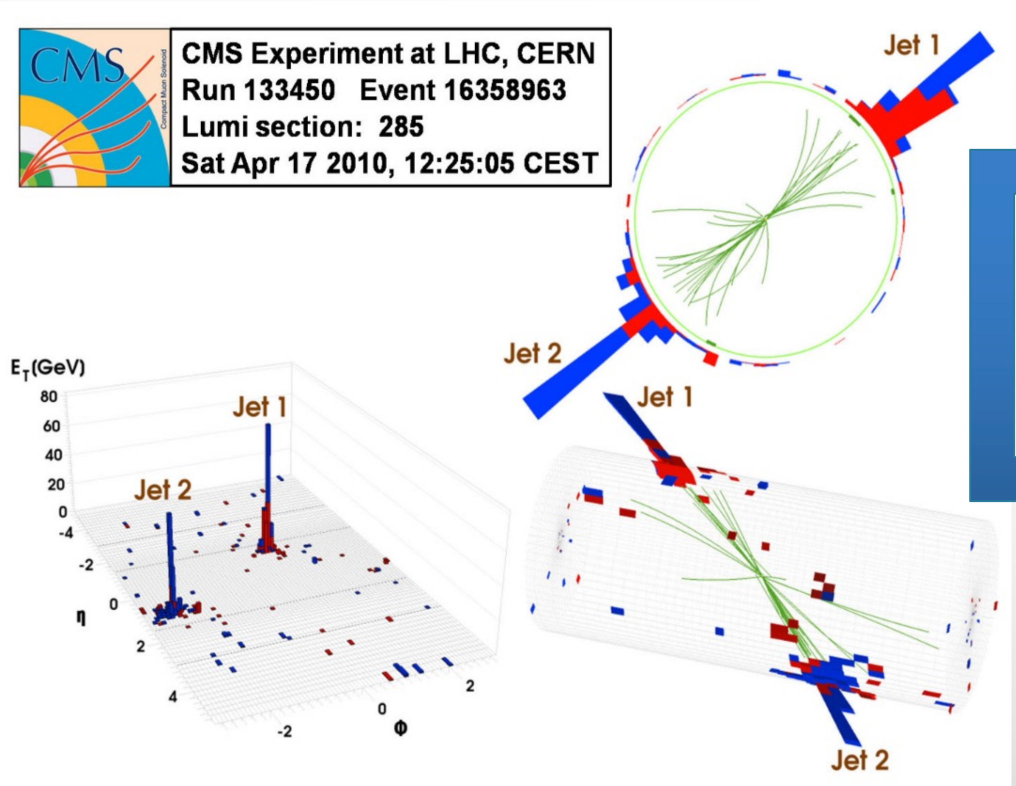
$$R(\Delta\eta,\Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

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

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

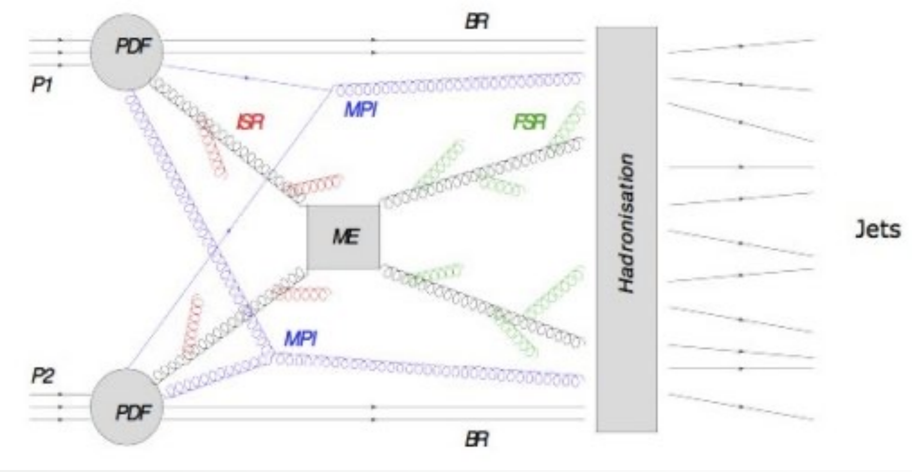
PRL 116,172301(2016)
PRL 116,172302(2016)
JHEP05 (2021), 290

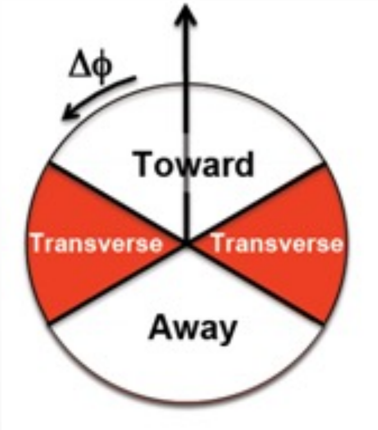
Hard interactions



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

Underlying events





Soft & semi-hard & hard
Beam remnants (BR): everything besides the hard (part of the) interaction, i.e

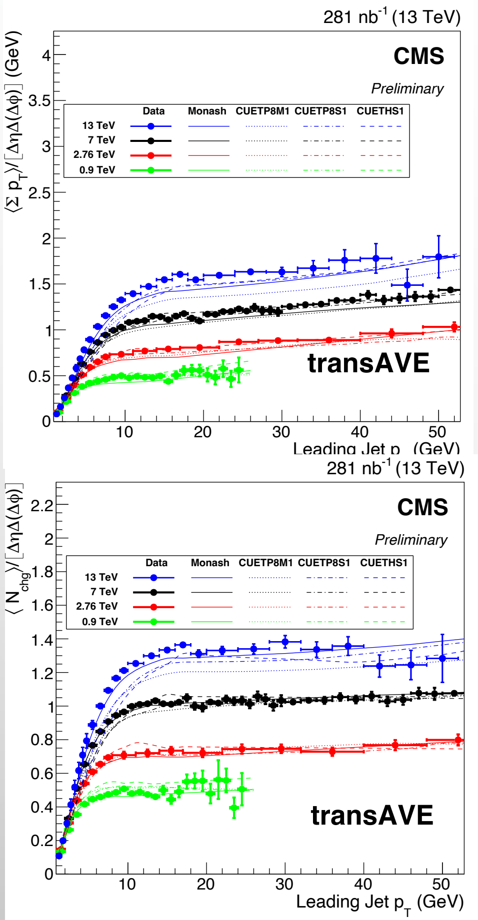
Initial (ISR) and final (FSR) state radiation

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

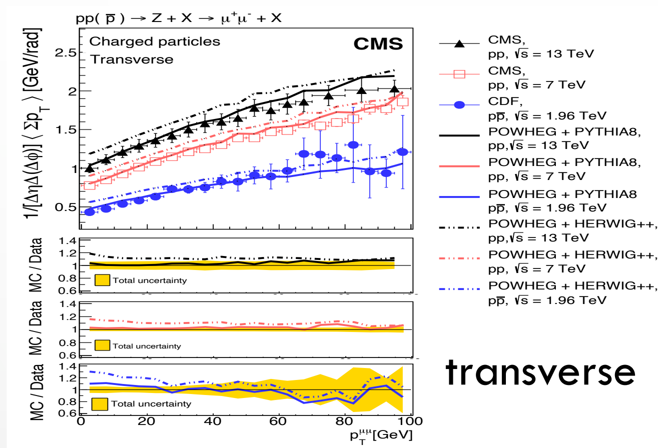
UE activity is typically studied in the transverse region in pp collisions as a function of the hard scale of the event, and at different centre-of-mass energies (√s):
Particle production in MinBias events or events with high energy track or jet (hadronic events)
Drell-Yan events, Top events (new)

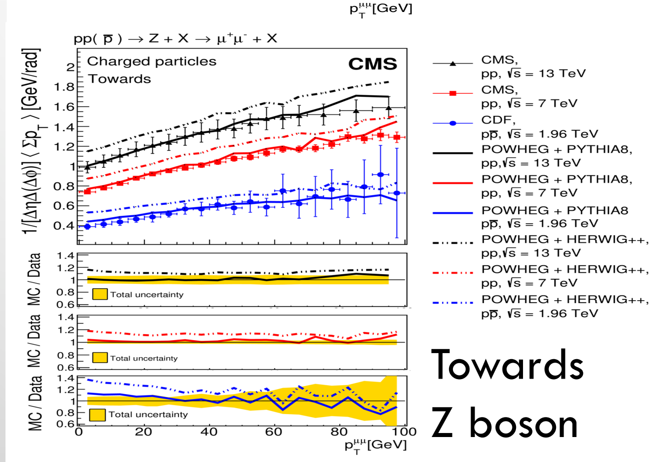
Underlying events

High p_T track or Tracker jets

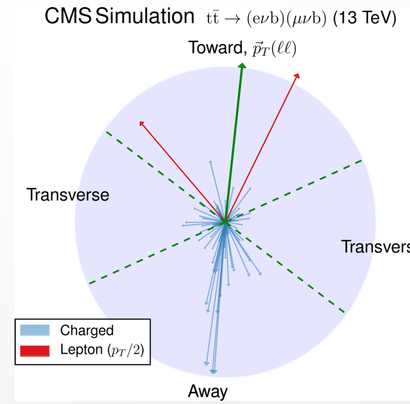


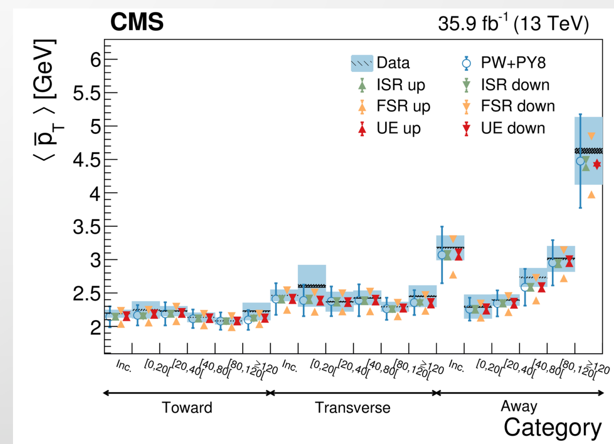
Z+jets





ttbar events





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

Double Parton scattering (DPS)

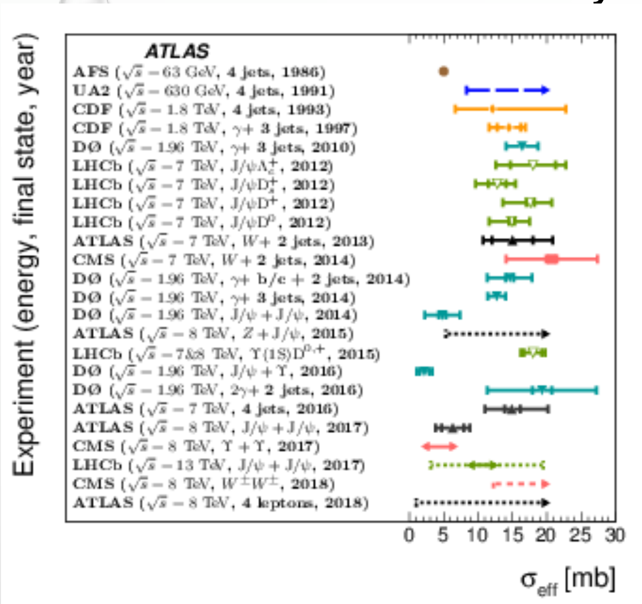
Two and more hard interactions within the same production vertex can happen.

DPS is characterized by

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

σ_{eff} is 2-10 (10 to 20) mb for g(q)

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



First observation in same sign WW at 13 TeV (138 fb^{-1}):

CMS-PAS-SMP-21-013, Accepted by PRL

σ_{DPS}^{WWinc}=80.7 ±11.2(stat)+9.5(syst)-8.6(syst)±12.1(model) fb

σ_{DPS}^{WWfid}=6.28 ±0.81(stat)±0.69(syst) ±0.37(model) fb

Observed significance = 6.2

σ_{eff} = 12.2 +2.9-2.2 mb

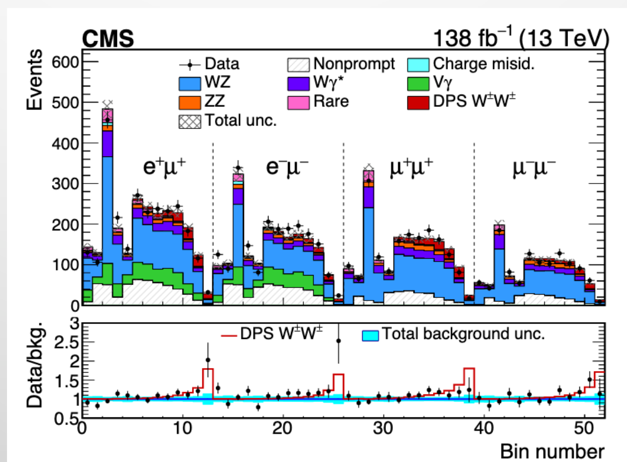
DPS with 4 jets events

JHEP01 (2022) 177 (13 TeV):

A strong dependence of the extracted values of σeff on the model used to the describe the SPS contribution is observed.

σ_{eff} = 7-35 mb

σ_{DPS}=15-70 nb



DPS with Z+jets

JHEP 2110(2021)176

Give the additional possibility to constrain MPI models

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

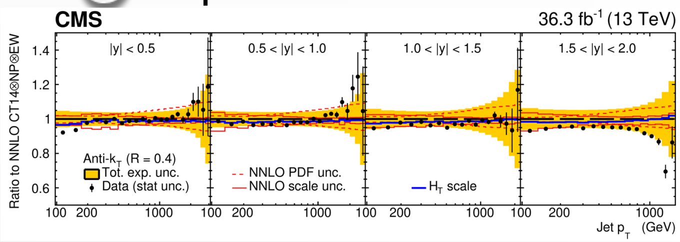
Process	Sensitivity
W mass measurement	Valence quarks
W,Z production	Quark flavor separation
W+c production	Strange quark
Drell-Yan, high mass	Sea quark, high-x, photon PDF
Drell-Yan low mass	Low-x, resummation
W,Z+jets	Gluon medium-x
Inclusive jets, multijets	Gluon and $\alpha_S(M_Z)$
Direct photon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

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

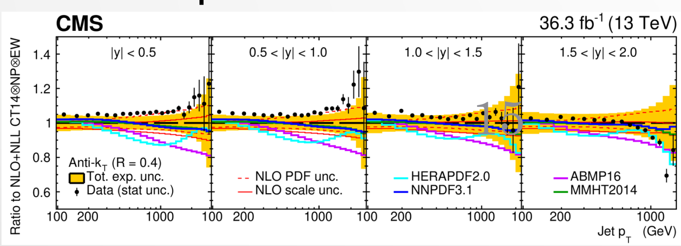
Jet production: sensitivity to g-PDF and to α_S

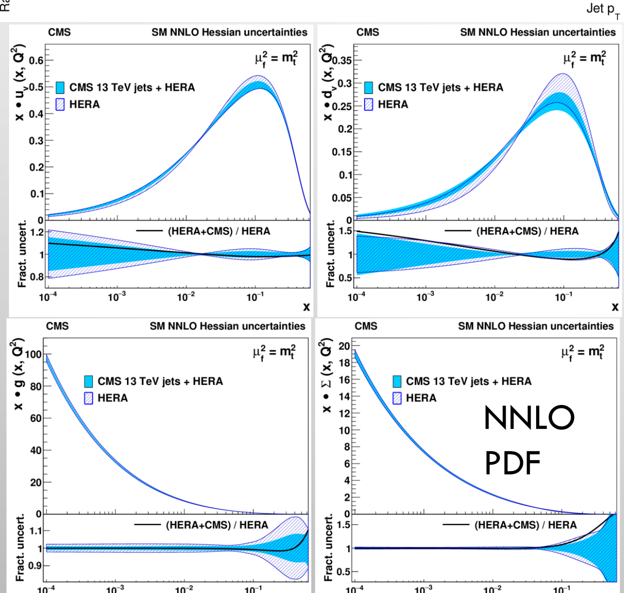
CMS, 13 TeV, Integrated luminosity 36.3 fb^{-1}

Comparison with NNLO



Comparison with NLO+NLL



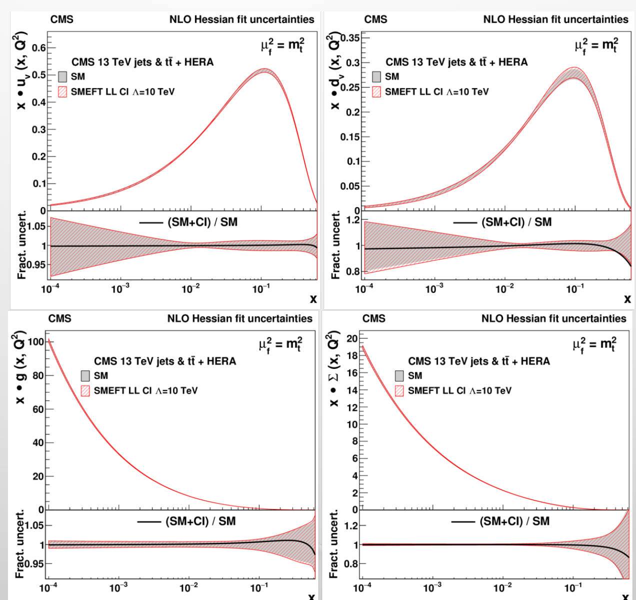


Double-differential inclusive jet production + HERA DIS + the normalized triple-differential ttbar cross-section, DGLAP evolution

PDF and $\alpha_S(M_Z)$ = 0.1170+-0.0019 at NNLO (approximated by k from NLO), uncertainties comparable with world average

PDF at NLO extracted simultaneously with Wilson coefficient in EFT (SMEFT)

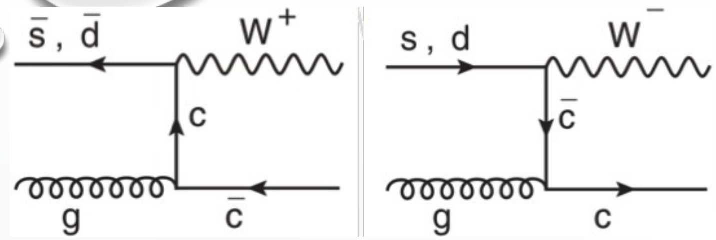
NLO PDF with Contact Interactions



No evidence for Contact Interactions:
95% confidence level exclusion limit for the left-handed model with constructive Interference
Λ > 24 TeV

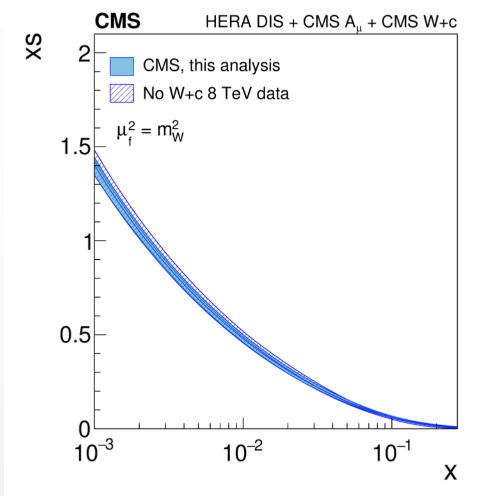
JHEP 02(2022) 142

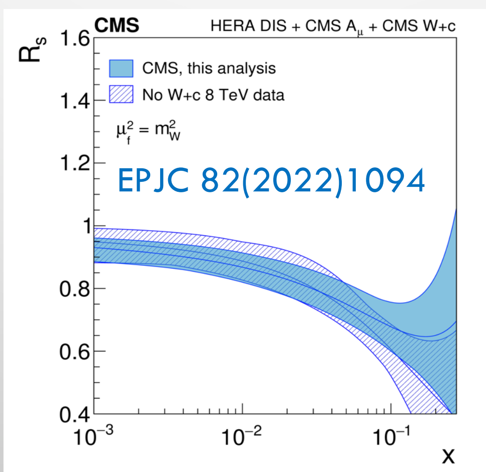
W+c: strange quark PDF



$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

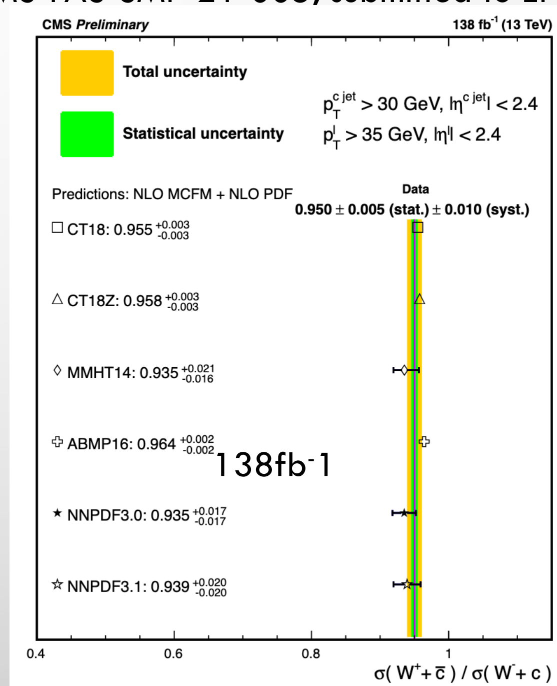
PDFs are probed at
$< x > \approx 0.007$
at the scale of W mass
13 TeV (CMS, 36 fb^{-1}):
σ (W + c) = 1026
± 31 (stat) ± 72 (syst) pb

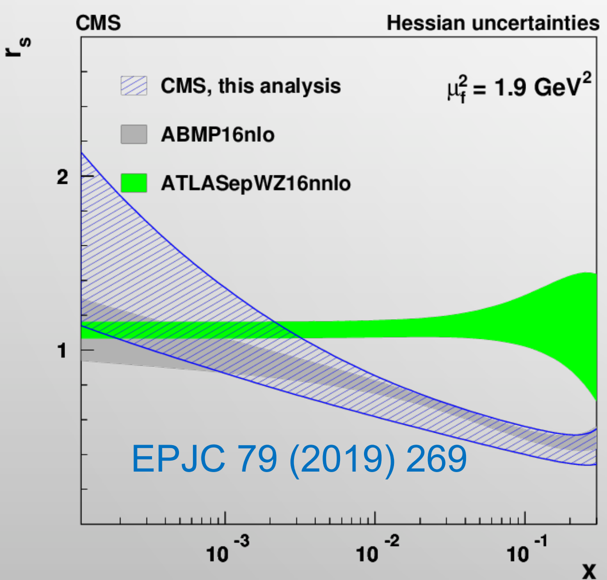




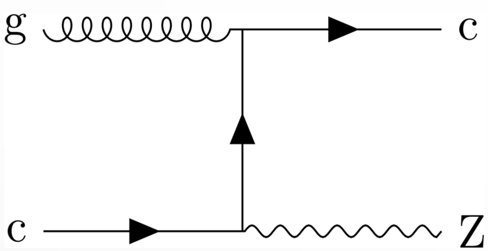
From neutrino scattering Rs=0.5
At Q2=1.9 GeV2 strange
sea-quark density is suppressed

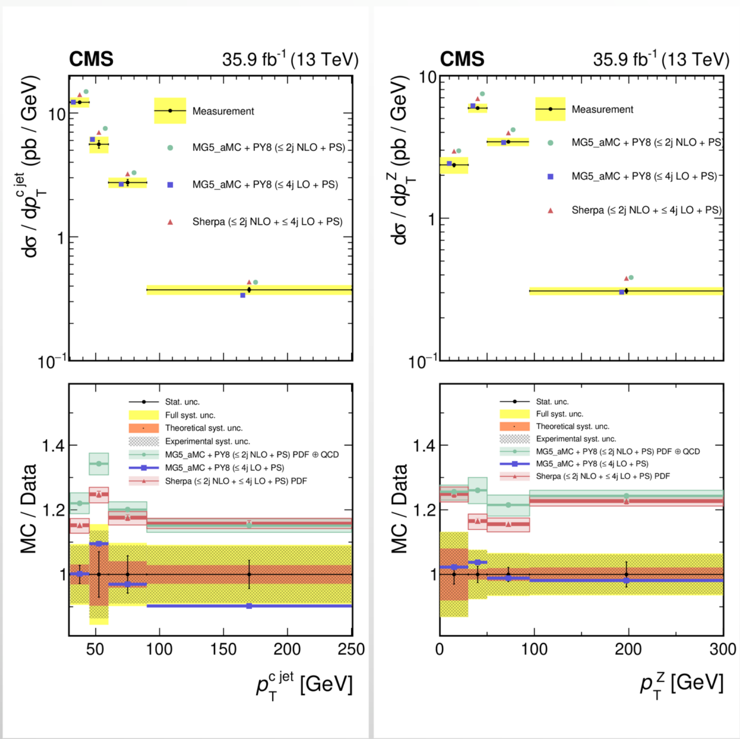
CMS-PAS-SMP-21-005, submitted to EPJC





Z+c: towards c-PDFs





One step before c-quark PDF extraction

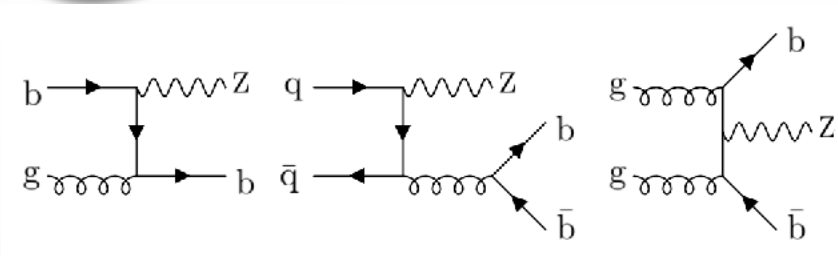
Inclusive Z+c cross-section:
405.4 ± 5.6 (stat)
± 24.3 (exp)
± 3.7 (theo) pb
MadGraph5+MCatNLO:
524.9 ± 11.7 (theo) pb

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 L0 -> PDF overestimate c-content?

JHEP04 (2021) 109
EPJC 78(2018) 287

Z+b: towards b-quarks PDFs and 4 vs 5-flavor schema



Current simulations are in NLO either in 4 or 5 FNS.

In 4 FNS b-quark does not contribute to PDF.

Massive b through gluon splitting

In 5 FNS b-quark typically massless but b contributes to PDF

CMS 137fb^{-1}

$|p_T|$>35 GeV, $p_T^{sublead}$>25 GeV

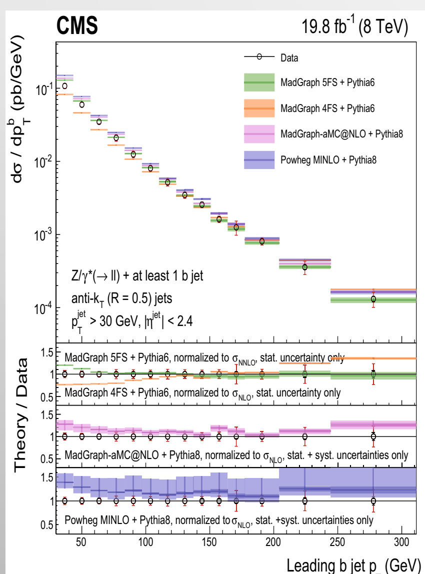
$|\eta|$<2.4, M_Z=[71-111] GeV

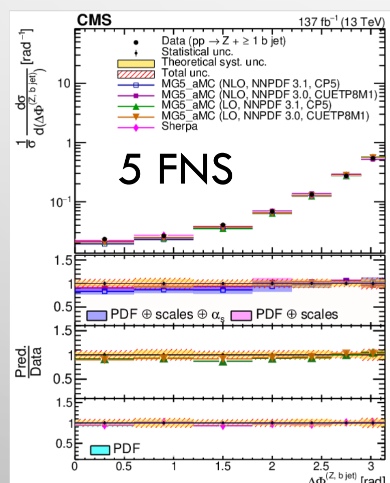
Generator b-jet p_T>30 GeV, $|\eta|$<2.4

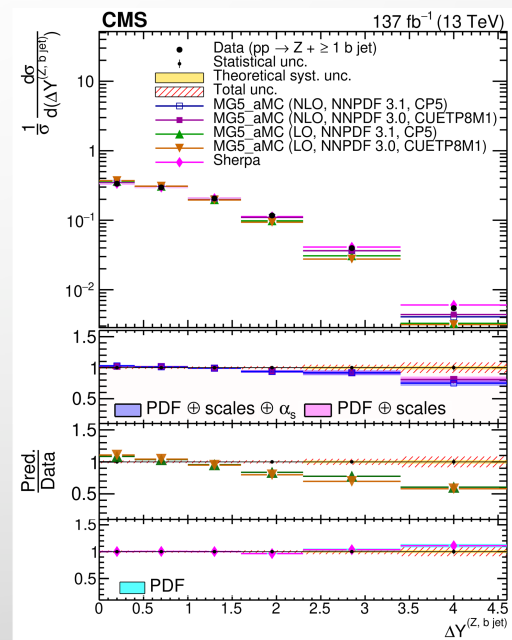
σ_{fid}(Z+>=1b) = 6.52+-0.04+-0.4+-0.014 pb

σ_{fid}(Z+>=2b) = 0.65+-0.03+-0.07+-0.02 pb

Normalized to fiducial Cross-section



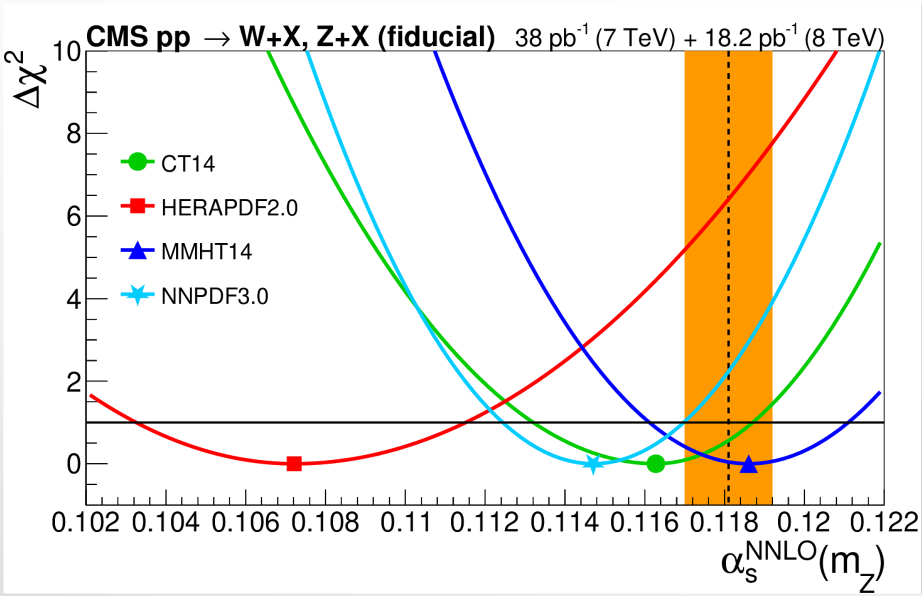


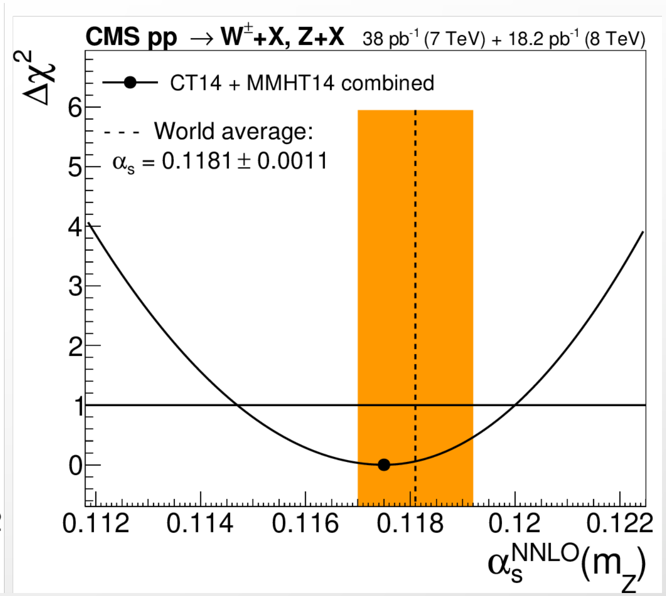


CMS: PRD 105 (2022) 092014
EPJC 77 (2017) 751

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).





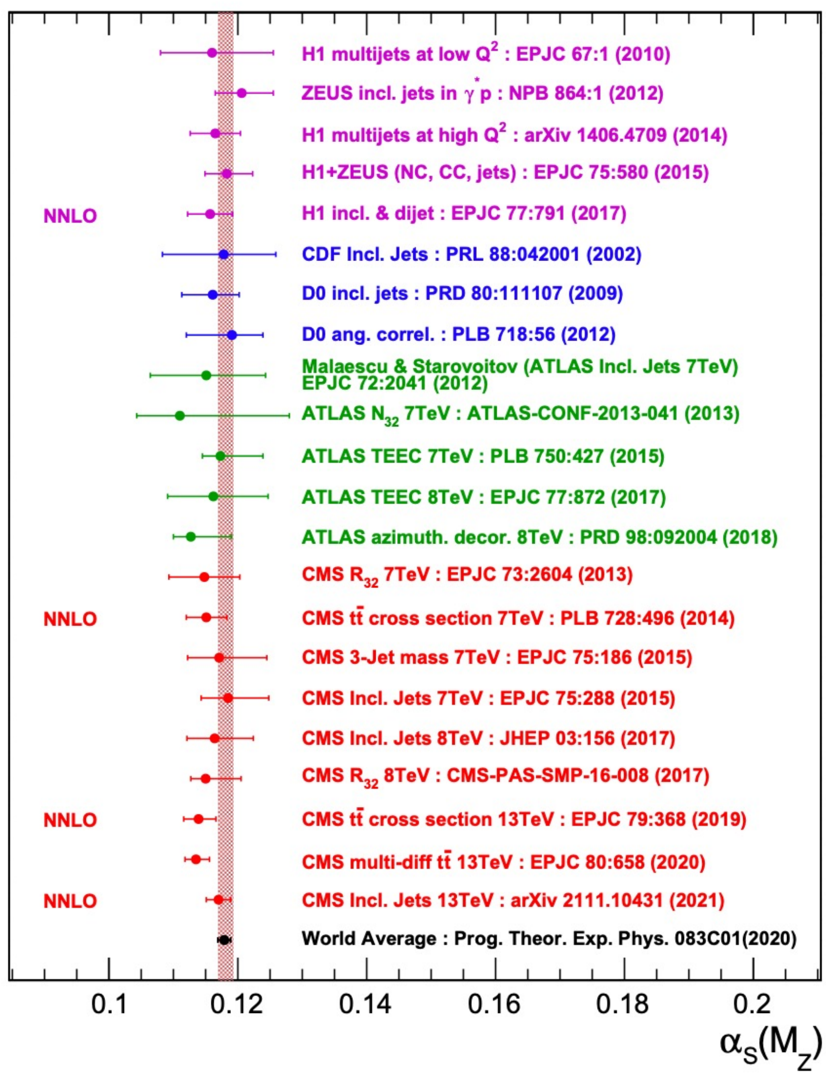
Cross-sections with CT14 and MMHT14 sets are the most sensitive to the underlying α_S value.
Robust and stable with respect to variations in the data and theoretical cross sections.
The result derived combining the CT14 and MMHT14 extractions:

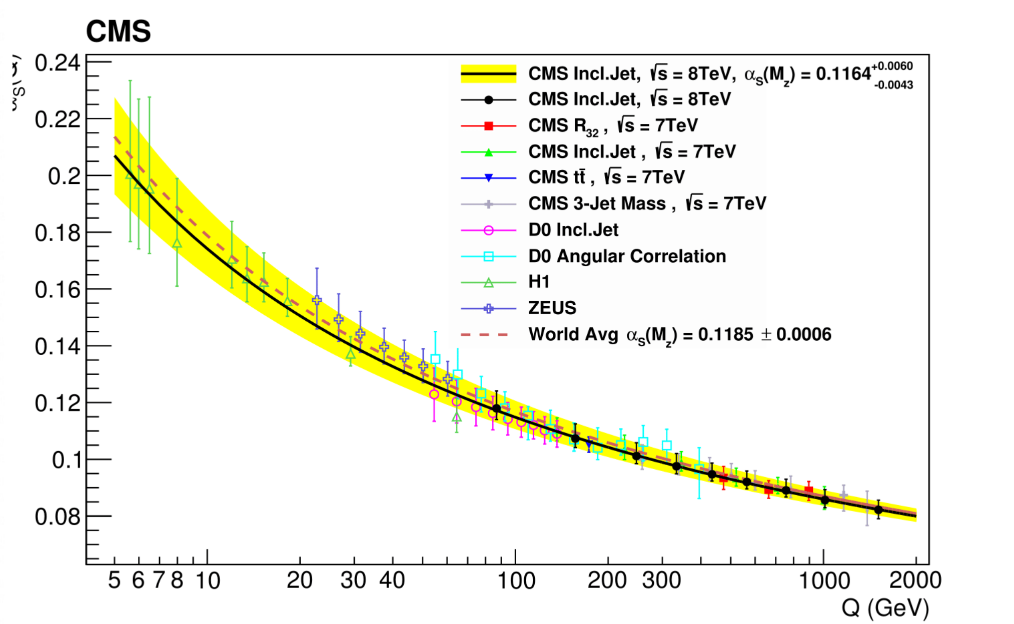
$\alpha_S(m_Z)$= 0.1175+0.0025−0.0028, has a ≈2.3%

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

JHEP 06 (2020) 018

Summary on α_S

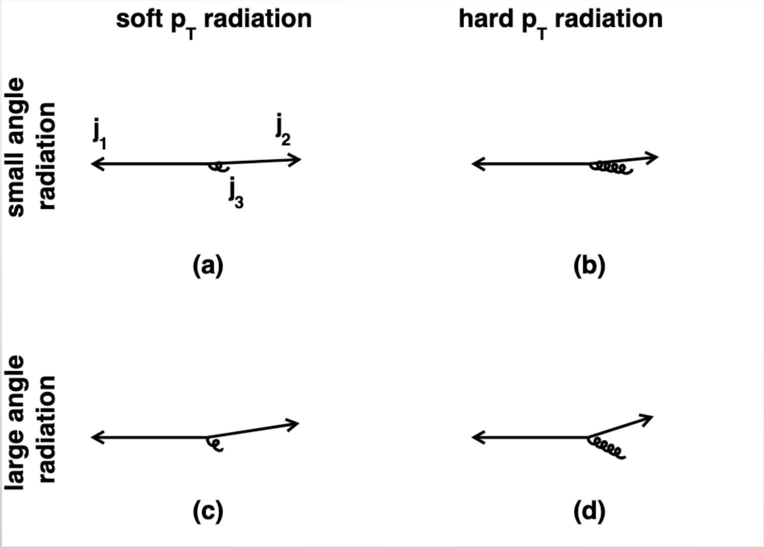




MULTI-JET CORRELATIONS

Theoretical predictions are based on

- **MATRIX ELEMENT EXPANSION AND PARTON SHOWER**
- **MULTI-PARTON INTERACTIONS AND HADRONIZATION**



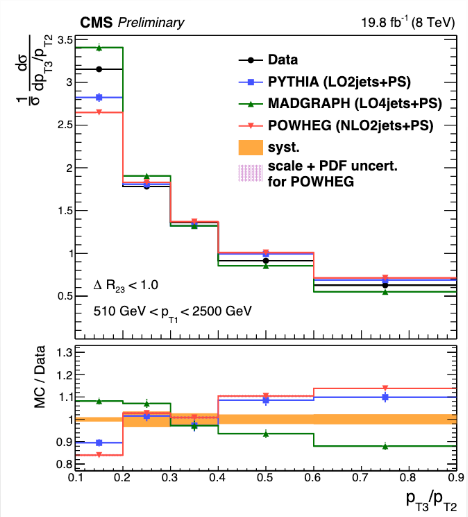
Study with 3 jets and Z+2jets events at 8 and 13 TeV

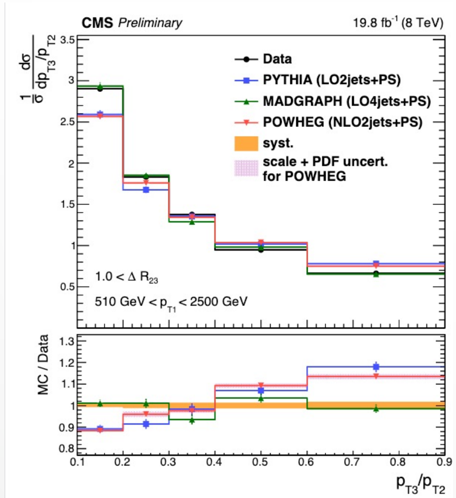
3-jet event	selection
transverse momentum of the leading jet (j_1)	$p_{T1} > 510\,\text{GeV}$
transverse momentum for each jet and rapidity for $j_{1,2}$	$p_T > 30\,\text{GeV}$, $\lvert y_{1,2}\rvert < 2.5$
azimuthal angle difference between j_1 andj_2	$2.14 < \Delta\phi_{12} < \pi$
transverse momentum ratio between j_2 andj_3	$0.1 < p_{T3}/p_{T2} < 0.9$
angular distance between j_2 and j_3	$R_{jet} + 0.1 < \Delta R_{23} < 1.5$
$Z + 2$ jet event	selection
transverse momentum of Z (j_1)	$p_{TZ} > 80\,\text{GeV}$, $\lvert y_Z\rvert < 2$
transverse momentum and rapidity for j_2	$p_{T2} > 80\,\text{GeV}$, $\lvert y_2\rvert < 1$
transverse momentum and rapidity for j_3	$p_{T3} > 20\,\text{GeV}$, $\lvert y_3\rvert < 2.4$
azimuthal angle difference between Z and leading j_2	$2 < \lvert\Delta\phi_{Z,2}\rvert < \pi$
dimuon mass	$70 < m_Z < 110\,\text{GeV}$
angular distance between j_3 andj_2	$0.5 < \Delta R_{23} < 1.5$

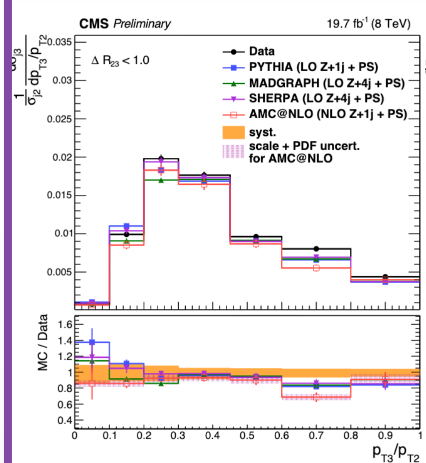
3-JET EVENTS VS Z+2JETS AT 8 TEV

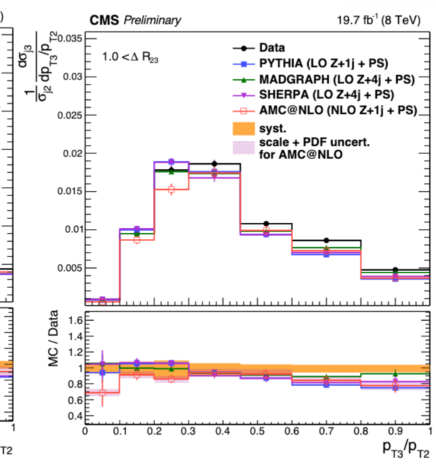
3 jets

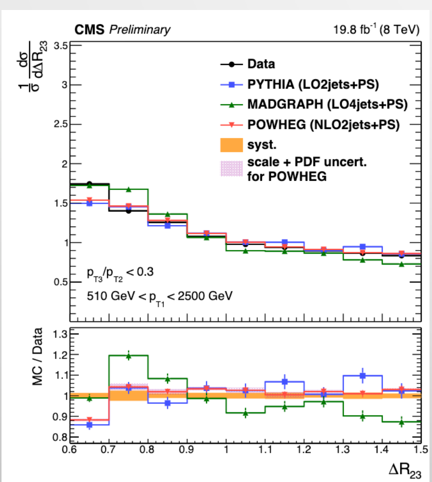
Z+jets

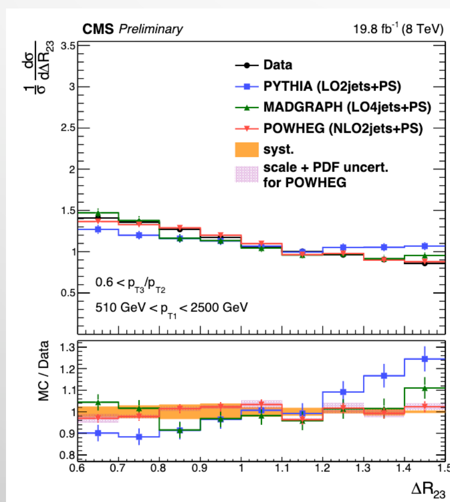


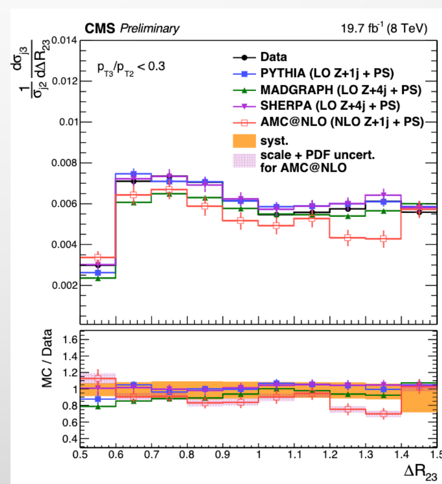


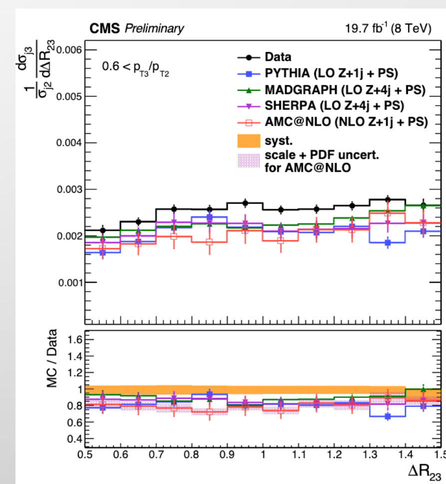












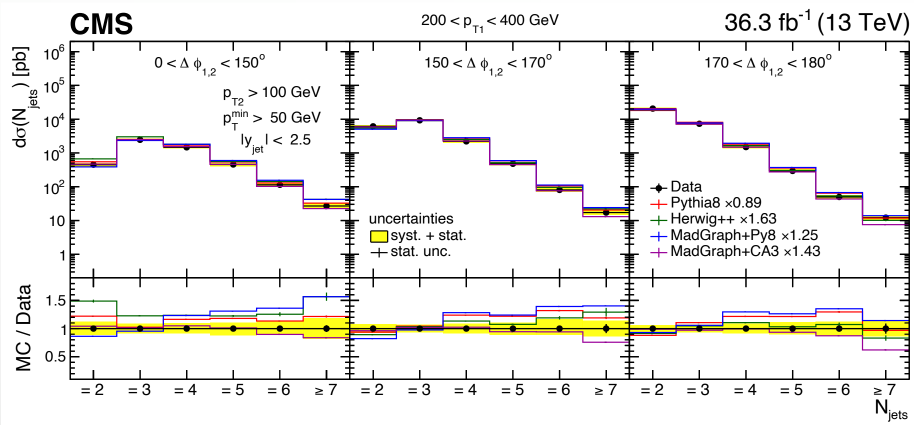
Normalization to Integral of histograms

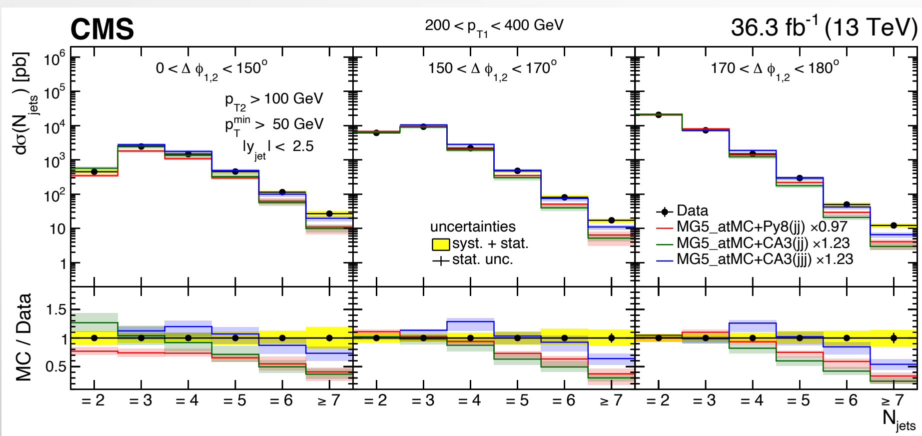
Normalization to Z+1jet events

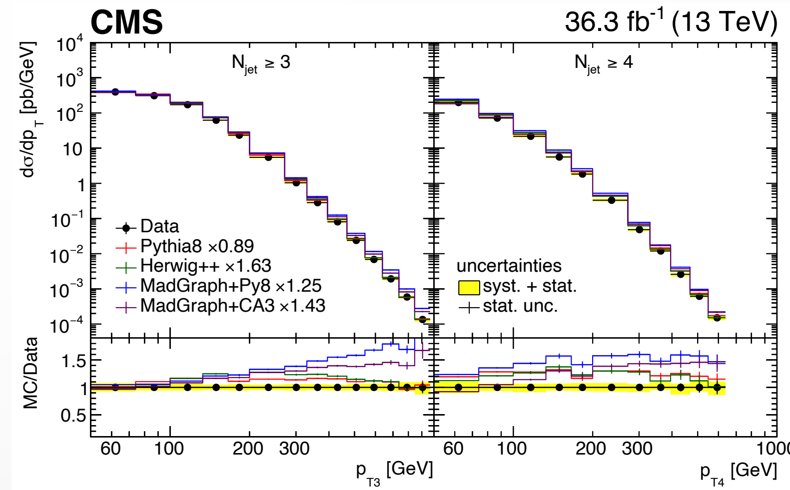
Allow to estimate the rate of 2nd jet

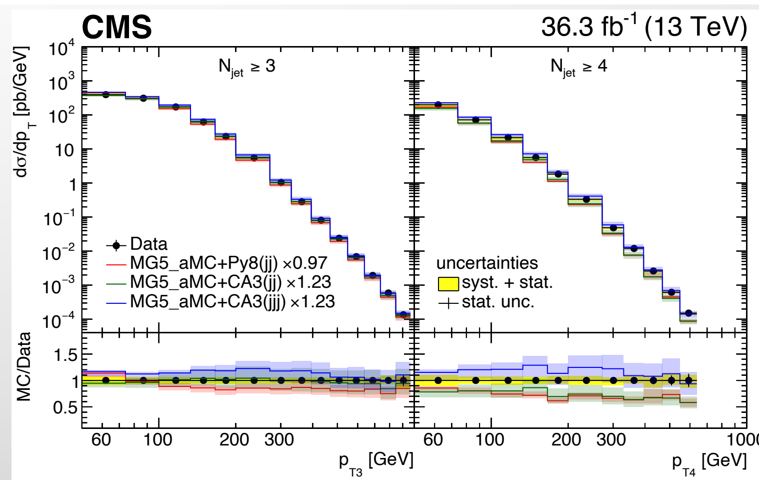
Eur. Phys. J. C 81 (2021) 852

MULTIJETS MULTIPLICITY AND PT









Stringent test of theoretical predictions.
NLO suplemented by PB-TMD and TMD
Parton shower gives better description of
Lower jet multiplicity cross-section

CMS-PAS-SMP-21-006

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.**

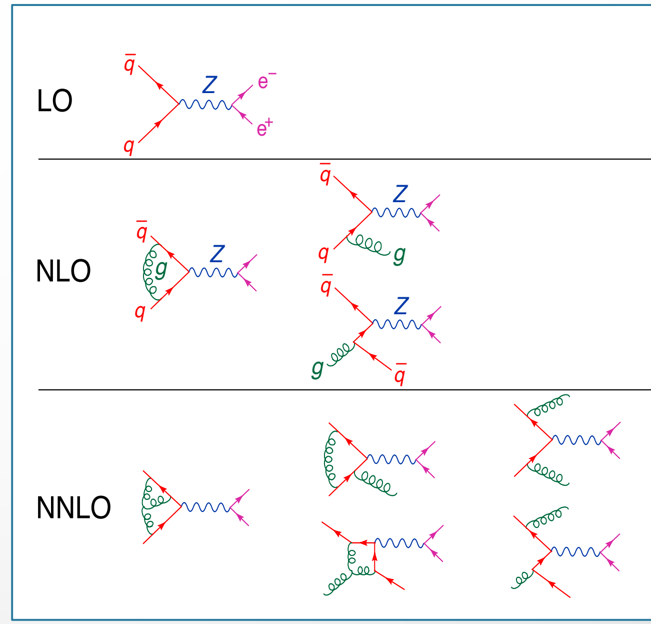
More results can be found in CMS public web page:
http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

Back-up

Perturbative QCD (pQCD)

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

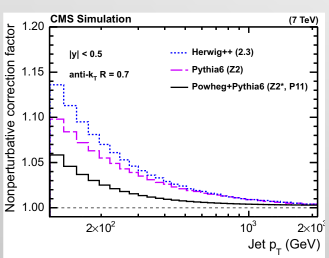
- ❑ **partially cancelled between real and virtual contributions,**
- ❑ **partially absorbed in PDFs and coupling renormalizations**



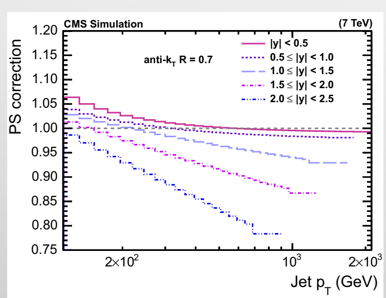
Finally, fixed order QCD calculations are matched with parton showers (PYTHIA or HERWIG) Monte-Carlo models which represent soft and collinear radiation patterns
OR in alternative approach non-perturbative and Electroweak corrections are applied as weights

NP corr PS corr EWK corr

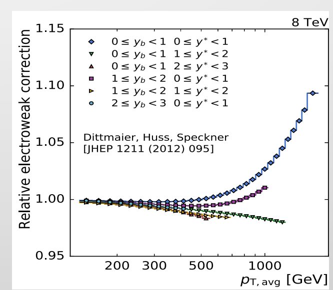
pQCD X



X



X



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

QCD Evolution equation

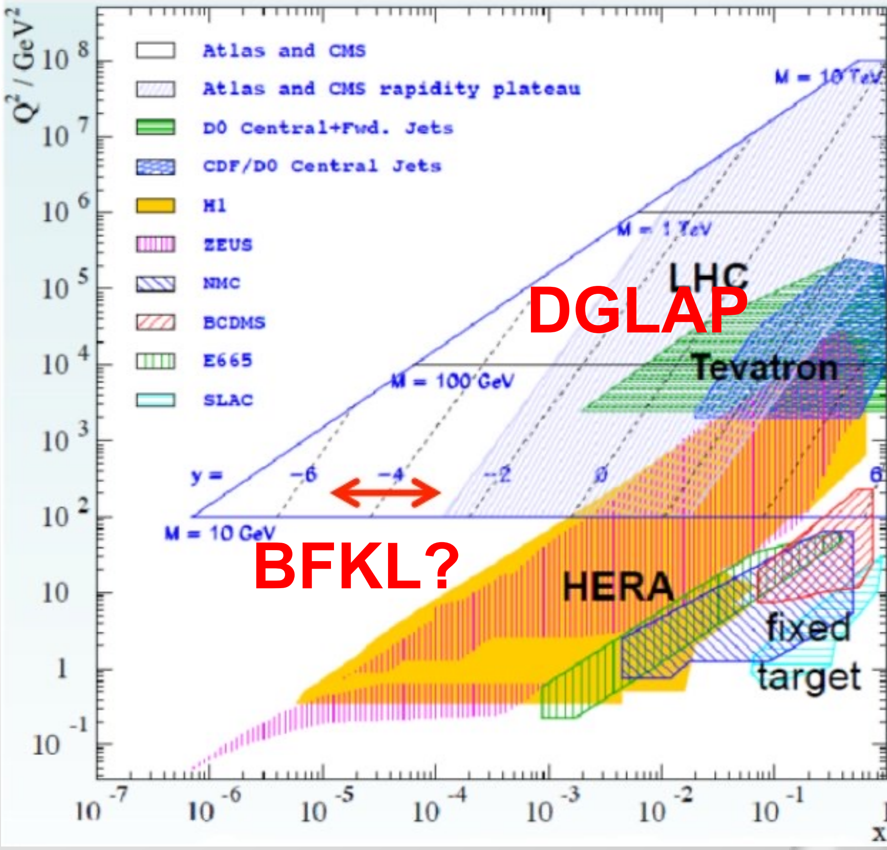
Connection between various scales in QCD (for instance, between PDF and the high-momentum scattering) is performed via evolution differential equations.

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)
- …

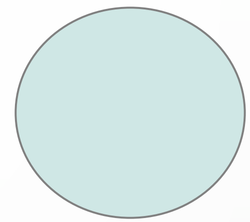
Non perturbative effects, Multi Parton Interaction (MPI) etc. models have to be tuned to data.

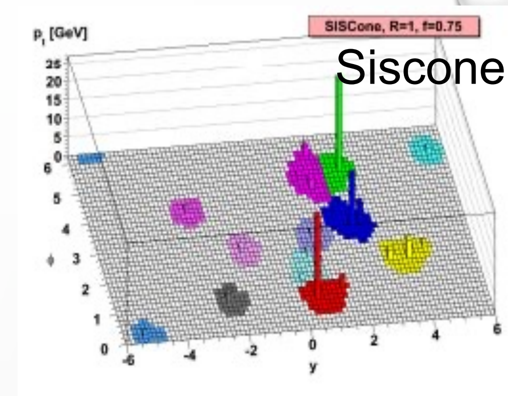


Jet clustering technique

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

Iterative cone



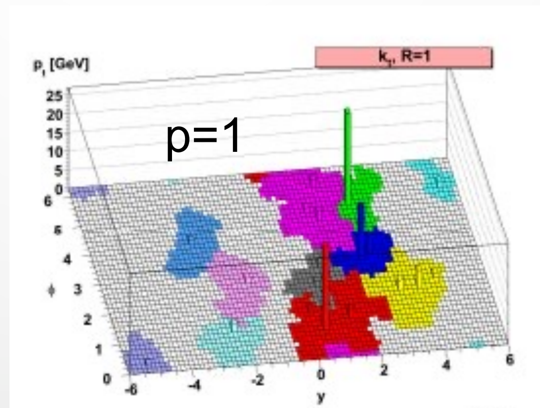


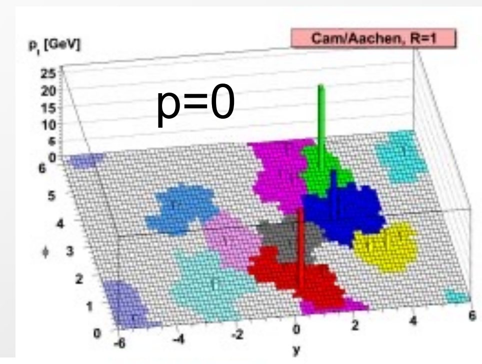
Successive recombination algorithms:

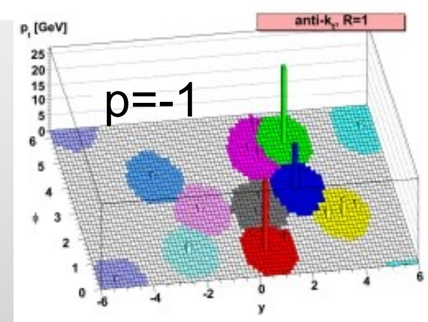
$$d_{ij} = min\left(k_{ti}^{2p}, k_{tj}^{2p}\right)\frac{\delta_{ij}^2}{R^2}$$

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

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







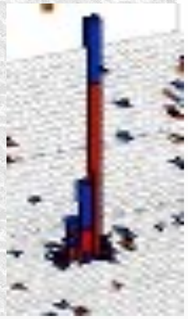
p=1 ->k_T jet algorithm
p=0 ->CA jet algorithm
p=-1 ->"Anti-k_T" jet algorithm

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

JHEP 1009 (2010) 091

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

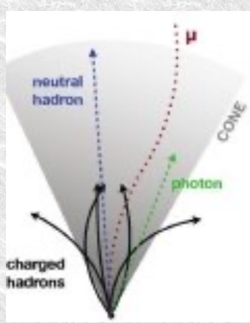
Tracker jets (TrackJets):
Jet clustered from Tracks

Subdetectors: Tracker

(ATLAS,CMS, ALICE)

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**

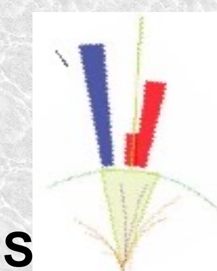


All subdetectors participate in reconstruction

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



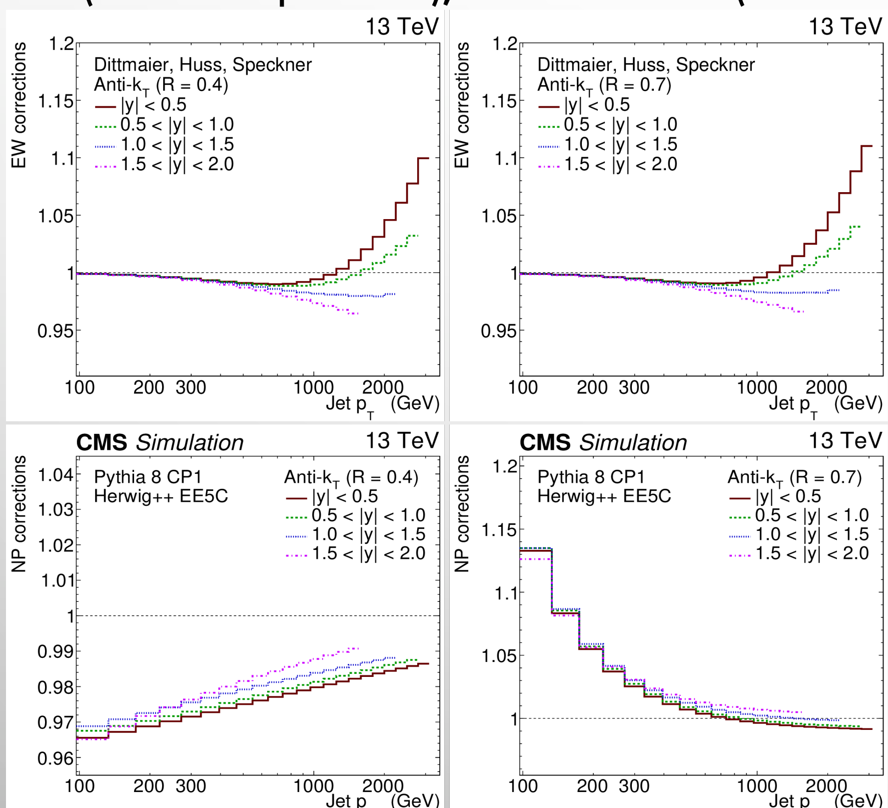
Addition to SMP-20-011 JHEP 02(2022) 142

Fixed pQCD at NLO and NNLO with NLOJet++ and NNLOJET

NLO calculation in FASTNLO. $\mu_f=\mu_R=p_{Tjet}$ (or HT)

NLO improved to NLO+NLL using MEKS

PDF sets: CT14, NNPDF 3.1, MMHT2014 (includes 7 TeV ATLAS and CMS jet data), ABM16 (no 7 TeV jet data), HERAPDF 2.0 (HERA DIS only)



EWK Corrections

At NLO accuracy

NP corrections:

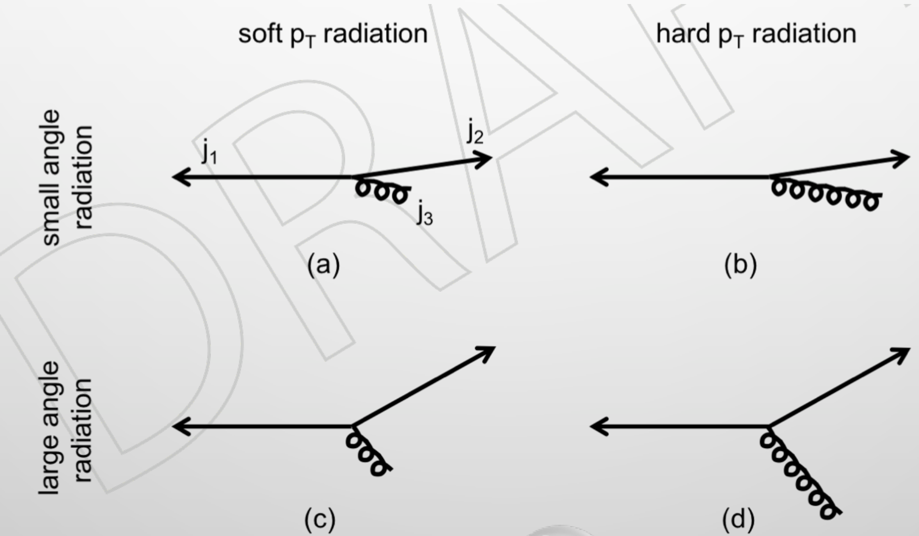
PYTHIA 8 CP1 tune

HERWIG++ EEC5 tune

Multi-jet correlations

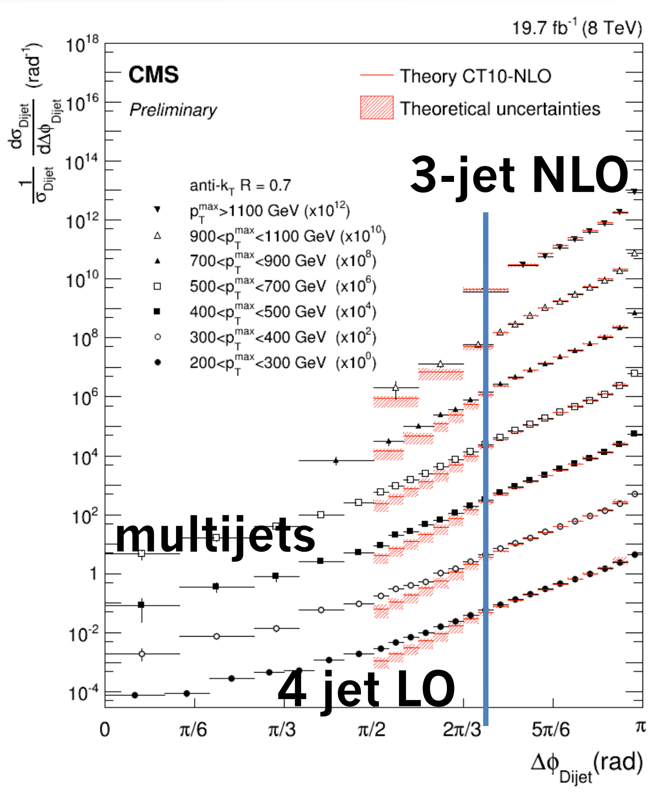
Theoretical predictions are based on

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

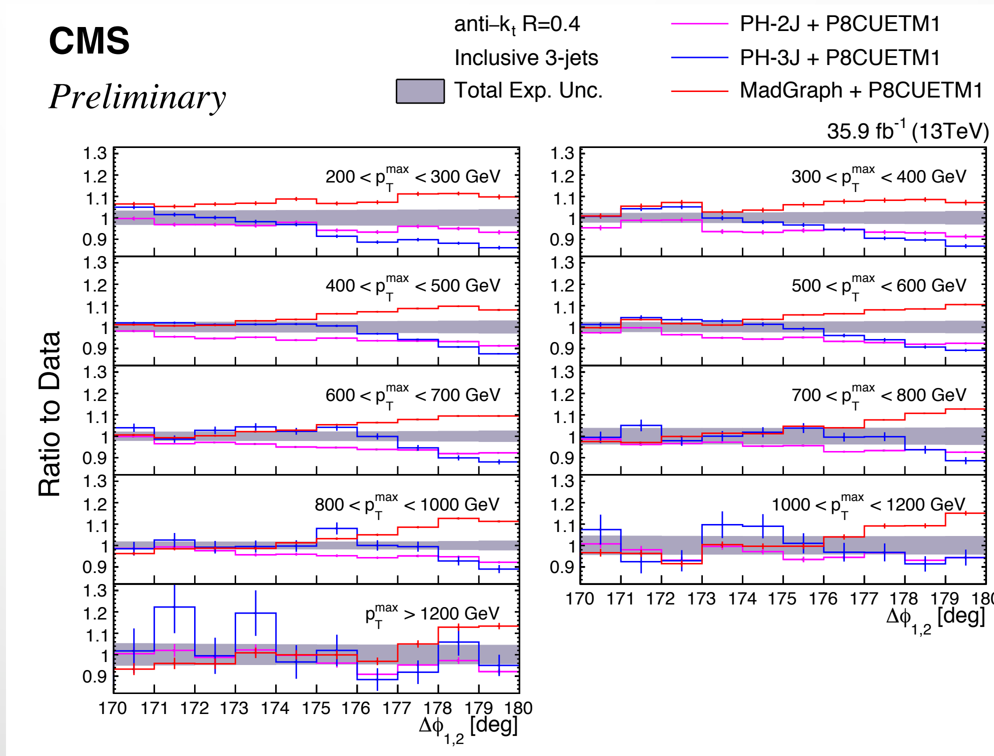


Azimuthal decorrelations

$\Delta\phi_{jj}$ 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



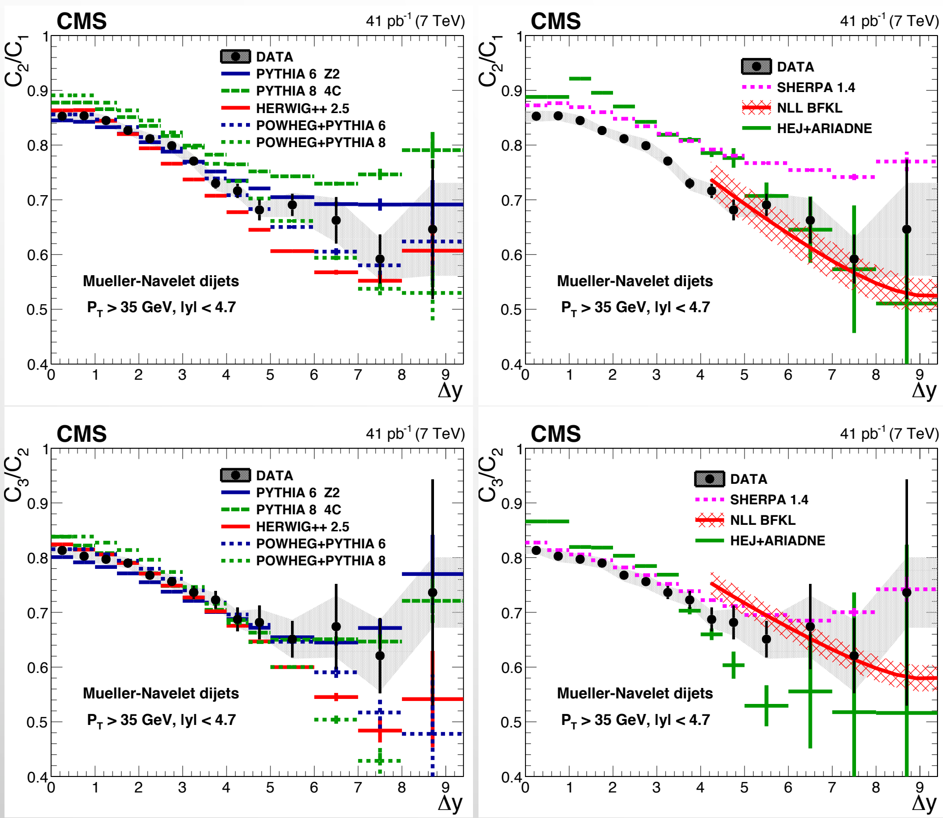
Comparison is done with fixed-order pQCD (NLO) and with LO ME+PS

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

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

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



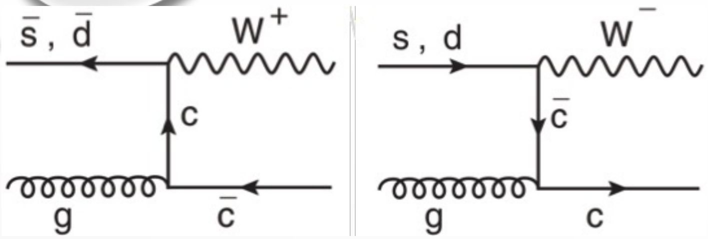
$C_n(\Delta y, p_{Tmin}) = \langle \cos(n(\pi - \Delta\phi)) \rangle$

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

JHEP08(2016)139

W+c: strange quark PDF



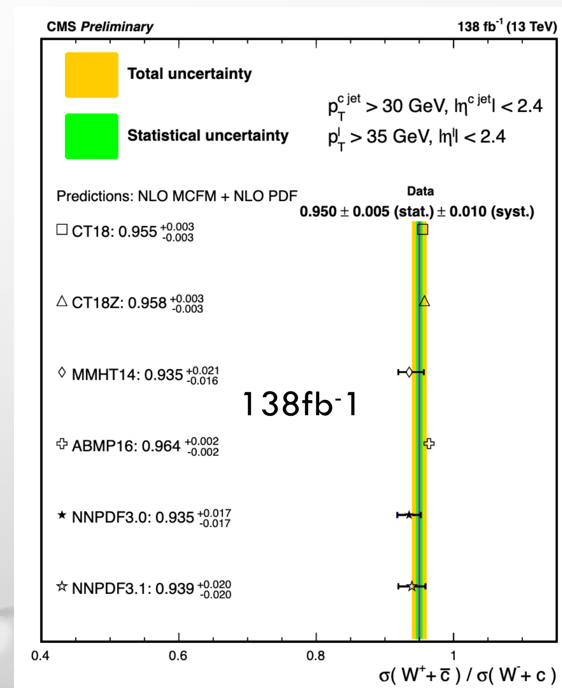
$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

From neutrino scattering Rs=0.5
At Q2=1.9 GeV2 strange
sea-quark density is suppressed

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

CMS-PAS-SMP-21-005

13 TeV (CMS, 36 fb^{-1}):
σ (W + c) = 1026 ± 31 (stat) ± 72 (syst) pb



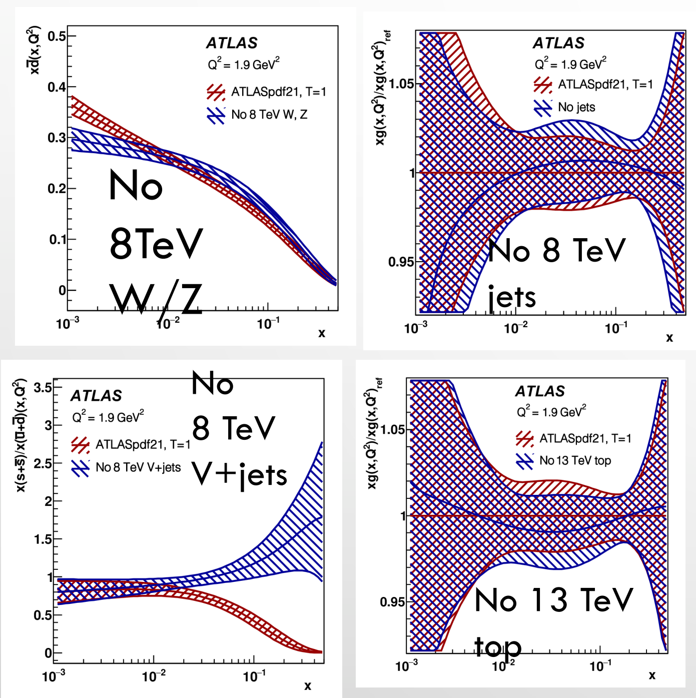
$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

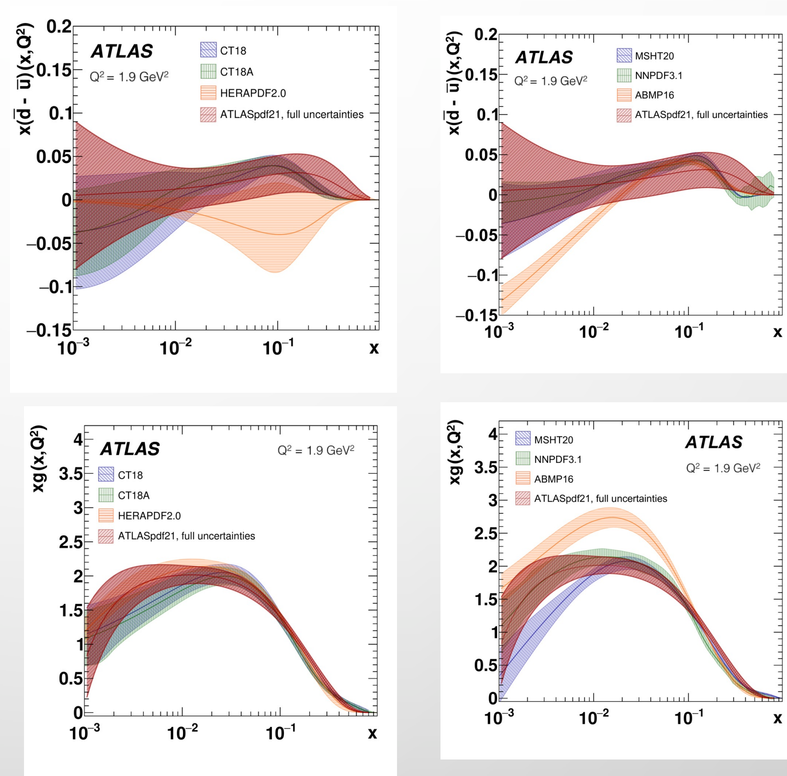
EPJC 79 (2019) 269

PDF global fit

7, 8, 13 TeV with 5, 20, 36 fb^{-1}

Differential cross-section if inclusive W+-, Z/γ* and W+-.Z+jets, ttbar, inclusive jets, direct Photons; DGLAP evolution is used

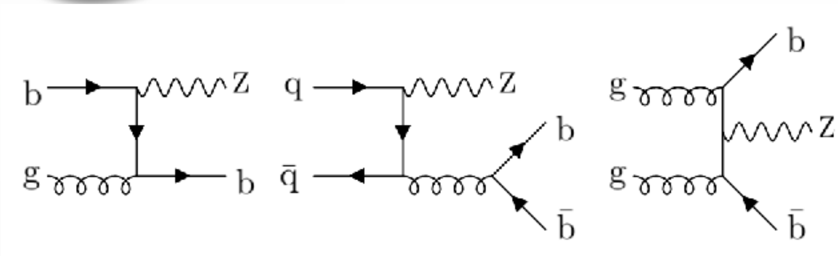




Resulting pdf set: ATLASpdf21

ATLAS: EPJC 82(2022) 438

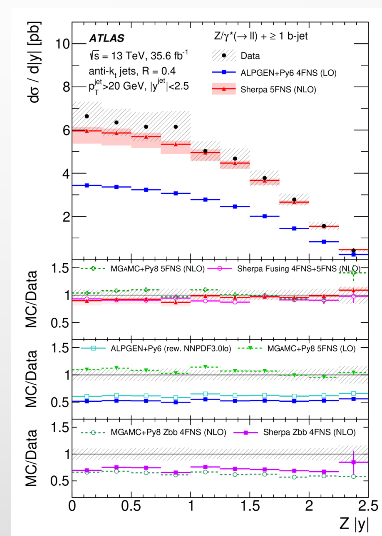
Z+b: towards b-quarks PDFs and 4 vs 5-flavor schema

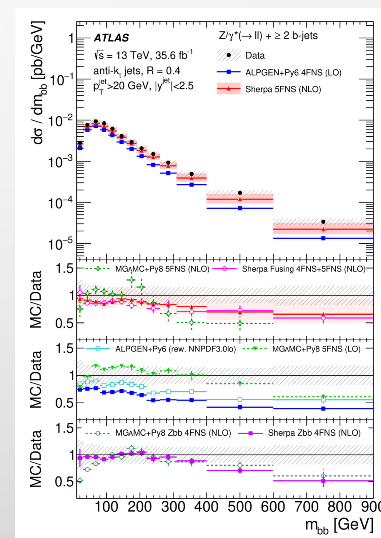


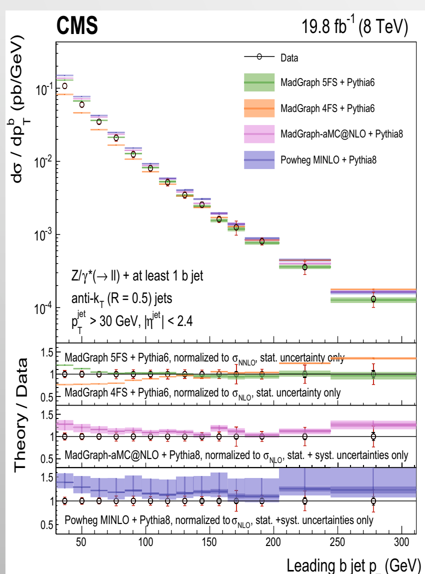
Current simulations are in NLO either in 4 or 5 FNS.
In 4 FNS b-quark does not contribute to PDF.
Massive b through gluon splitting
In 5 FNS b-quark typically massless but b contributes to PDF

CMS 137fb^{-1}
$|p_T|>35$ GeV, $p_T^{sublead}>25$ GeV
$|\eta|<2.4$, $M_Z=[71-111]$ GeV
Generator b-jet $p_T>30$ GeV, $|\eta|<2.4$
$\sigma_{fid}(Z+>=1b) = 6.52+-0.04+-0.4+-0.014$ pb
$\sigma_{fid}(Z+>=2b) = 0.65+-0.03+-0.07+-0.02$ pb

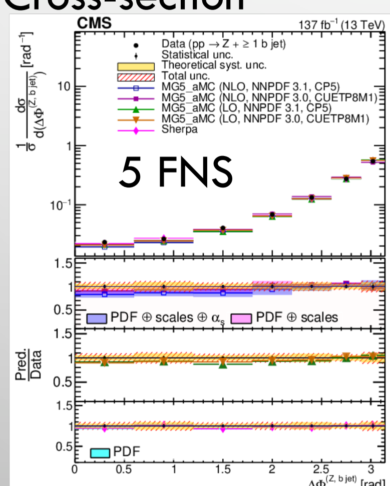
ATLAS 35.6 fb^{-1}







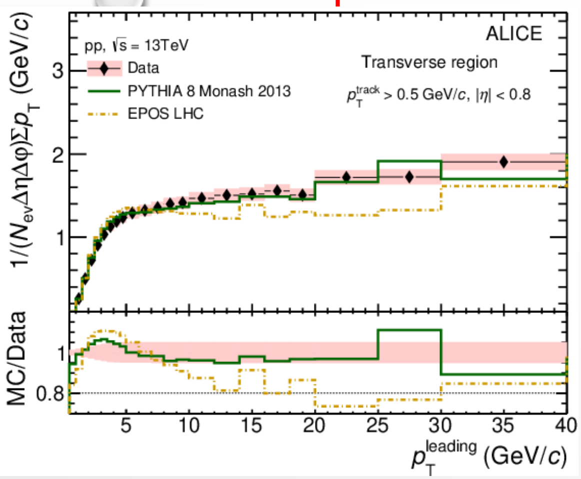
Normalized to fiducial Cross-section



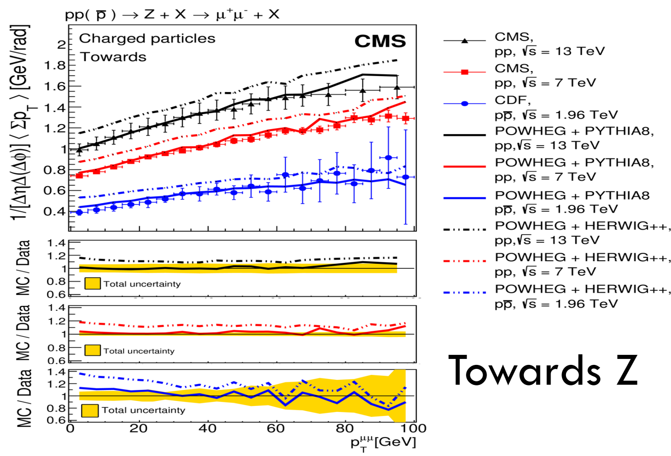
ATLAS: PRD2022 (submitted) – high-p_T b-quark
JHEP07 (2020)44
CMS: PRD 105 (2022) 092014
EPJC 77 (2017) 751

Underlying events

High p_T track
or Tracker jets

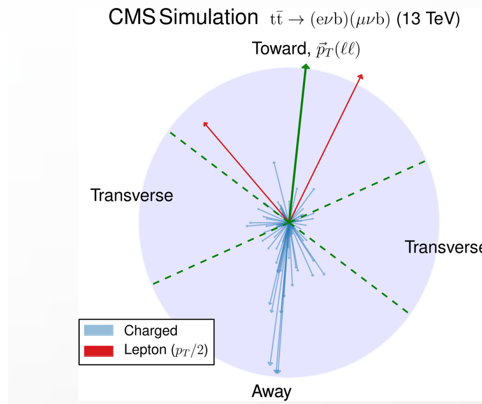


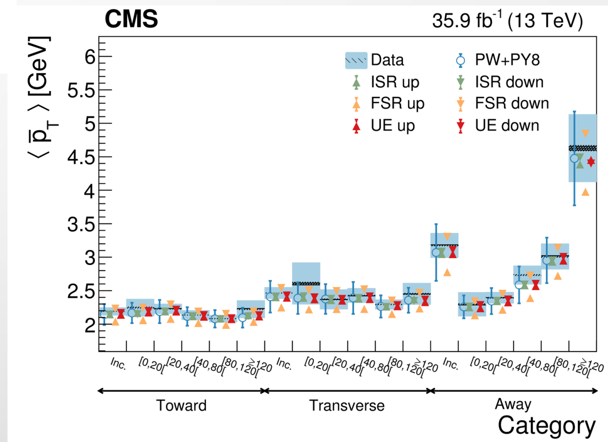
Z+jets

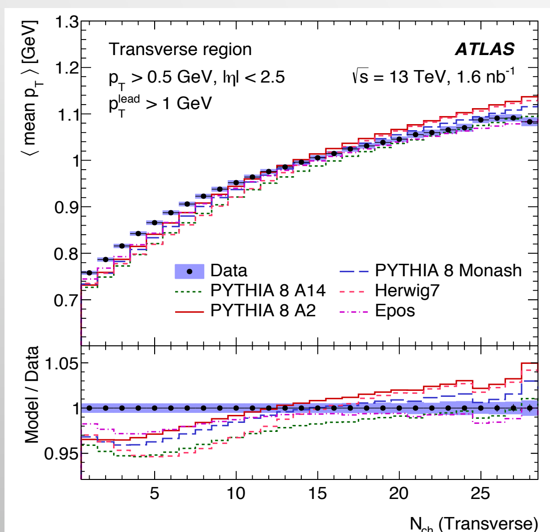


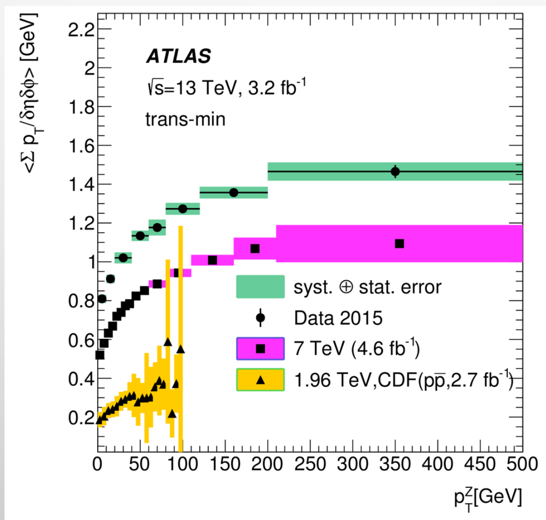
Towards Z

ttbar events







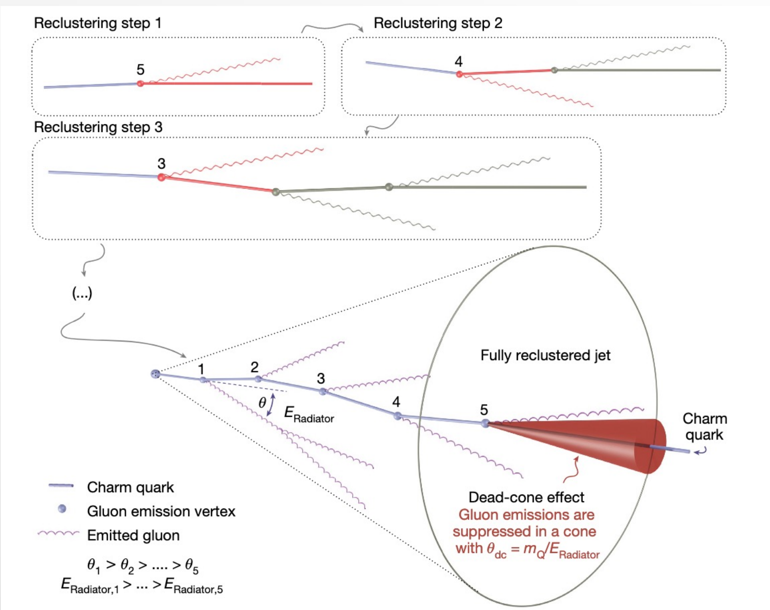


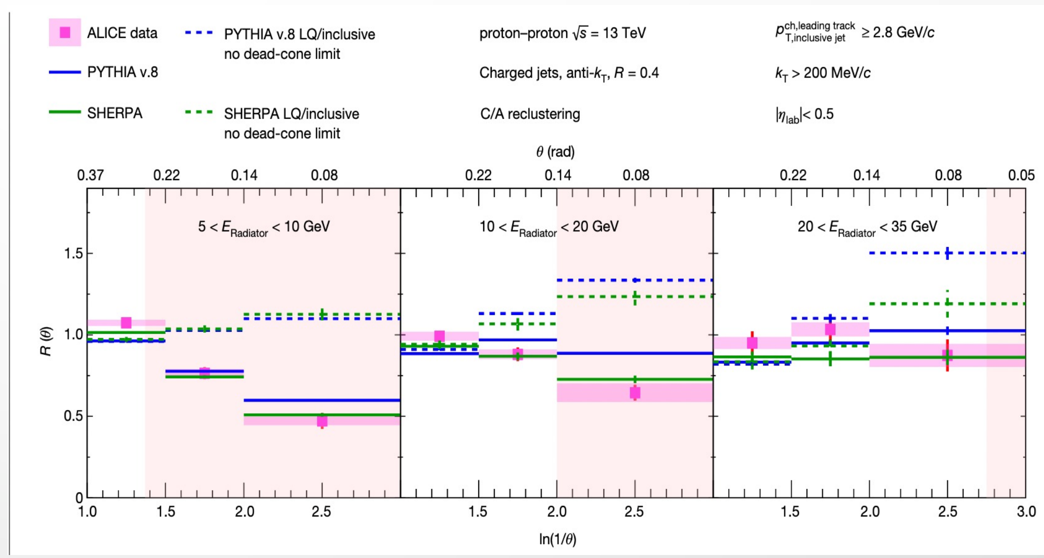
JHEP 07 (2018) 032
EPJC 79 (2019) 123
JHEP 09 (2015) 137
JHEP 03 (2017) 157
EPJC 79 (2019) 666
JHEP04 (2020) 192

Dead cone effect for heavy quarks

- J. Physics G: *Nucl. Part. Phys.* **17** 1602: dead cone in soft gluon radiation by heavy quark.

The dead cone size depends on m/E





$$R(\theta) = \frac{1}{N^{D^0 \text{ jets}}} \frac{dn^{D^0 \text{ jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \Bigg|_{k_T, E_{\text{Radiator}}}$$

First direct observation of the dead cone effect.

ALICE: Nature volume 605, p. 440–446 (2022)