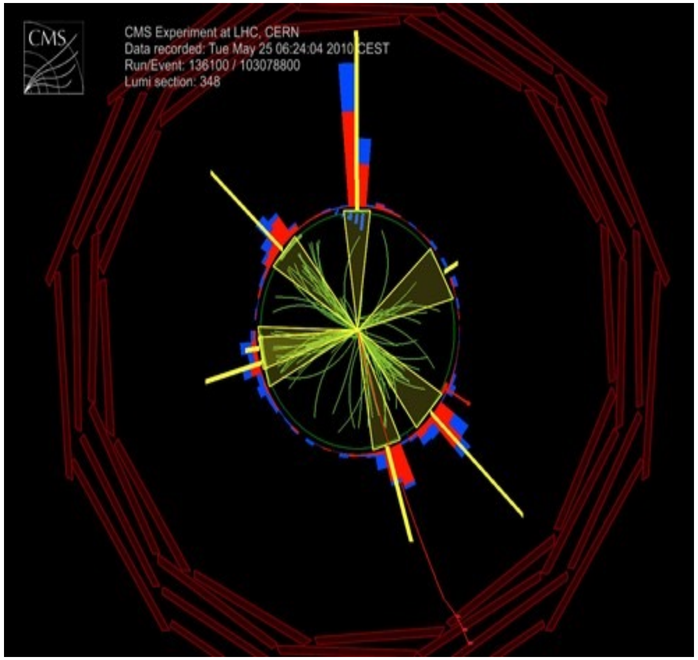
QCD Physics with ATLAS, ALICE and CMS detector



Olga Kodolova, SINP MSU and JINR

(on behalf of ATLAS, ALICE and CMS collaboration)

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

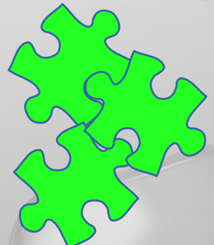
- QCD defines the hadronization process of partons whatever interaction mediator is in the hard production vertex

What we study:

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

How do we proceed?

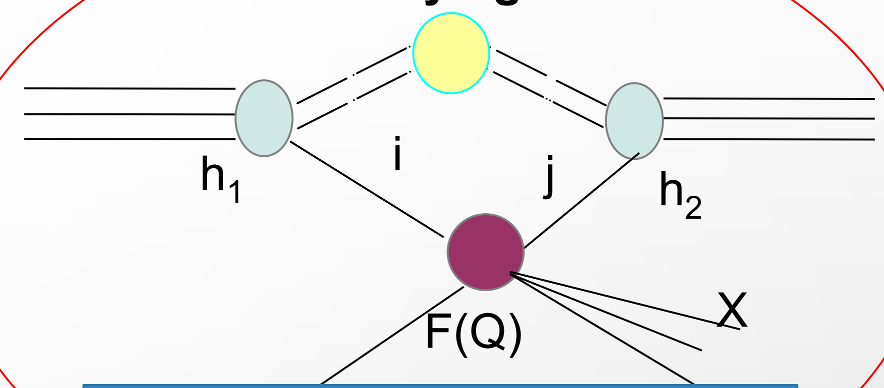
Practically,
we collect puzzles!



Some definitions

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**

Soft underlying event



Hard interaction: production of the high-p_T objects

$p_1 = x_1 P_1$

$p_2 = x_2 P_2$

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)

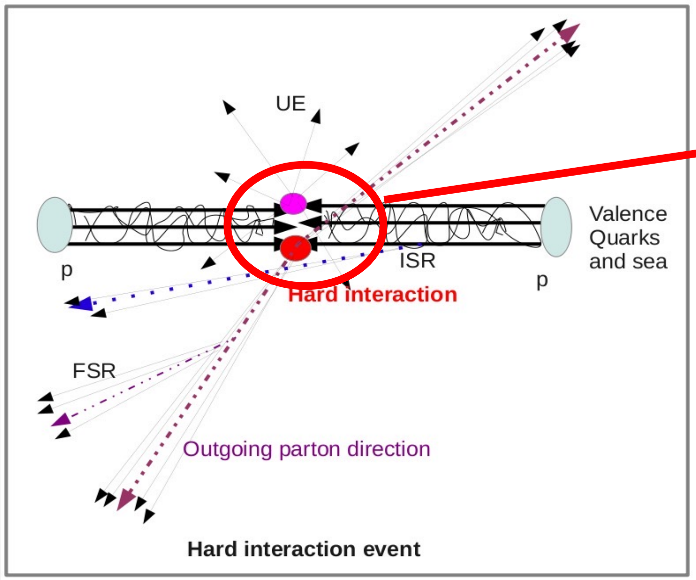
Partonic cross-section computed in pQCD

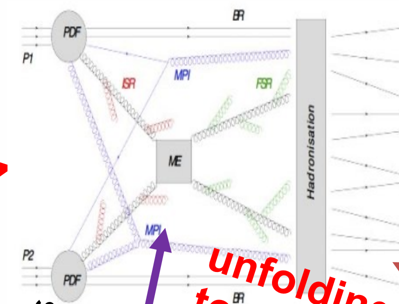
$$\hat{\sigma}_{ij} = \alpha_S^k \sum_n \left(\frac{\alpha_S}{\pi}\right)^n \sigma_{ij}^n$$

Fixed order pQCD

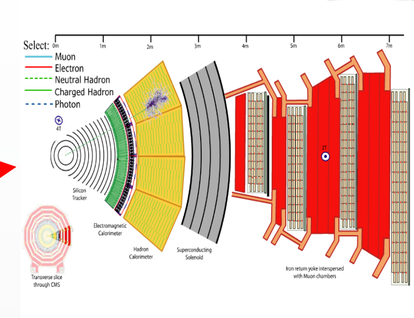
Soft interaction: production of the low-p_T hadrons

How do we proceed





particles



unfolding
towards particles level

propagation
towards particles
level

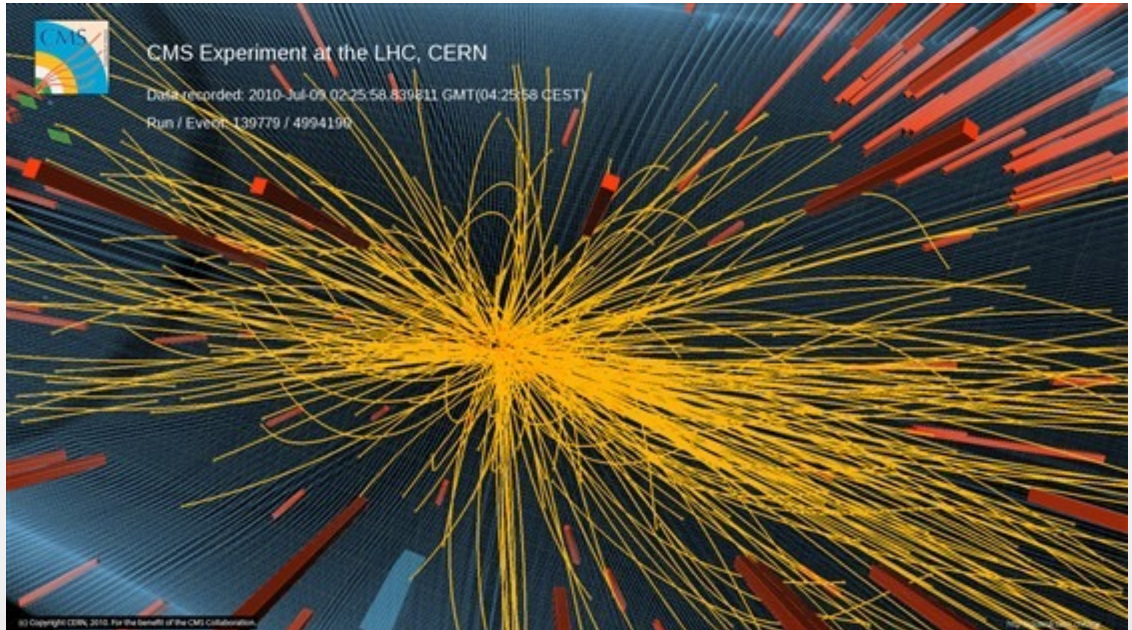
Incorrect task

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

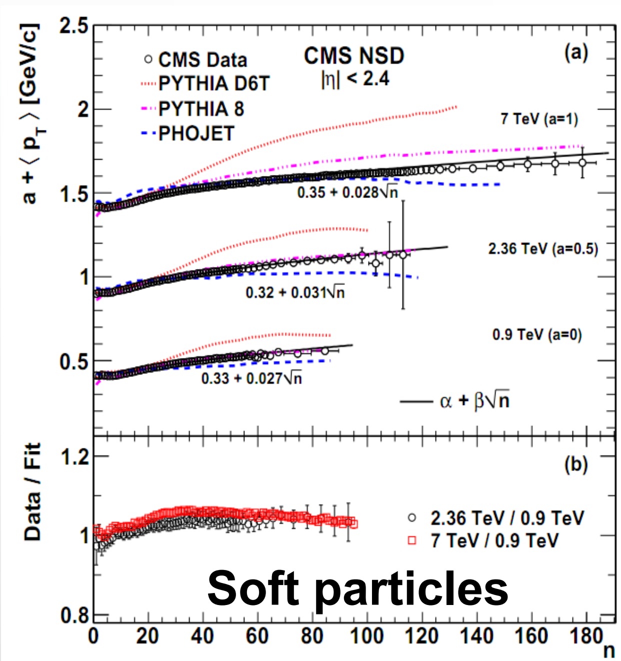
Theory blocks:
- Perturbative QCD (pQCD):
LO, NLO, NNLO calculations: ME + parton showering (PS), threshold resummation
- non-pQCD: (Multi-parton interactions (MPI), String/Cluster fragmentation models)

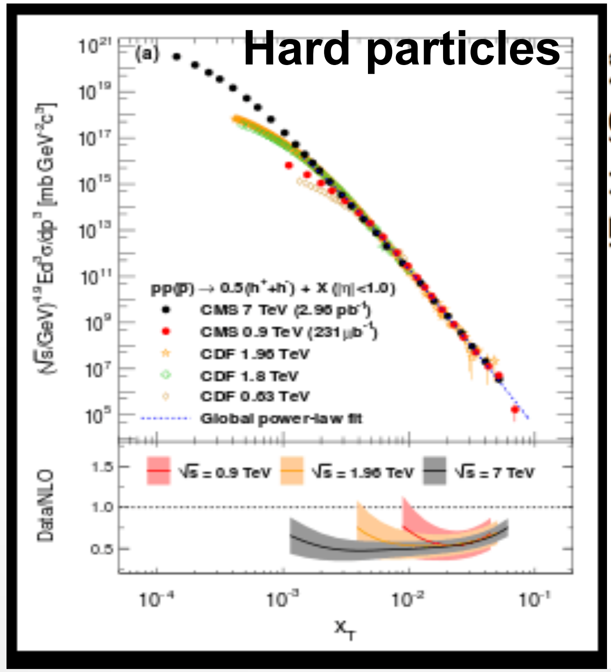
Soft particle production

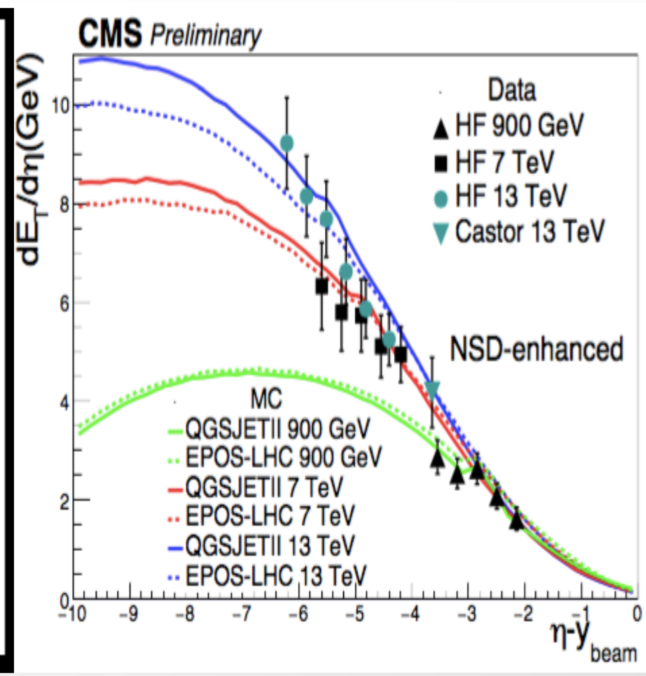


Charged particle multiplicity
Scaling, correlations
Underlying event

p_T & x_T & limiting fragmentation







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

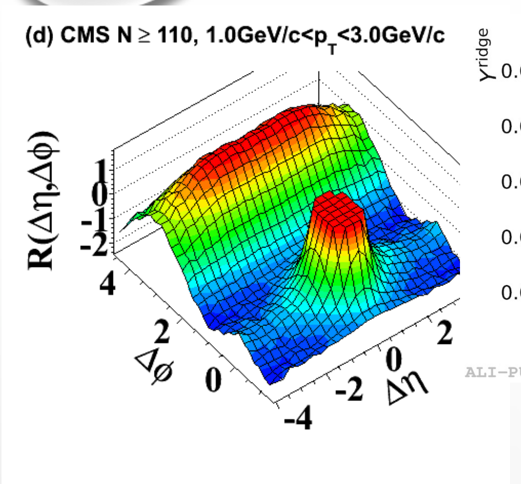
The CMS results are consistent with $x_T=2p_T/\sqrt{s}$ scaling (pQCD prediction) with exponent N=4.9 +- 0.1

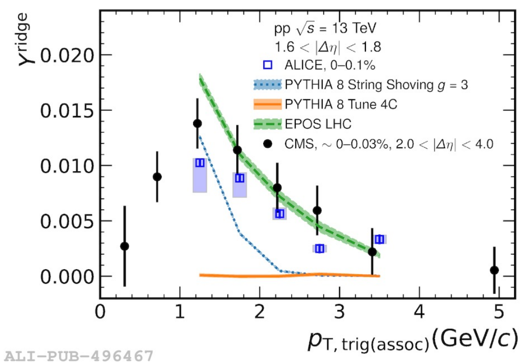
Consistent with the hypothesis of limiting fragmentation: production of forward particles is independent on collision energy

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 - I

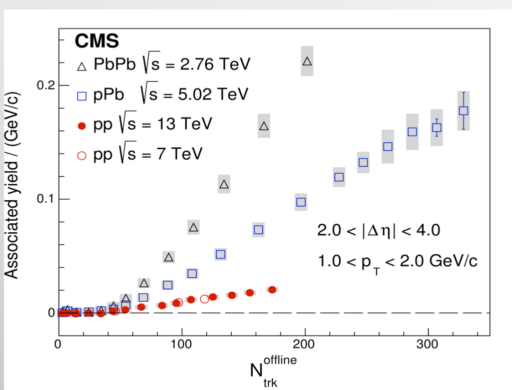


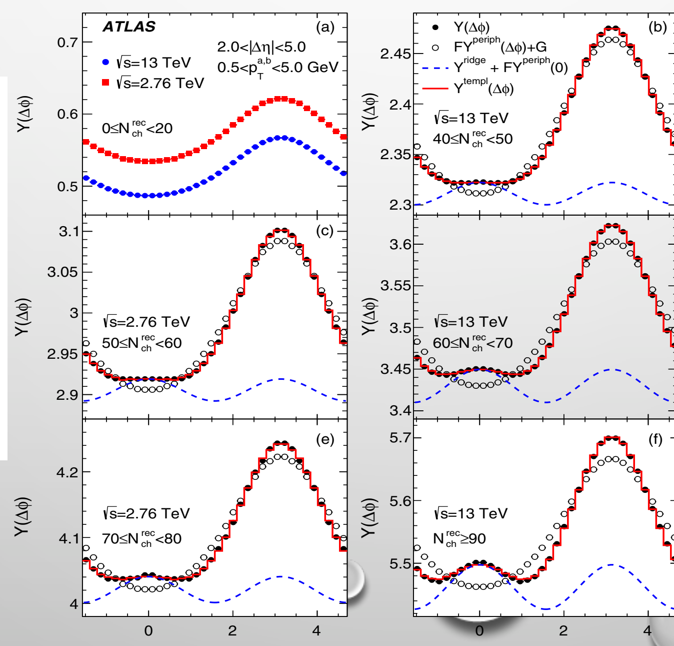


Qualitatively described effect:
PYTHIA8 string shoving:
interacting strings
EPOS LHC:
hydrodynamical evolution
Of high-density core (formed by color
String fields)

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

Ridge at $\Delta\phi \sim 0$ and large $\Delta\eta$ at high multiplicity in pp events at intermediate p_T





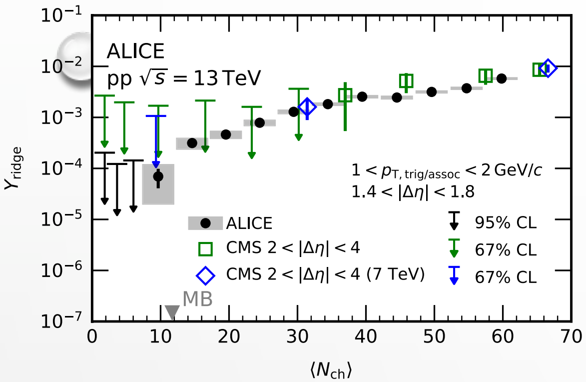
$$R(\Delta\eta,\Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

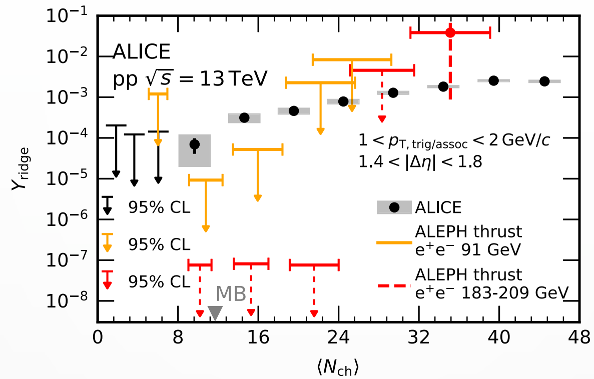
$$B_N(\Delta\eta,\Delta\phi) = \frac{1}{N^2}\frac{d^2N^{\text{mixed}}}{d\Delta\eta d\Delta\phi}$$

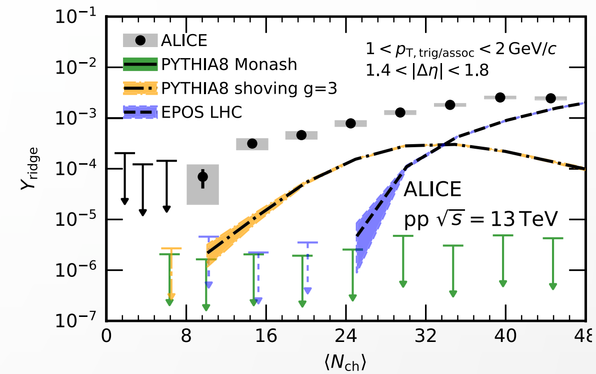
$$S_N(\Delta\eta,\Delta\phi) = \frac{1}{N(N-1)}\frac{d^2N^{\text{signal}}}{d\Delta\eta d\Delta\phi}$$

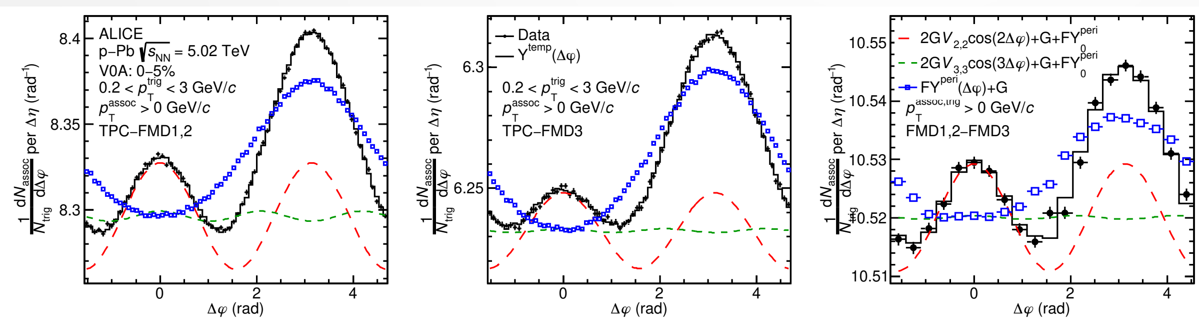
PRL 116,172301(2016)
PRL 116,172302(2016)
JHEP05 (2021), 290

Long-range correlations - II

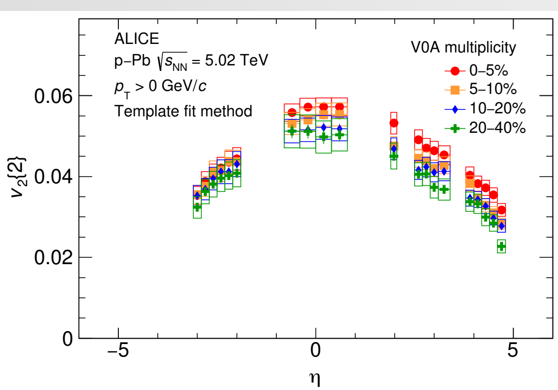


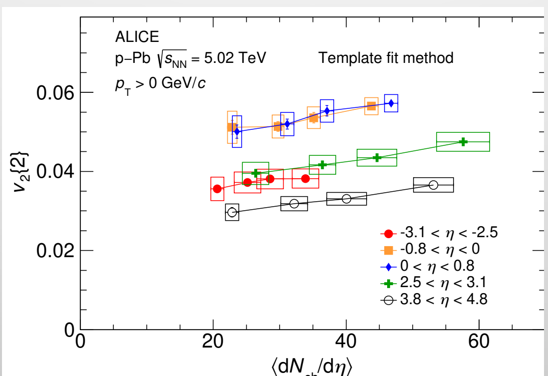






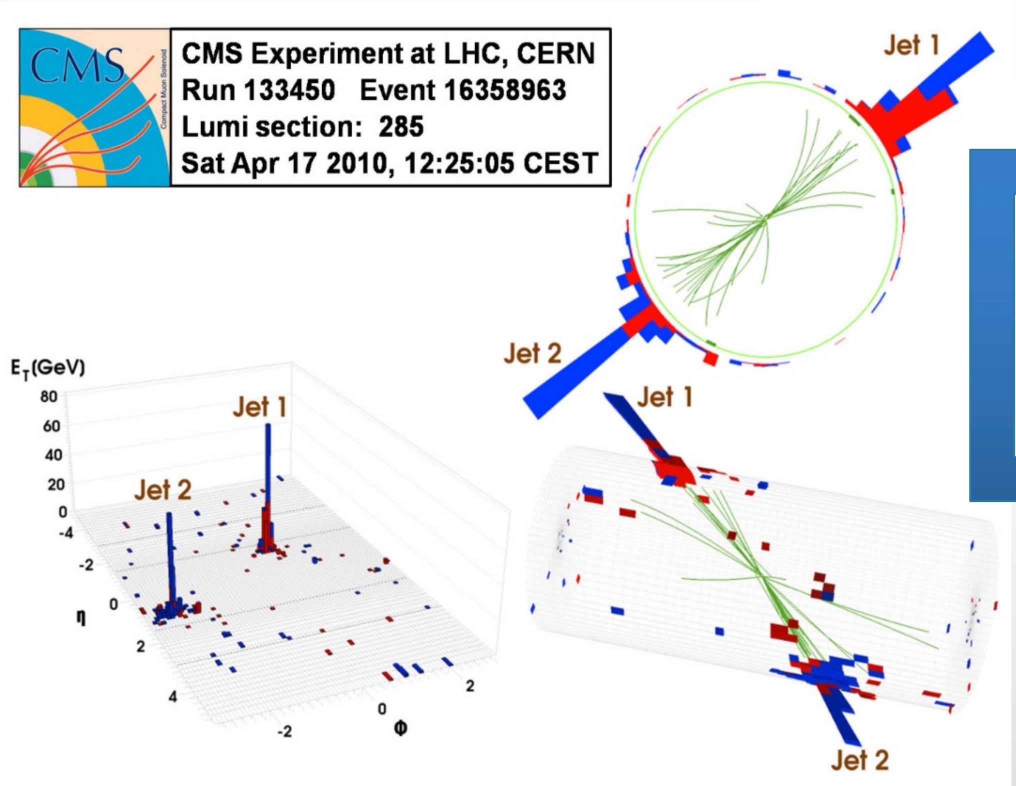
The “ridge” structure is observed up to a rapidity gap of 8 units between the trigger and the associate particles, in central events.





PRL 132(2024)172302
JHEP 01(2024) 199

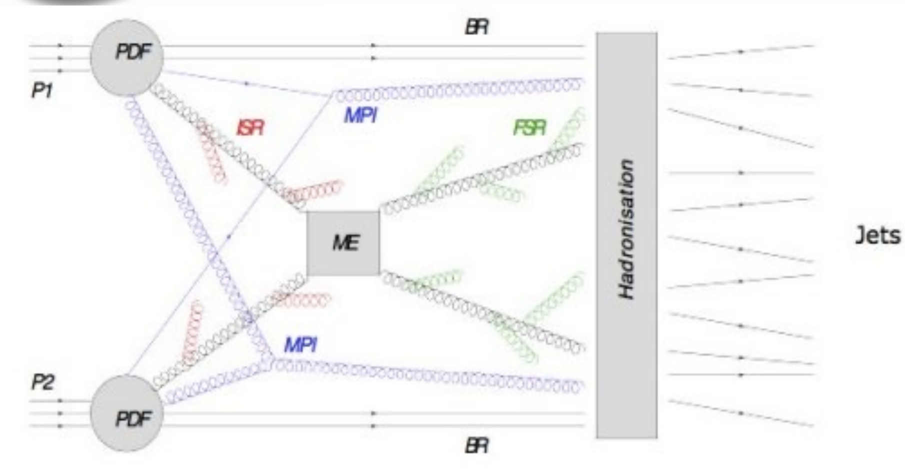
Hard interactions

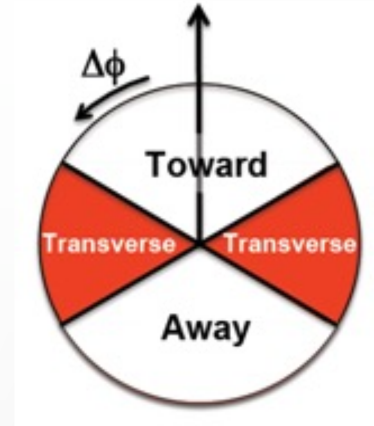


PDFs and α_S measurement

- **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

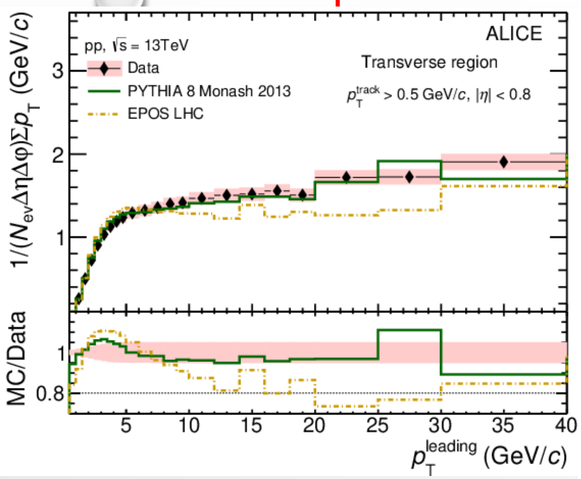
UE activity is typically studied in the transverse region in pp collisions as a function of the hard scale of the event, and at different centre-of-mass energies (√s):
Particle production in MinBias events or events with high energy track or jet (hadronic events)
Drell-Yan events, Top events (new)

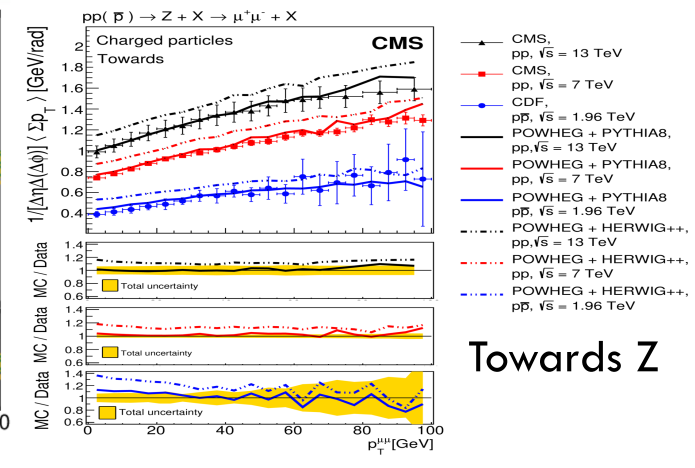
Underlying events

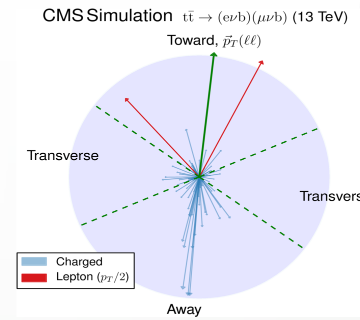
ttbar events

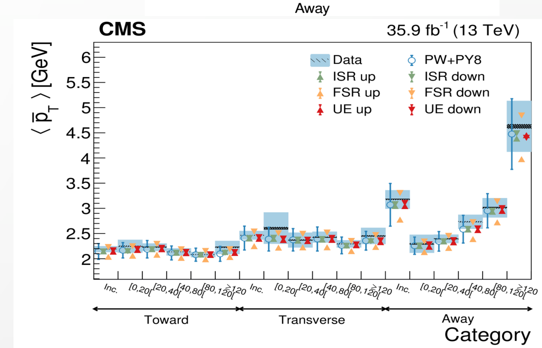
High p_T track or Tracker jets

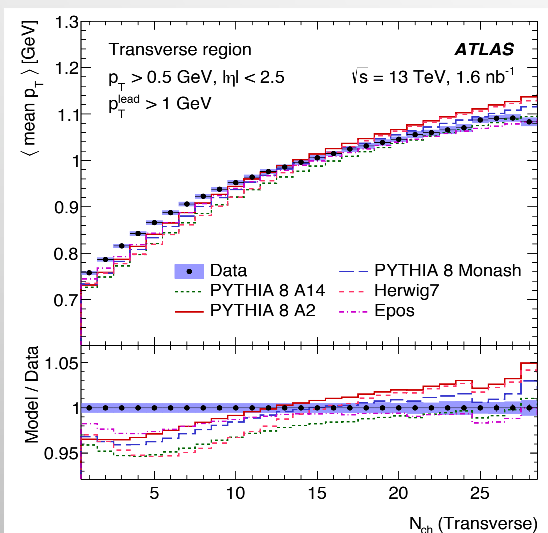
Z+jets

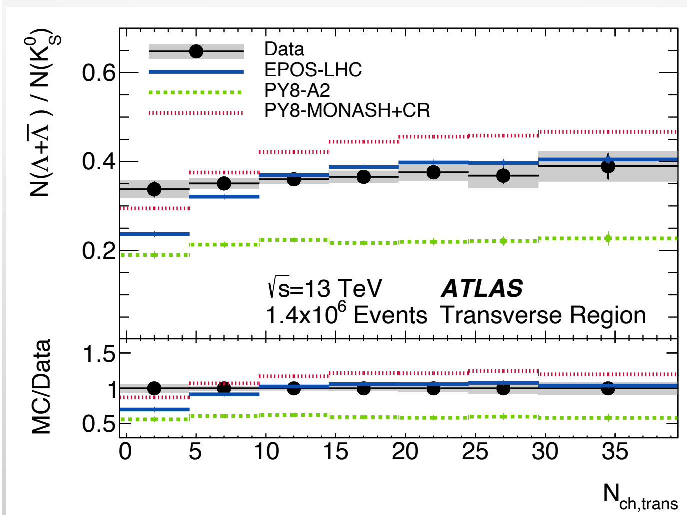


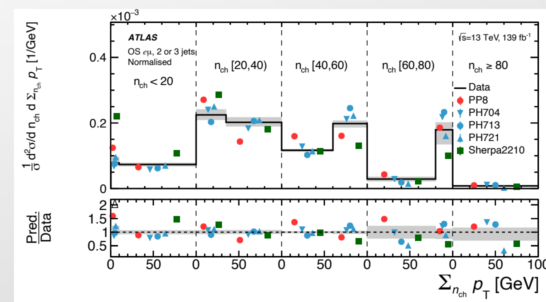












Strange hadrons flow disagrees with some of the MC models

JHEP 07 (2018) 032
EPJC 79 (2019) 123
JHEP 09 (2015) 137
JHEP 03 (2017) 157
EPJC 79 (2019) 666
JHEP 04 (2020) 192
arXiv:2405.05048, subm to EPJC
EPJC 83(2023)518

Double Parton scattering (DPS)

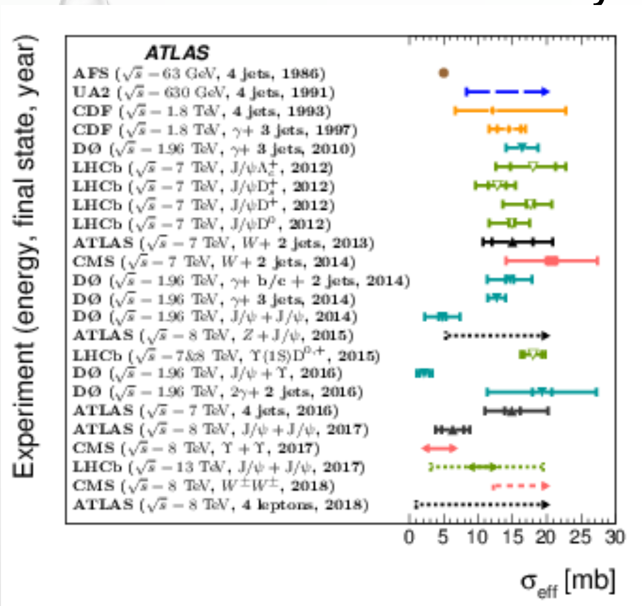
Two and more hard interactions within the same production vertex can happen.

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)

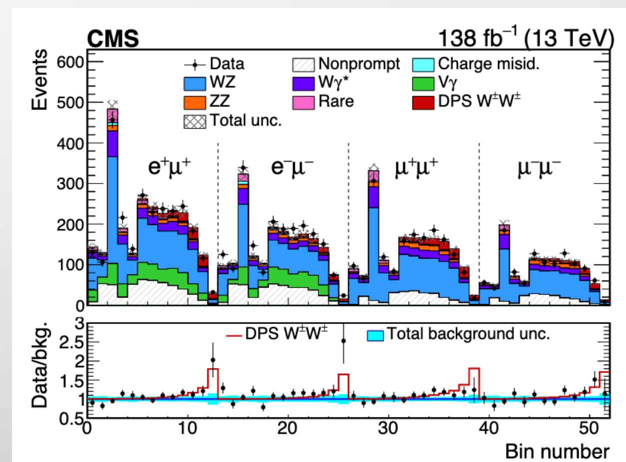
T(b) is the overlap function of two interacting hadrons



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

Phys.Rev.Lett.131(2023)091803

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),
JHEP11 (2016) 110 (7 TeV):
A strong dependence of the extracted values of σ_{eff} on the model used to the describe the SPS contribution is observed.
σ_{eff} = 7-35 mb
σ_{DPS}=15-70 nb

DPS with 4 leptons (8 TeV)

PL 790(2019)595

The lower limit on σeff at 95% CL is 1.0 mb

DPS with Z+jets

JHEP 10(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

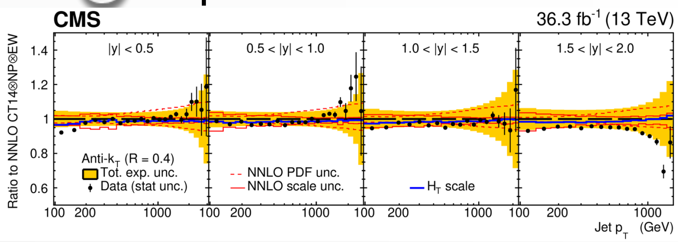
Process	Sensitivity
W mass measurement	Valence quarks
W,Z production	Quark flavor separation
W+c production	Strange quark
Drell-Yan, high mass	Sea quark, high-x, photon PDF
Drell-Yan low mass	Low-x, resummation
W,Z+jets	Gluon medium-x
Inclusive jets, multijets	Gluon and $\alpha_S(M_Z)$
Direct photon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

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

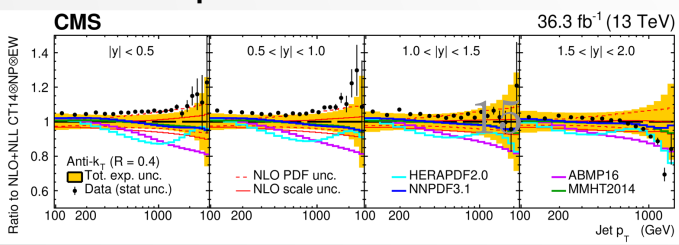
Jet production: sensitivity to g-PDF and to α_S

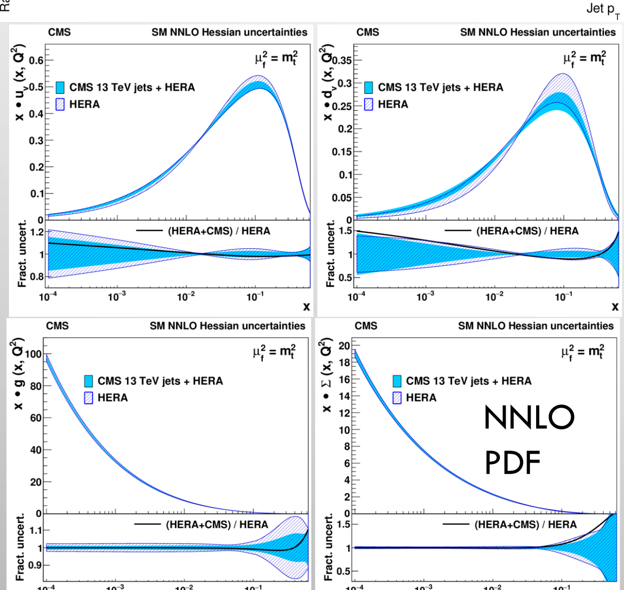
CMS, 13 TeV, Integrated luminosity 36.3 fb^{-1}

Comparison with NNLO



Comparison with NLO+NLL

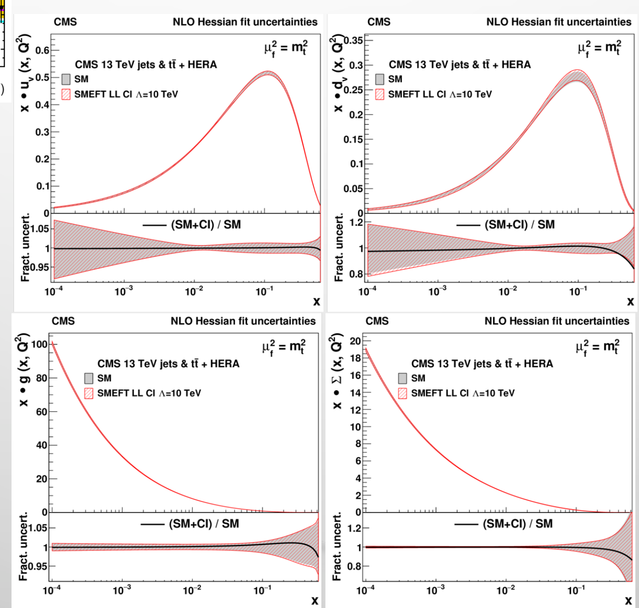




Double-differential inclusive jet production + HERA DIS + the normalized triple-differential ttbar cross-section, DGLAP evolution

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

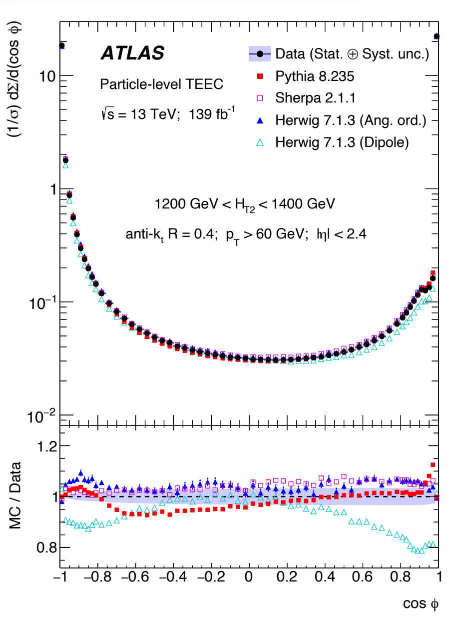
Λ > 24 TeV

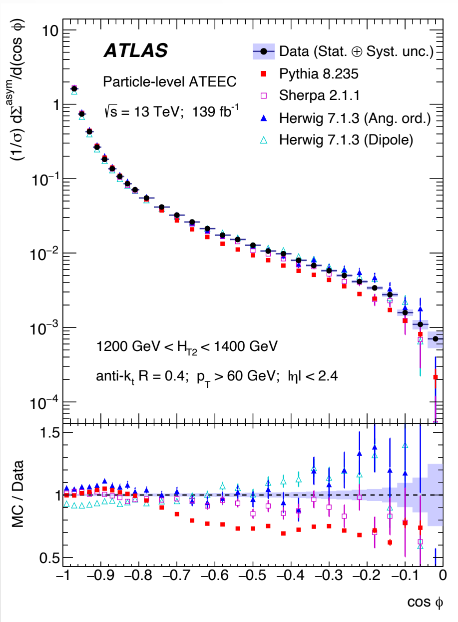
JHEP 02(2022) 142, addendum JHEP12(2022)035

Multijets correlation and strong couplings

RGE predicts the $a_S(Q)$ dependence but not the absolute value

Transverse Energy-Energy Correlation (TEEC)
Azumythal asymetry (ATEEC) **136 fb^{-1}**





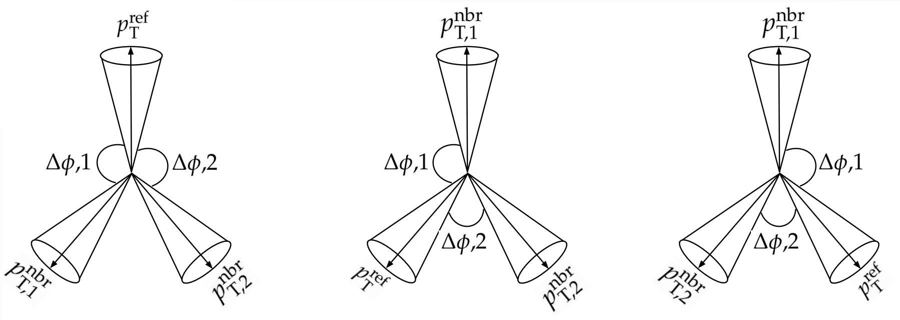
NNLO accuracy for MMHT2014, CT14, NNPDF3.0
NNLO solution of RGE

$a_S(M_Z)$=0.1175+-0.0006(exp)+0.0034-0.0017(th)

$a_S(M_Z)$=0.1185+-0.0009(exp)+0.0025-0.0012(th)

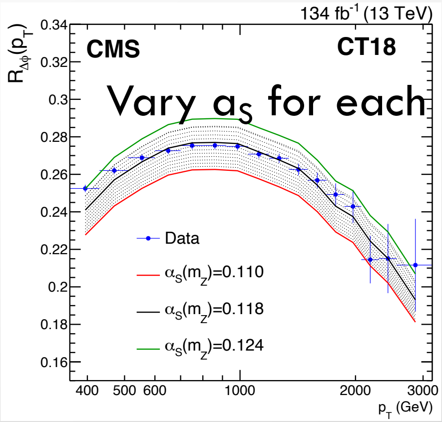
EPJC 84 (2024) 842
JHEP07(2023)85

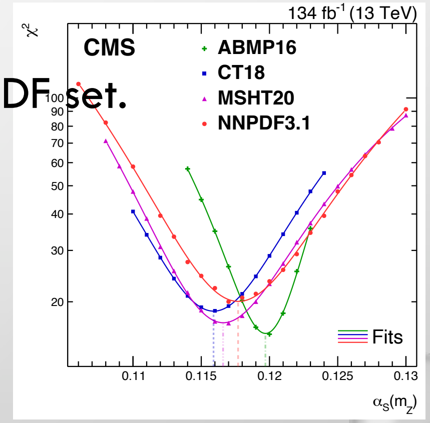
Azimuthal correlations in >=3jets events
Third jet is in $2\pi/3<\delta\phi< 7\pi/8$ **134 fb^{-1}**



$$R_{\Delta\phi}(p_T) = \frac{\sum_{n=0}^{\infty} nN(p_T,n)}{\sum_{n=0}^{\infty} N(p_T,n)} \sim a_S$$

Vary a_S for each PDF set.





$a_S(M_Z)$=0.1177+-0.0013(exp)+0.0116-0.0073(th) at NLO accuracy

Energy correlators, evolution equation and strong couplings

The NLO + NNLL$_{approx}$ theoretical predictions are corrected to hadron-level and normalized to the measured data.

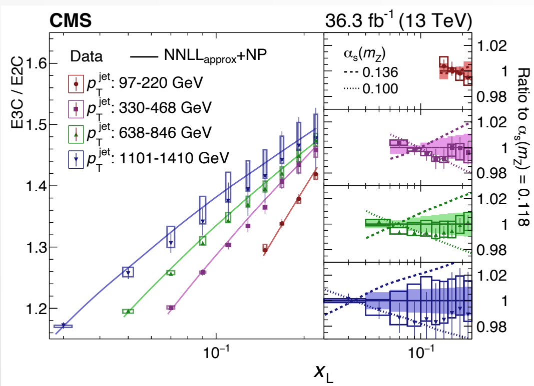
The different x_L regions provide information on the dynamics of jet formation, so that one can examine the DGLAP equations.

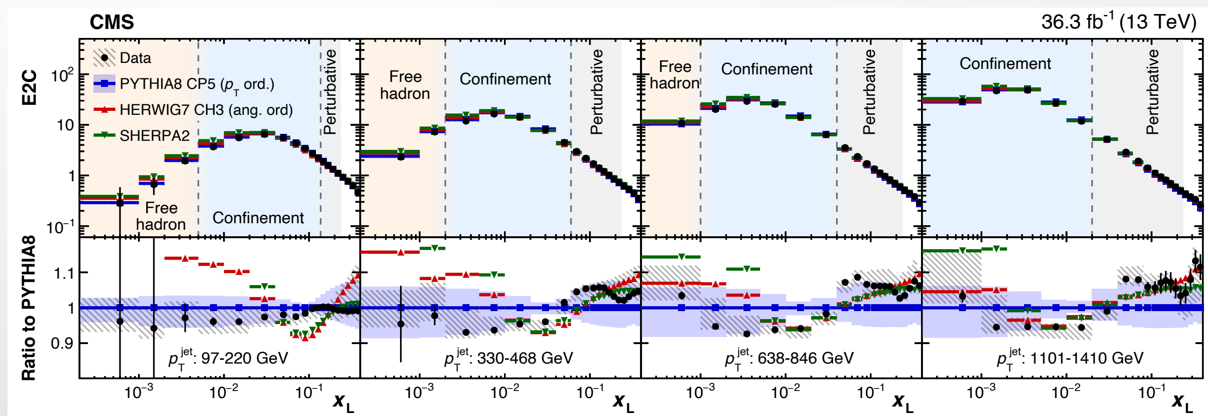
In QCD calculations: E3C/E2C~$\alpha_S \ln(x_L)$

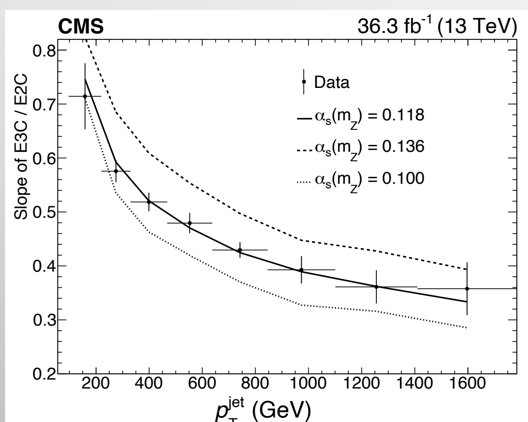
E3C=$\sum_{i,j,k}^{n} d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{k,j}))$

E2C=$\sum_{i,j}^{n} d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j})$

x_L-maximum distance between pair of particles.



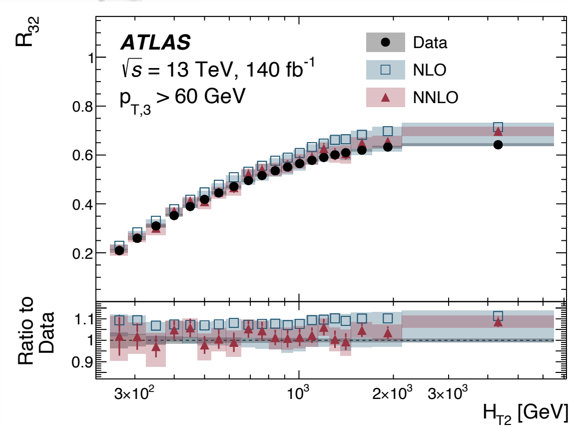


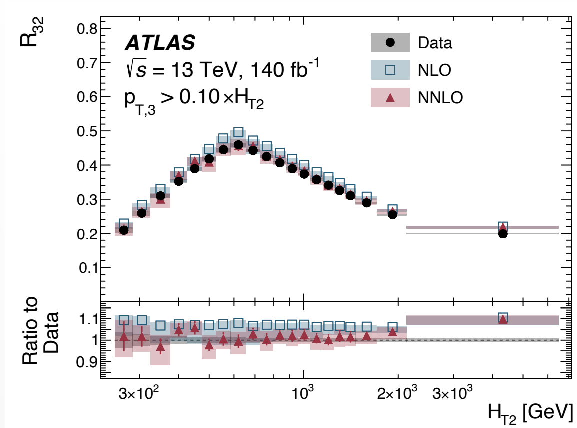


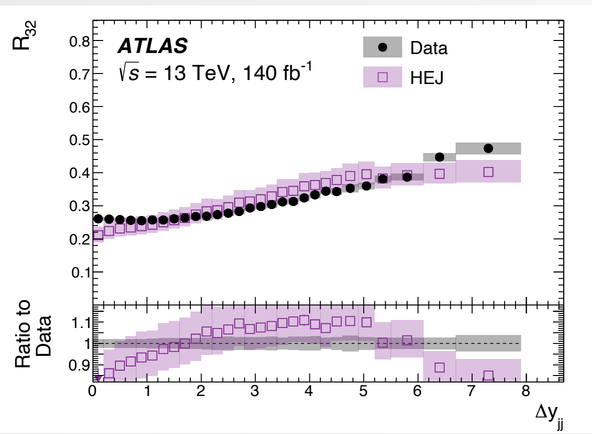
$a_S(M_Z)=0.1229^{+0.0014}_{-0.012}(\text{stat})^{+0.003}_{-0.0033}(\text{theo})^{+0.0023}_{-0.0036}(\text{exp})$

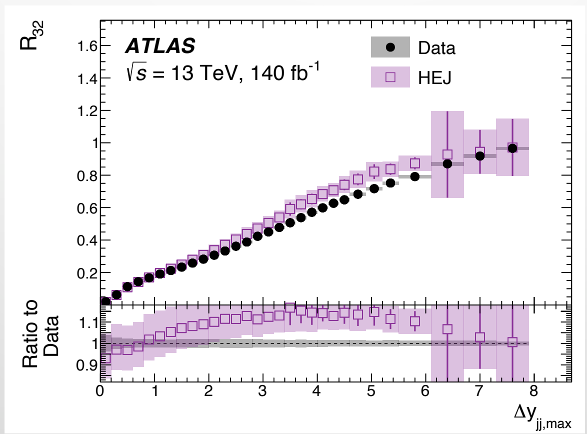
PRL 133 (2024) 071903

Jet ratios and strong coupling









R32, R43, R54 ratios

NLO predictions with NLOJet++
Convoluted with NNLO PDFs
(LHAPDFs, CT18, NNPDF4.0,
MSHT20, ATLASpdf21)

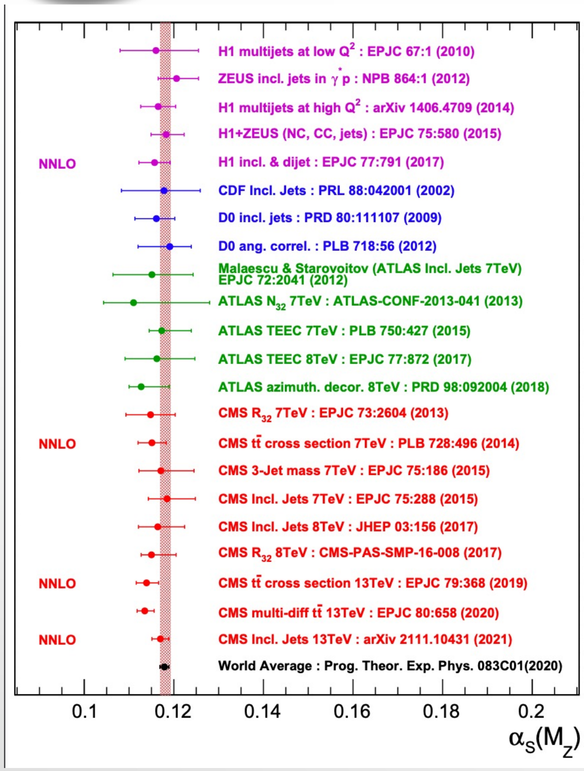
NNLO predictions
Avhlib, OpenLoops2,
FivePoinsAmplitudes
PentagonFunctions++

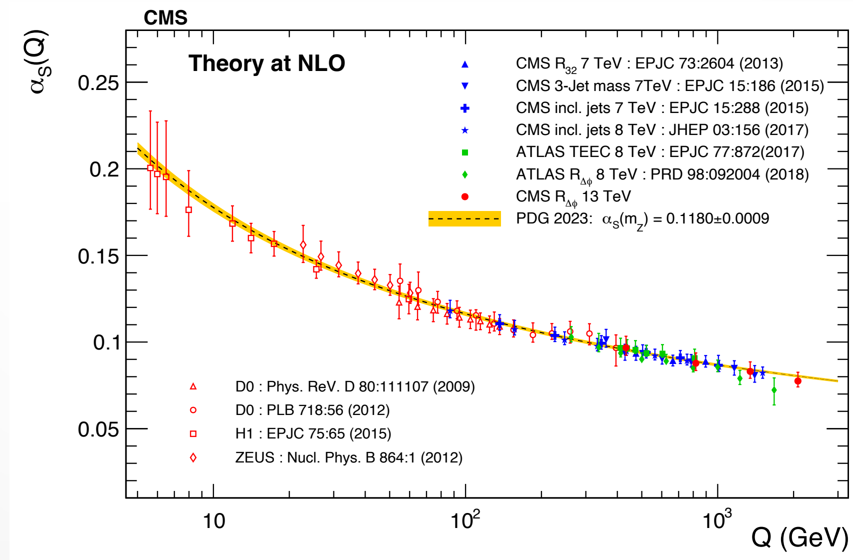
HEJ Predictions
leading logariphmic QCD
corrections to all order of a_S
resummation and matching
to fixed order

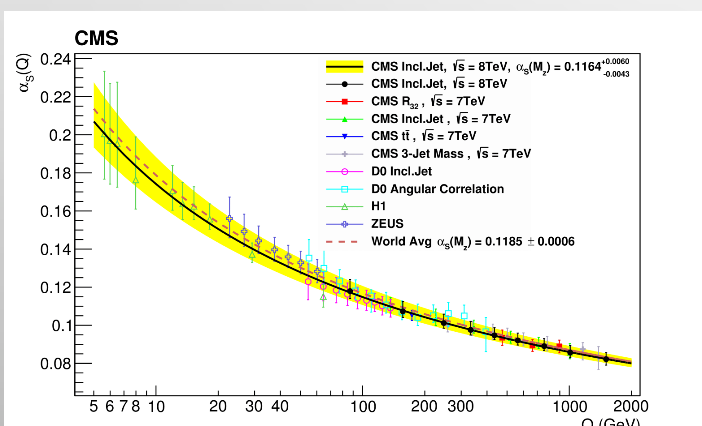
RIVET is available
arXiv:2405.20206 Submitted to PRD

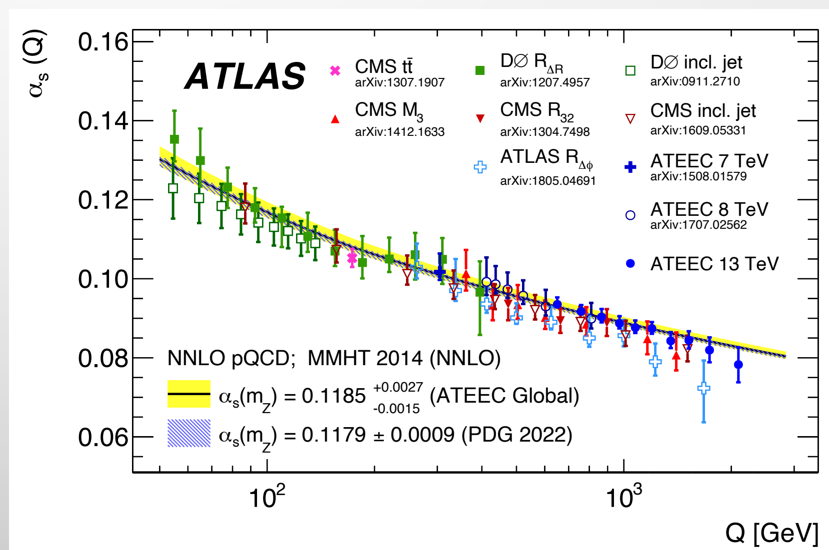
Nf=5 schema
a_S=0.118
Factorization and renormalization
schema - H_T

Summary on α_S

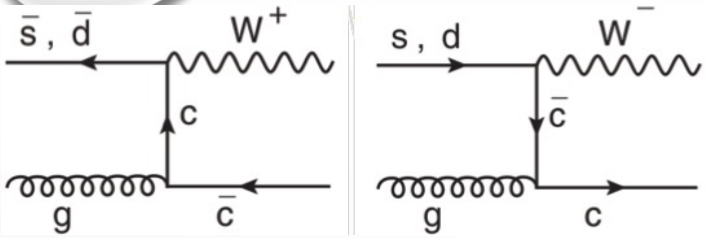


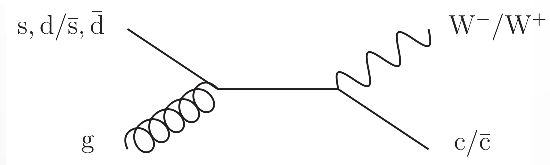




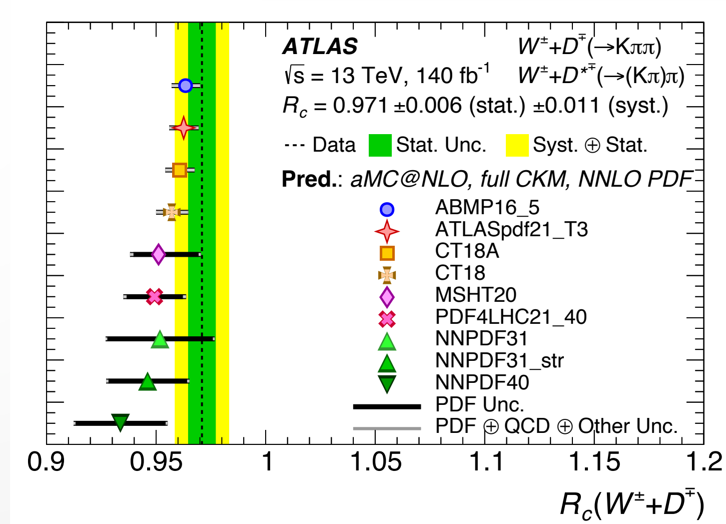


W+c: strange quark PDF





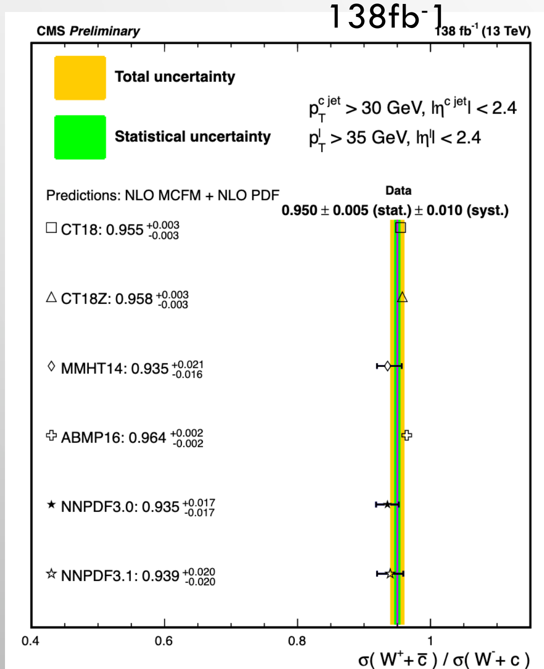
$$R_c^{\pm} = \frac{\sigma_{fid}^{OS-SS}(W^+ + D^{(*)})}{\sigma_{fid}^{OS-SS}(W^- + D^{(*)})}$$



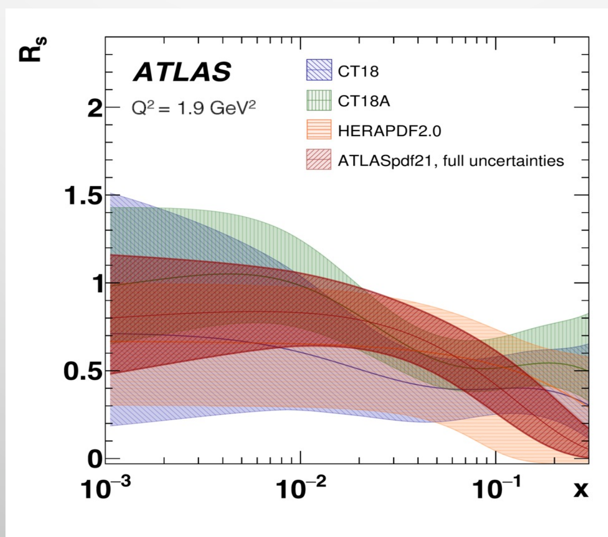
PDFs are probed at
< x >≈ 0.007
at the scale of W mass

Up-to NNLO predictions

138fb-1



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



s-$\bar{s}$ asymetry

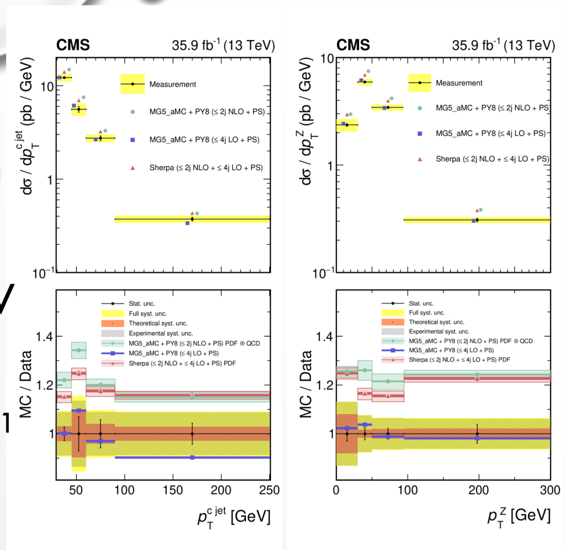
ATLAS: $0.971 \pm 0.006(stat) \pm 0.011(syst)$

CMS: $0.95 \pm 0.005(stat) \pm 0.010(syst)$

EPJC 79 (2019) 269
JHEP 07 (2021) 22
EPJC 82(2022)438
PRD 108(2023)032012
EPJC 84 (2024) 27

Z+c: towards c-PDFs (towards c-PDF)

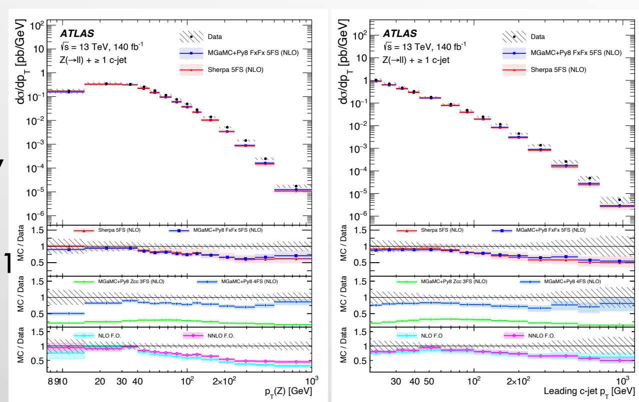
CMS
13 TeV
36 fb^{-1}



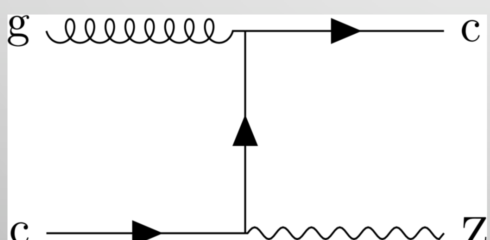
Inclusive Z+c cross-section:
405.4 ± 5.6 (stat)
± 24.3 (exp)
± 3.7 (theo) pb
MadGraph5+MCatNLO:
524.9 ± 11.7 (theo) pb

MCatNLO 2.2.2 and Sherpa 2.2 overestimate Z+c cross-section at NLO and MCatNLO agreed with data at LO.
FxFx for NLO, MLM for LO
Cross-sections are normalized to NNLO with FEWZ 3.1.
NNPDF3.0

ATLAS
13 TeV
140 fb^{-1}

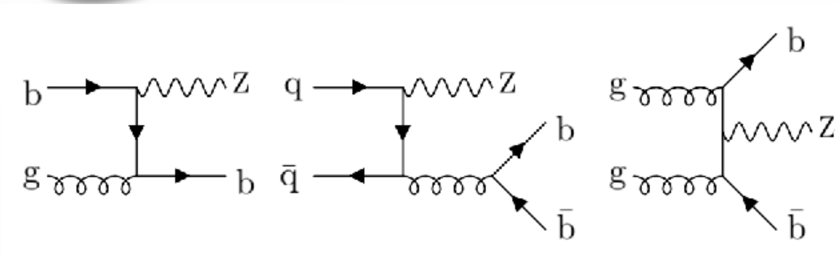


Both p_T spectra are described well by MGaMC+Py8 FxFx and Sherpa 2.2.11 at NLO in the soft part, while above 40–50 GeV (80–100 GeV) for Z boson (c-jet) p_T the data cross-section is significantly underestimated by these predictions.



JHEP04 (2021) 109
EPJC 78(2018) 287
arXiv:2403.15093, accepted by EPJC

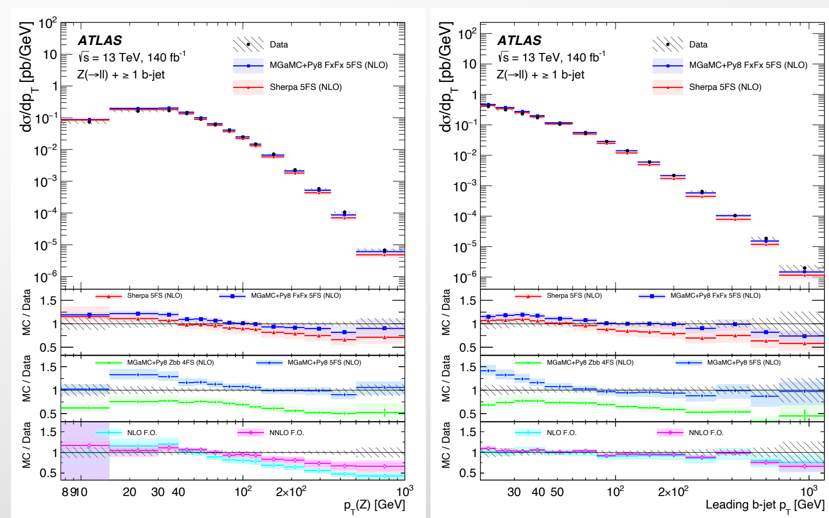
Z+b: towards b-quarks PDFs and 4 vs 5-flavor schema

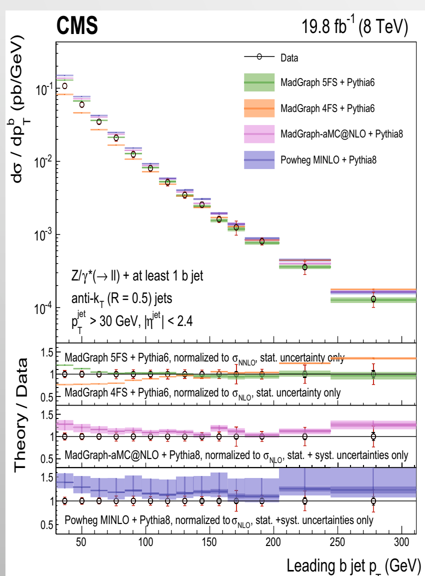


Current simulations are in NLO either in 4 or 5 FNS.
In 4 FNS b-quark does not contribute to PDF. Massive b through gluon splitting
In 5 FNS b-quark typically massless but b contributes to PDF

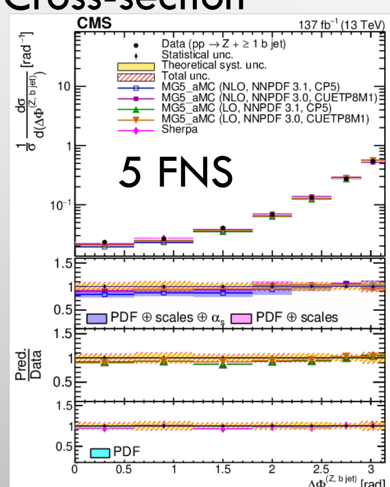
CMS 137fb^{-1}
$|p_T| > 35$ GeV, $p_T^{sublead} > 25$ GeV
$|\eta| < 2.4$, $M_Z = [71-111]$ GeV
Generator b-jet $p_T > 30$ GeV, $|\eta| < 2.4$
$\sigma_{fid}(Z+>=1b) = 6.52 +- 0.04 +- 0.4 +- 0.014$ pb
$\sigma_{fid}(Z+>=2b) = 0.65 +- 0.03 +- 0.07 +- 0.02$ pb

ATLAS 140 fb^{-1}



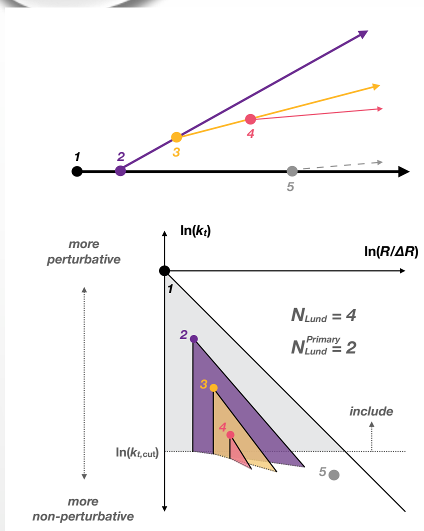


Normalized to fiducial Cross-section



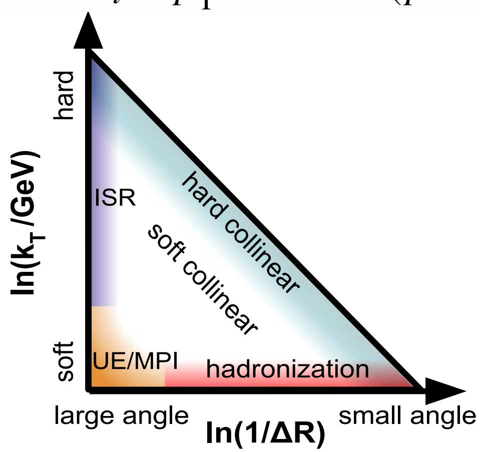
ATLAS: PRD 108 (2023) 012022
JHEP07 (2020)44
arXiv:2403.15093, accepted by EPJC
CMS: PRD 105 (2022) 092014
EPJC 77 (2017) 751

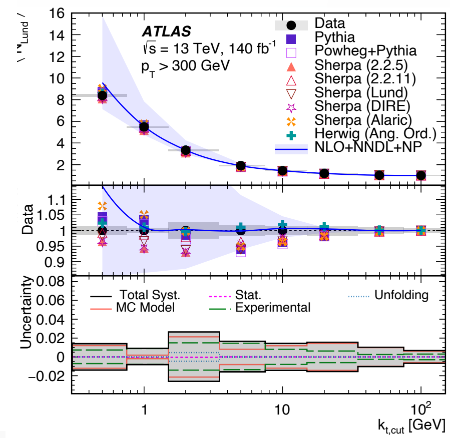
Jet substructure and Lund plane

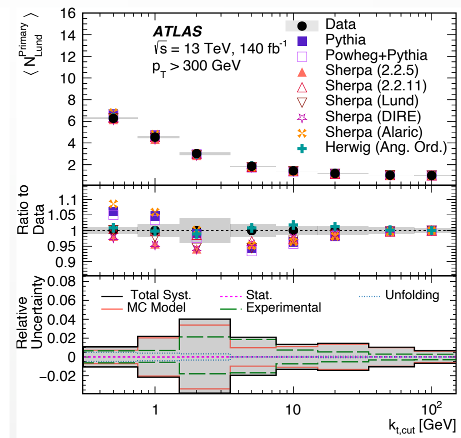


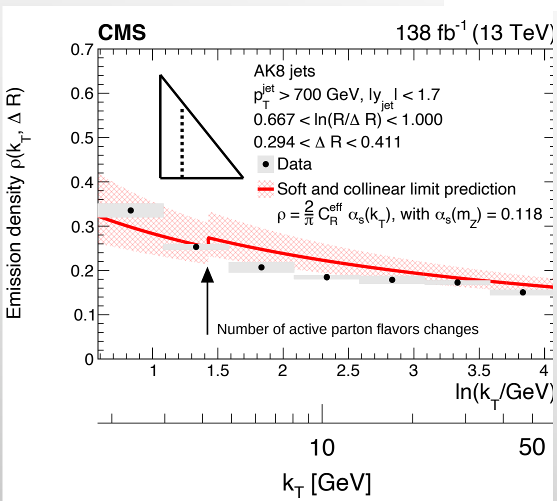
Reclustering with CA algo.

$$k_t = p_{\mathrm{T}}^{\mathrm{emission}} \cdot \Delta R(p^{\mathrm{emission}}, p^{\mathrm{core}})$$



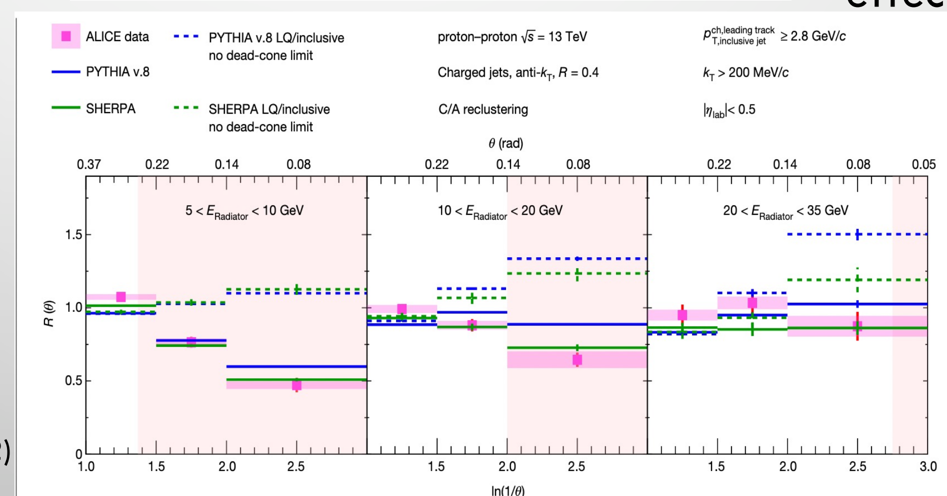






$$R(\theta) = \frac{1}{N^{D^0\,\mathrm{jets}}} \frac{dn^{D^0\,\mathrm{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\mathrm{inclusive\ jets}}} \frac{dn^{\mathrm{inclusive\ jets}}}{d\ln(1/\theta)} \Bigg|_{k_T, E_{\mathrm{Radiator}}}$$

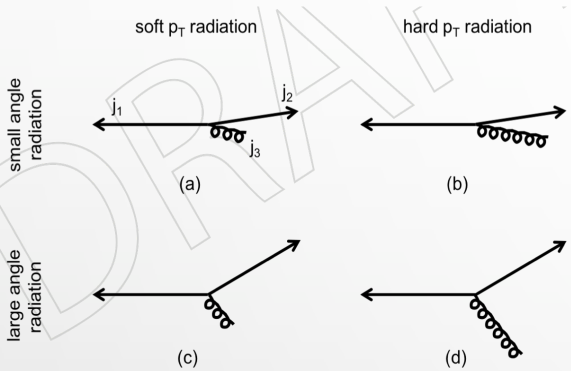
First direct observation of the dead cone effect for heavy Q.



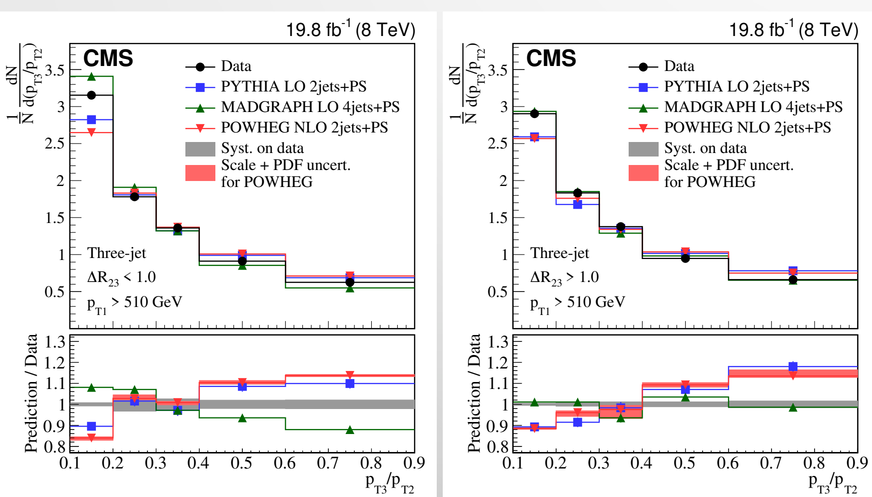
CMS: JHEP 05 (2024) 116
ATLAS: Submitted to: Phys. Lett. B
ALICE: Nature volume 605, p. 440–446 (2022)

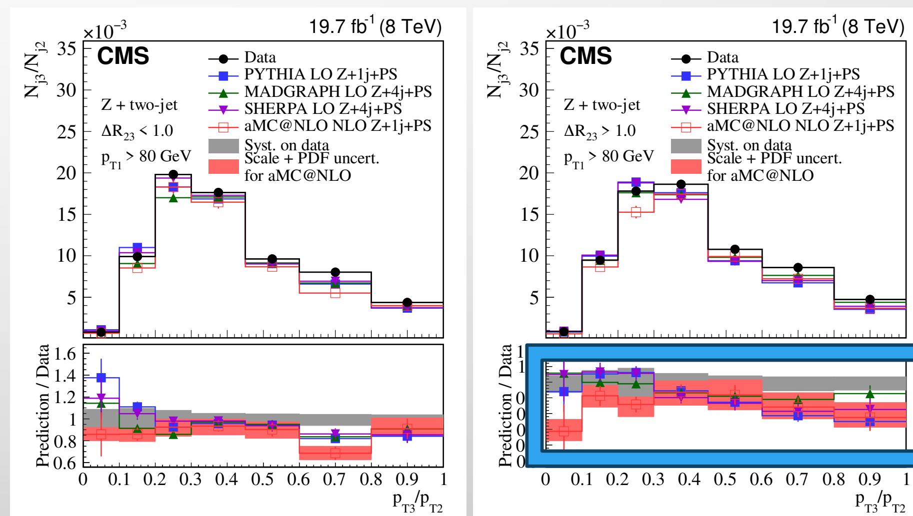
Angular distance and momentum ratio for 3 high-p_T objects

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



Three-jet events	
Transverse momentum of the leading jet (j_1)	$p_{T1} > 510$ GeV
Transverse momentum of each jet and rapidity of $j_{1,2}$	$p_T > 30$ GeV , $\|y_{1,2}\| < 2.5$
Azimuthal angle difference between j_1 and j_2	$\pi - 1 < \Delta\phi_{12} < \pi$
Transverse momentum ratio between j_2 and j_3	$0.1 < p_{T3}/p_{T2} < 0.9$
Angular distance between j_2 and j_3	$R_{jet} + 0.1 < \Delta R_{23} < 1.5$
Number of selected events at $\sqrt{s} = 8$ (13) TeV	777 618 (613 254)
Z + two-jet events	
Transverse momentum of the Z boson (j_1)	$p_{T1} > 80$ GeV, $\|y_1\| < 2$
Transverse momentum and rapidity of j_2	$p_{T2} > 80$ GeV , $\|y_2\| < 1$
Transverse momentum and rapidity of j_3	$p_{T3} > 20$ GeV, $\|y_3\| < 2.4$
Azimuthal angle difference between Z and j_2	$2 < \|\Delta\phi_{12}\| < \pi$
Dimuon mass	$70 < m_{\mu^+\mu^-} < 110$ GeV
Angular distance between j_3 and j_2	$0.5 < \Delta R_{23} < 1.5$
Number of selected events	15 466





EPJC81(2021)852

Partially compensated by ttbar and VV processes

Azimuthal correlations in Z+jets at 13 TeV

Table 2: Particle-level phase space definition

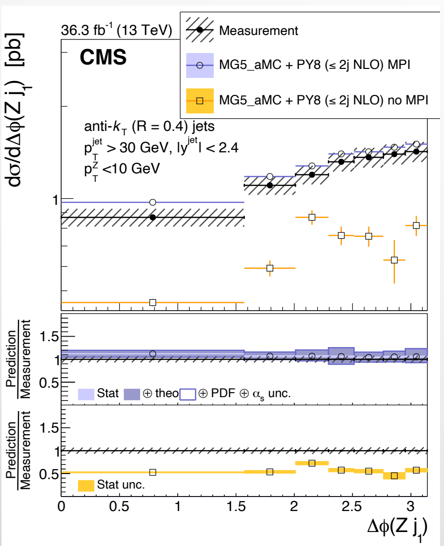
object	requirement
leading (subleading) lepton	$p_T > 25(20)$ GeV, $\|\eta\| < 2.4$
lepton-jet separation	$\Delta R_{\ell,j} > 0.4$
lepton pair mass	$76 < m_{\ell^+\ell^-} < 106$ GeV
jet	$p_T > 30$ GeV, $\|\eta_{jet}\| < 2.4$

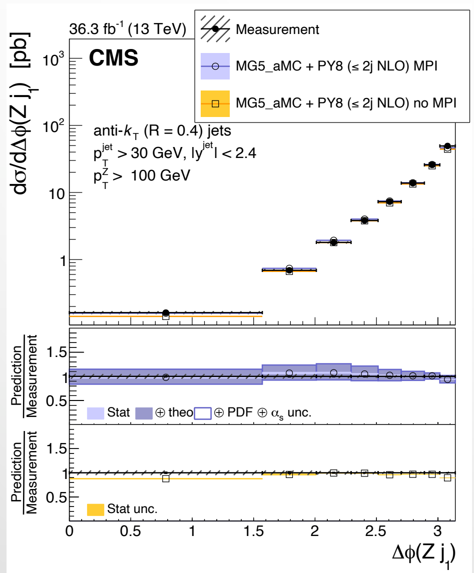
$\Delta R(l,j) > 0.4$

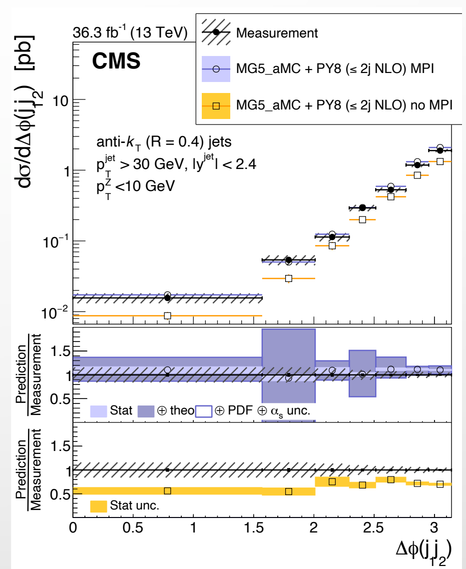
$p_T^Z < 10$ GeV , $p_T^{jet} > 30$ GEV, $|y_{jet}| < 2.4$

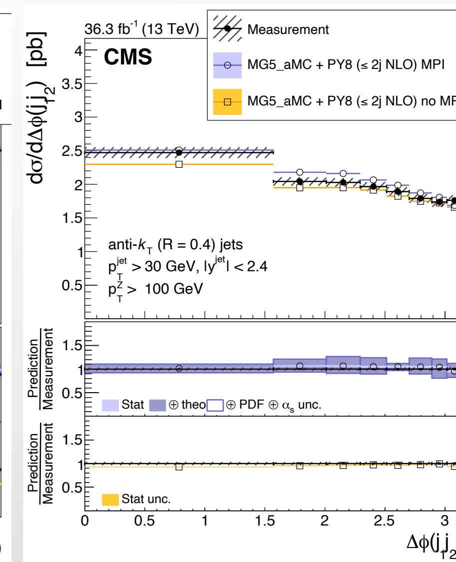
30 GeV $< p_T^Z < 50$ GeV, $p_T^{jet} > 30$ GEV , $|y_{jet}| < 2.4$

$p_T^Z > 100$ GeV , $p_T^{jet} > 30$ GEV , $|y_{jet}| < 2.4$









Z at Low p_T with high p_T jet (~1% of events has high p_T jet) is emitted from high p_T jet (EWK correction)

Z at high p_T with jets: Z+jets is the dominant process

EPJC 83(2023) 722

Summary

- ALICE, ATLAS, 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
- ALICE, ATLAS, 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

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

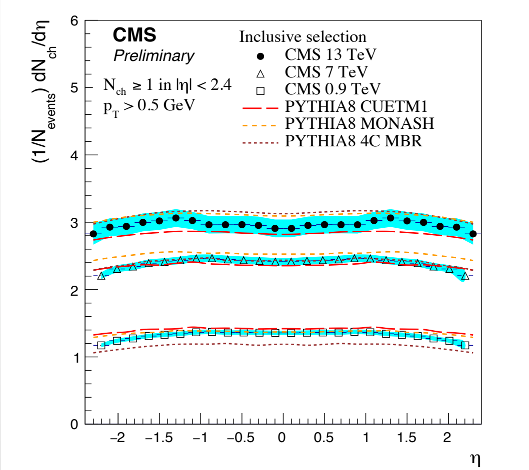
https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults

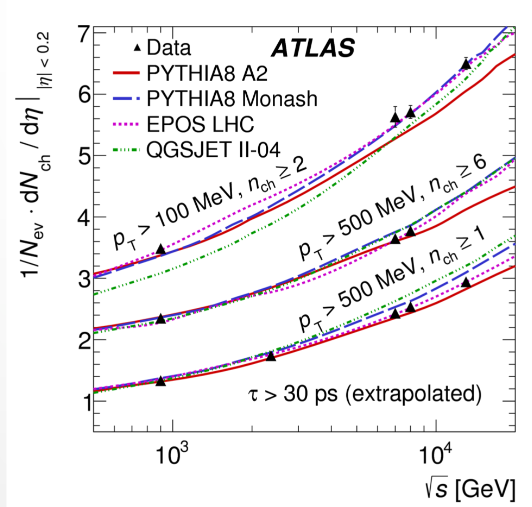
Back-up

Charged particles

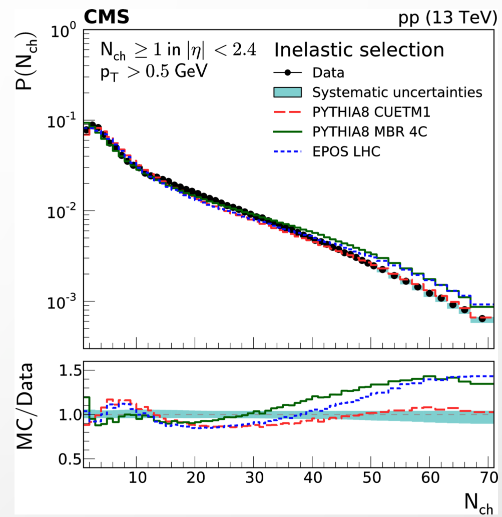
new input to the dynamics of soft hadronic interactions: interplay between soft and hard processes: no one MC describes data in all configurations

p_T>500 MeV, |η|<2.4

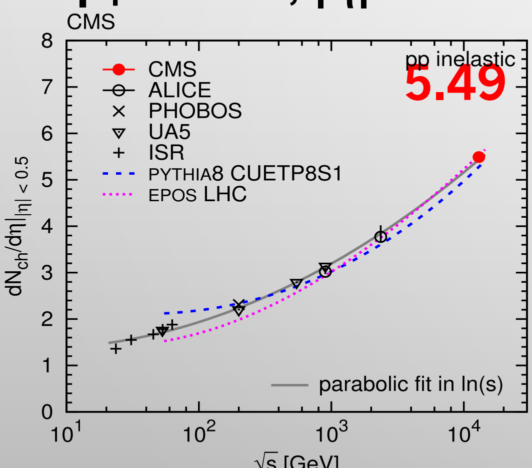




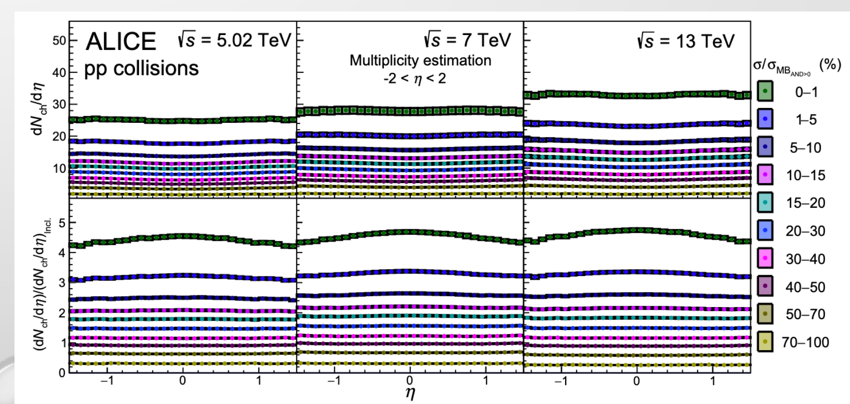
change of the slope at n~20



p_T>0 MeV, |η|<0.5

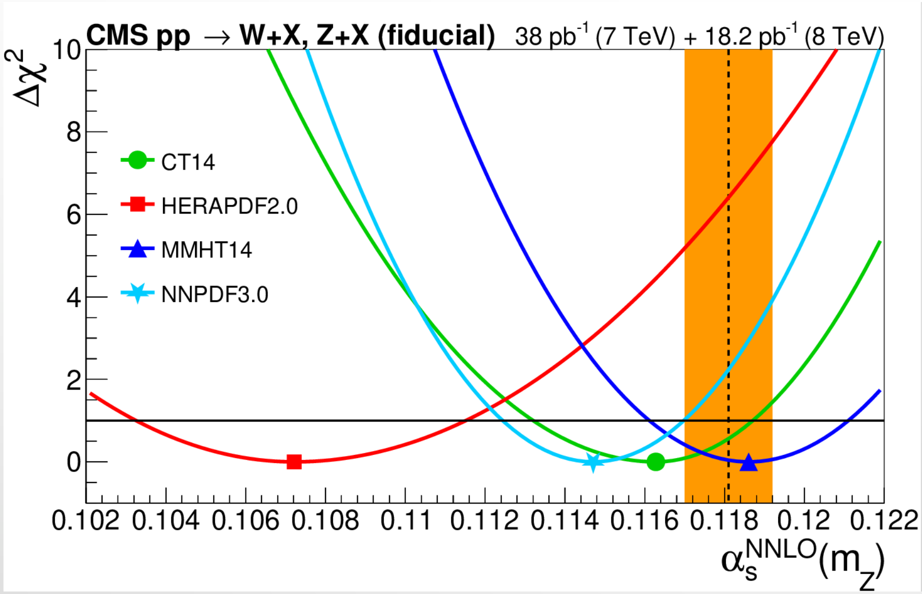


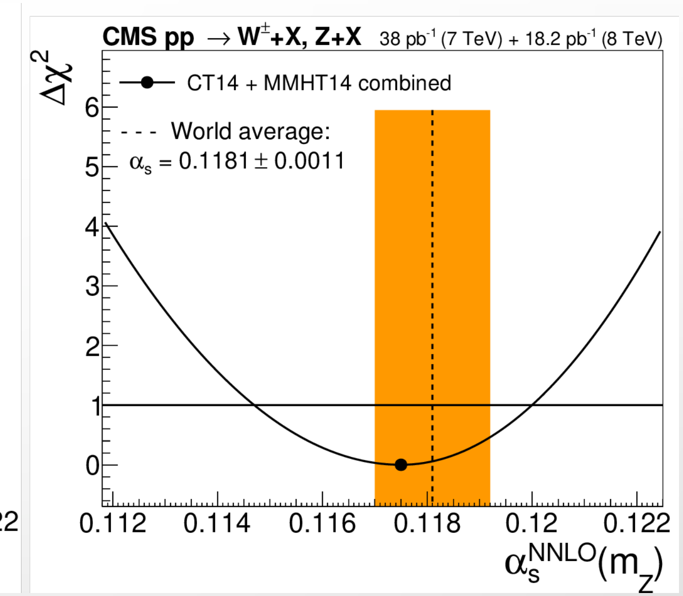
CMS-PAS-FSQ-15-008
EPJC 78 (2018) 697
PLB 751(2015)143
JHEP 01 (2011) 079
EPJC 76(2016) 502
EPJC 81(2021) 630



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 varying $\alpha_S(m_Z)$ and compare theoretical predictions to experimental data (12 samples with different decay modes).





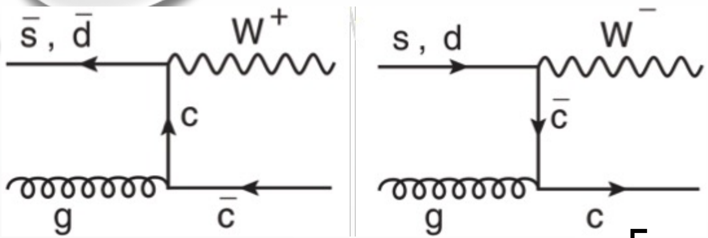
Cross-sections with CT14 and MMHT14 sets are the most sensitive to the α_S value.
Robust and stable with respect to variations in the data and theoretical cross sections.
$\alpha_S = 0.1163^{+0.0024}_{-0.0031}$ (CT14) or $0.1072^{+0.0043}_{-0.0040}$ (HERAPDF2.0) or $0.1186^{+0.0025}_{-0.0025}$ (MMHT14) or $0.1147^{+0.0023}_{-0.0023}$ (NNPDF3.0)
The result derived combining the CT14 and MMHT14 extractions:

$$\alpha_S = 0.1175^{+0.0025}_{-0.0028}$$

CMS:JHEP 06 (2020) 018

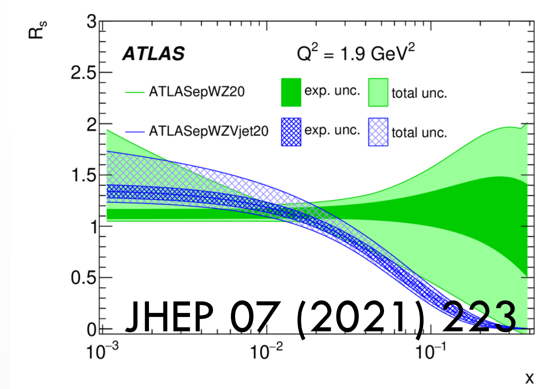
This extracted value is fully compatible with the current world average.

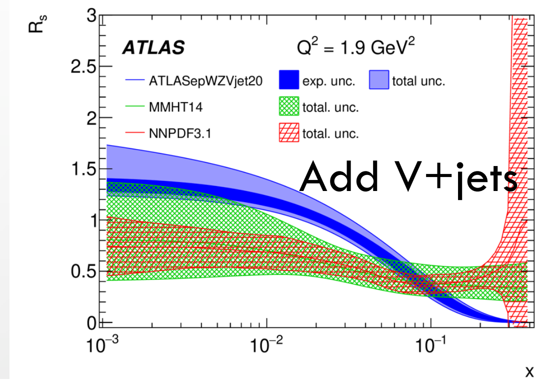
W+c: strange quark PDF



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

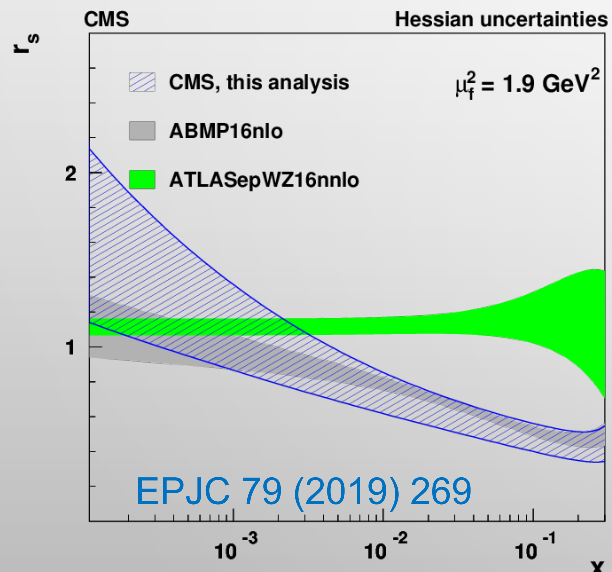
From neutrino scattering Rs=0.5
At Q2=1.9 GeV2 strange sea-quark density is suppressed
ATLAS: W,Z - strange sea-quark density is enhanced – seen only by ATLAS



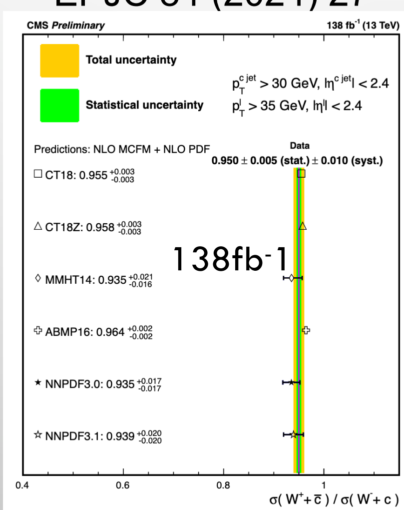


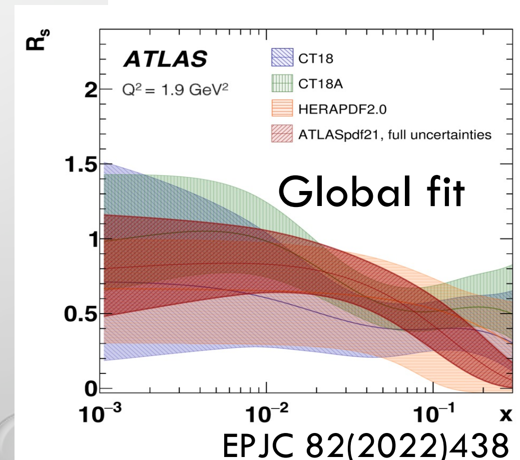
PDFs are probed at
$< x > \approx 0.007$
at the scale of W mass

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



EPJC 84 (2024) 27

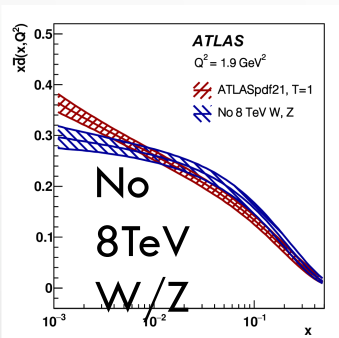


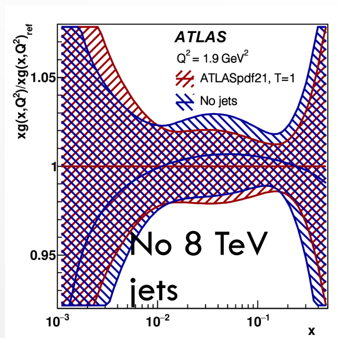


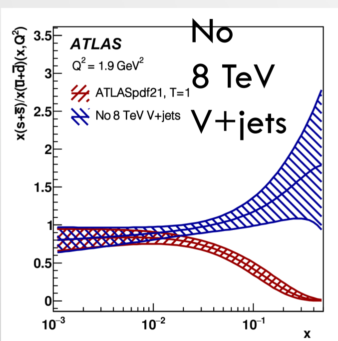
PDF global fit

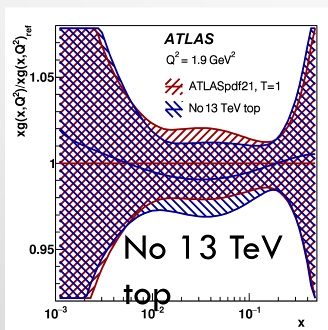
7, 8, 13 TeV with 5, 20, 36 fb^{-1}

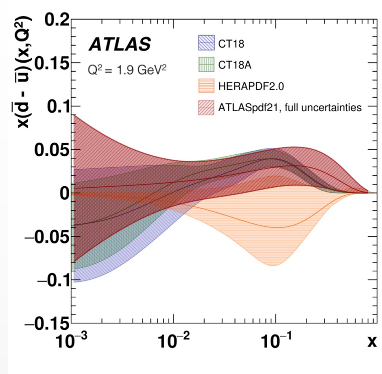
Differential cross-section if inclusive W+-, Z/γ^* and W+-.Z+jets, ttbar, inclusive jets, direct Photons; DGLAP evolution is used

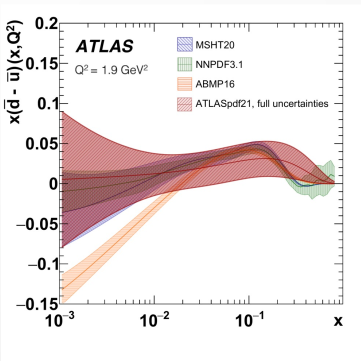


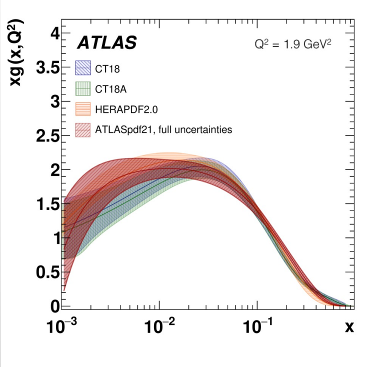


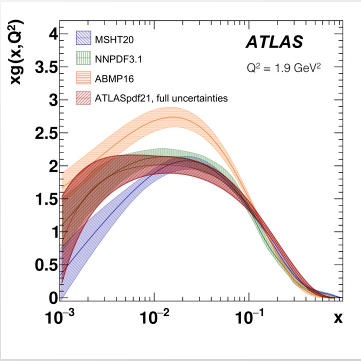












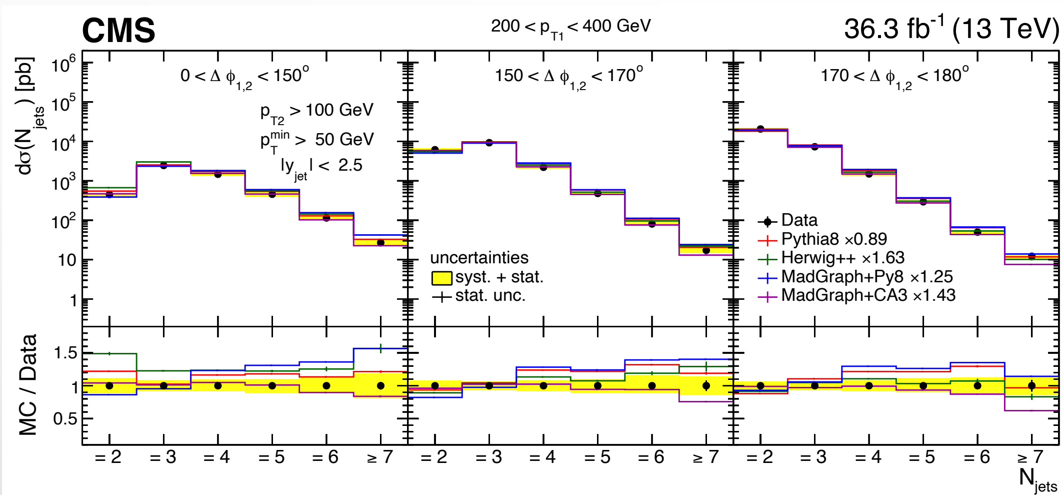
Resulting pdf set: ATLASpdf21

ATLAS: EPJC 82(2022) 438

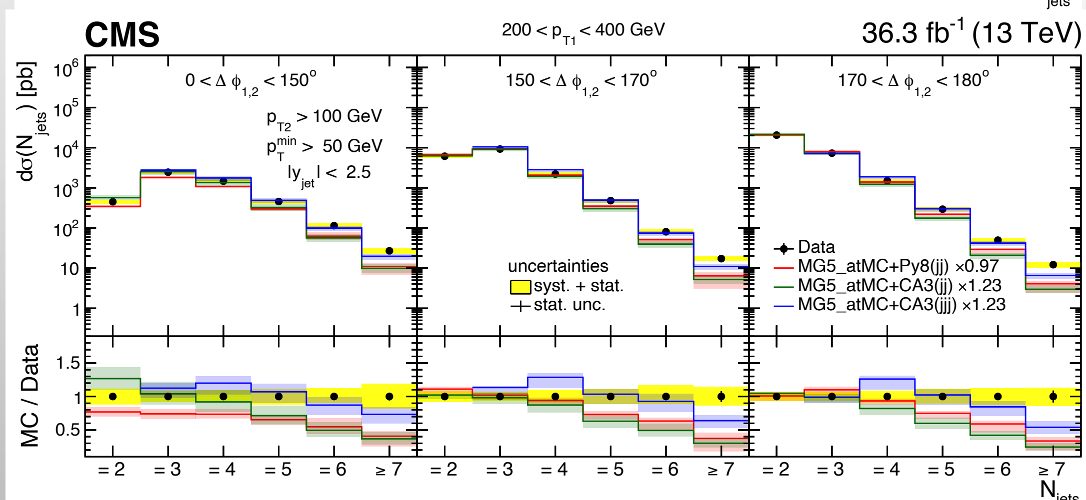
Jet multiplicity and jet pt in multijet events

Transverse momentum dependent (TMD) PDF
Probability branching method (PB)

Jet selections: $|y|<2.5$
$p_T^{j1}>200$ GeV, $p_T^{j2}>100$ GeV
$p_T^{j3}>50$ GeV



NLO dijets calculations with PB TMD PDF with TMD parton showering describe low-multiplicity region with less amount of tunable parameters then with conventional parton showering

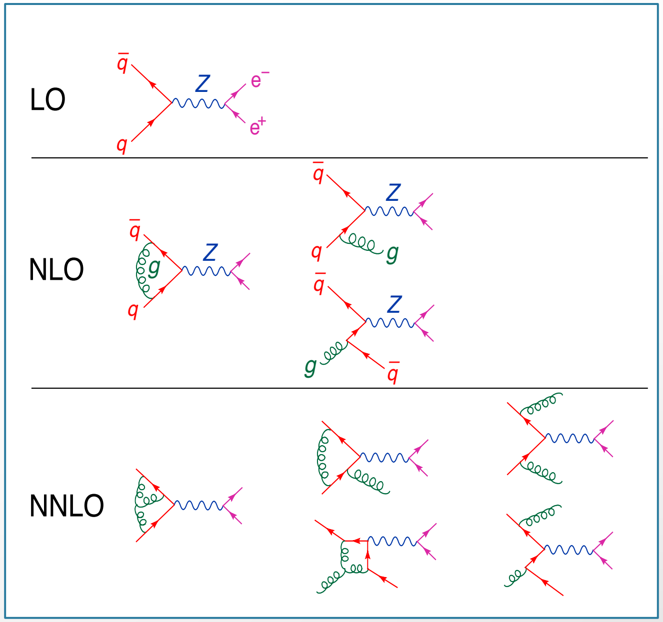


Noone generator describes
Full jet mulyiplicity range and
p_T dependence up to 4th jet

EPJC 83(2023)742
CMS PAS-SMP-21-006

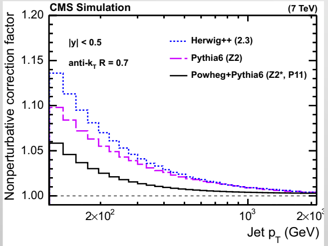
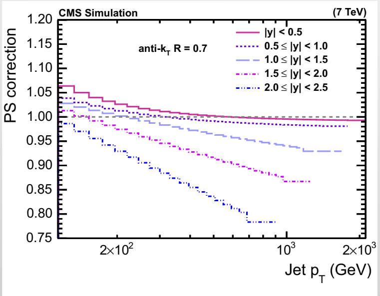
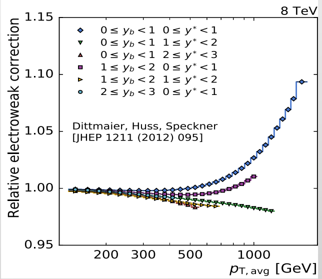
Perturbative QCD (pQCD)

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

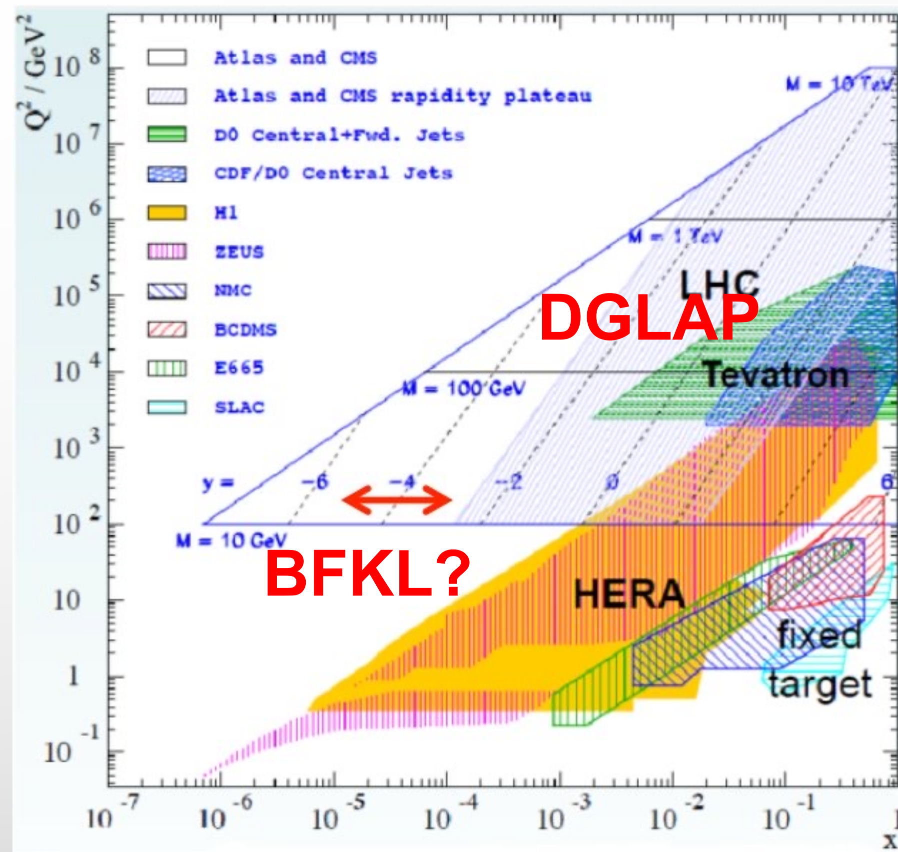
Connection between various scales in QCD (for instance, between PDF and the high-momentum scattering) is performed via evolution differential equations.

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)
- …

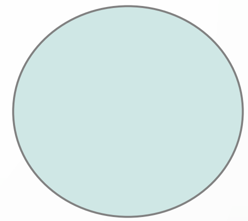
Non perturbative effects, Multi Parton Interaction (MPI) etc. models have to be tuned to data.

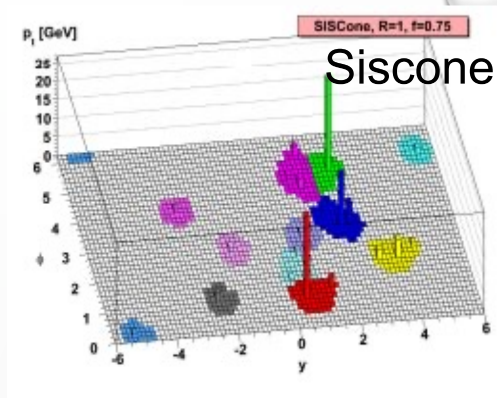


Jet clustering technique

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

Iterative cone



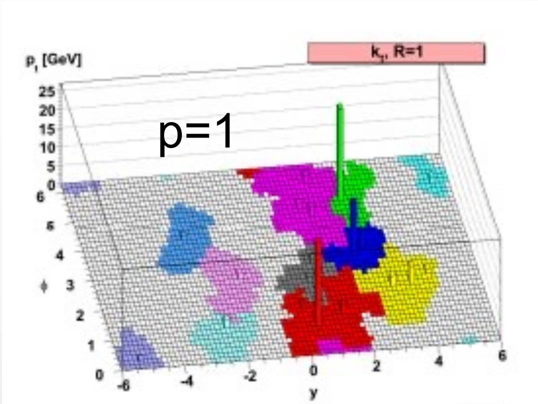


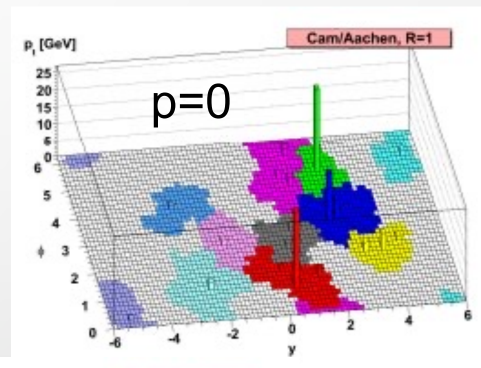
Successive recombination algorithms:

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

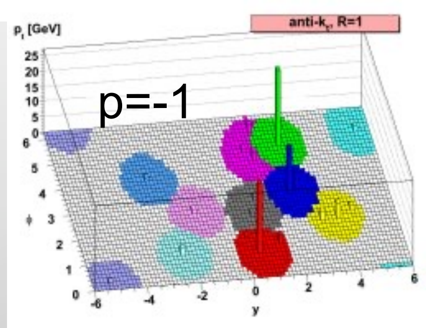
$$d_{iB} = k_{ti}^{2p}$$

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

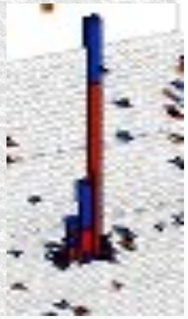


CMS uses R=0.5,0.7 in Run1
R=0.4,0.6 in Run2
ATLAS uses R=0.4,0.6 in Run1,2

JHEP 1009 (2010) 091

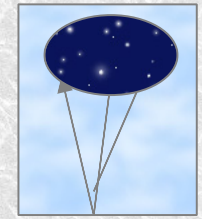
Jet reconstruction in detector

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

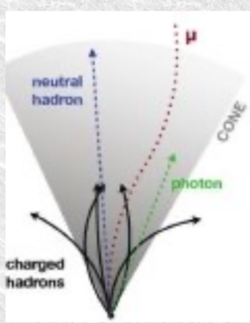


Subdetectors: Tracker

(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

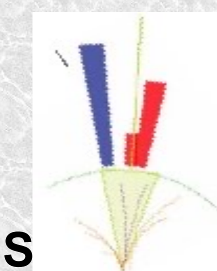
PFMET **CMS**



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

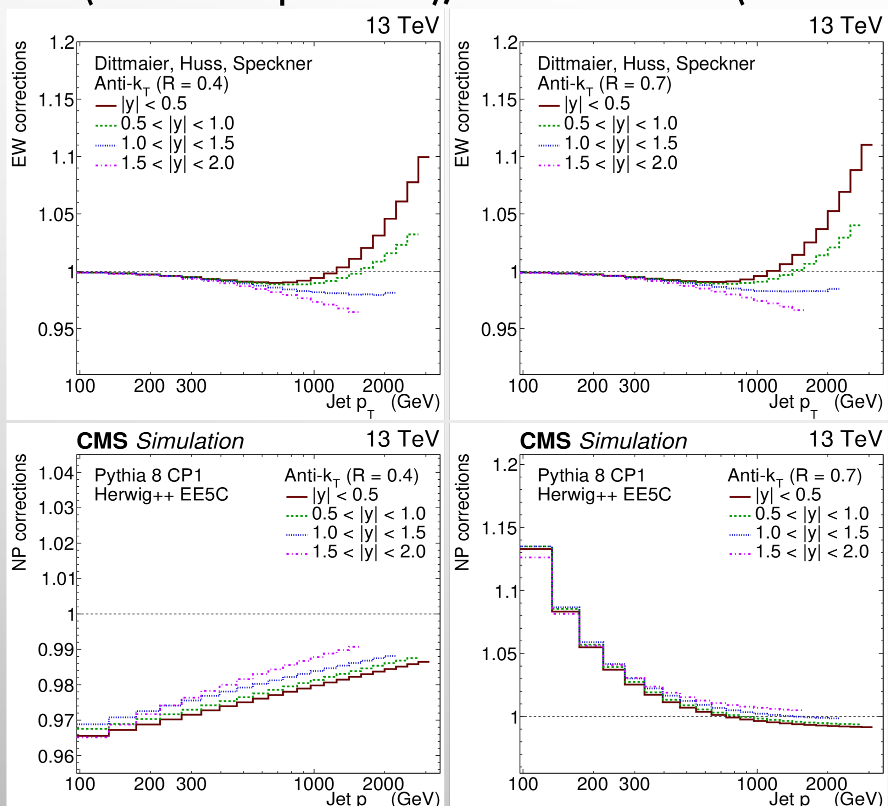
Fixed pQCD at NLO and NNLO with NLOJet++ and NNLOJET

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

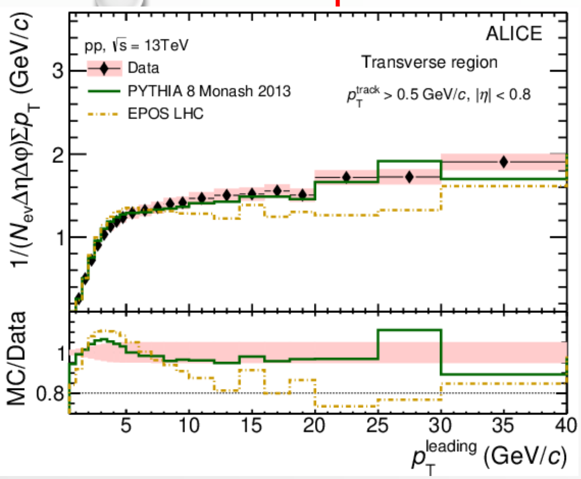
NP corrections:

PYTHIA 8 CP1 tune

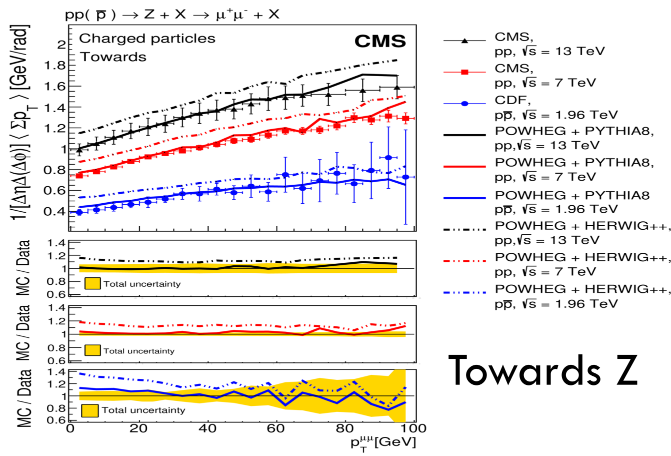
HERWIG++ EEC5 tune

Underlying events

High p_T track
or Tracker jets

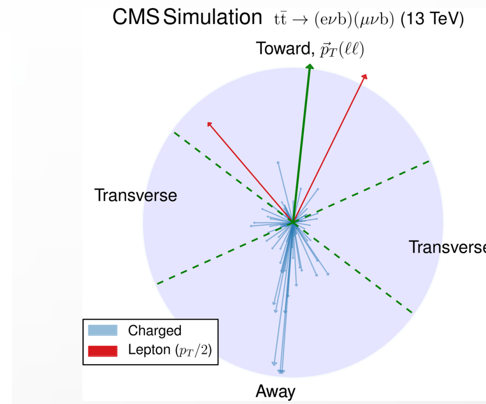


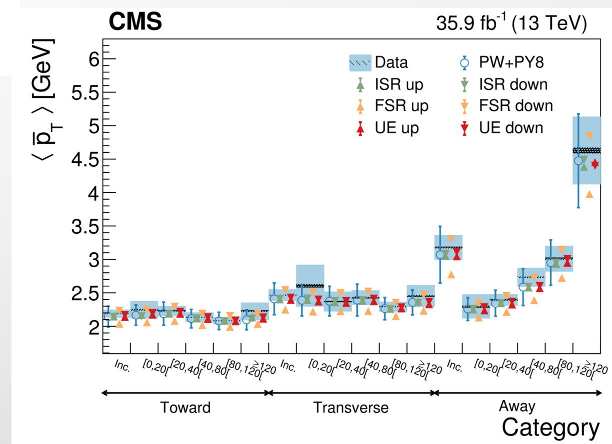
Z+jets

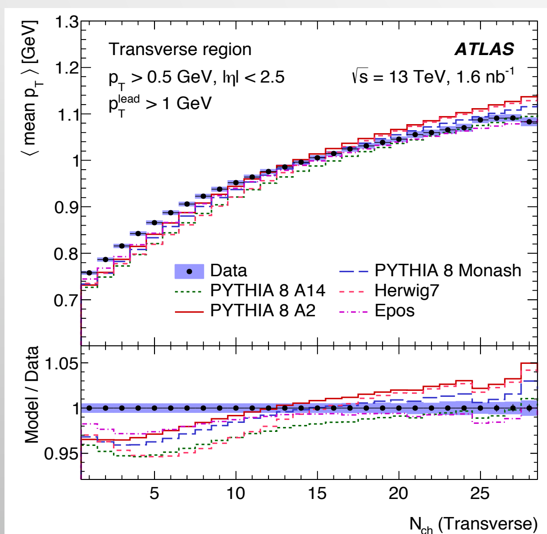


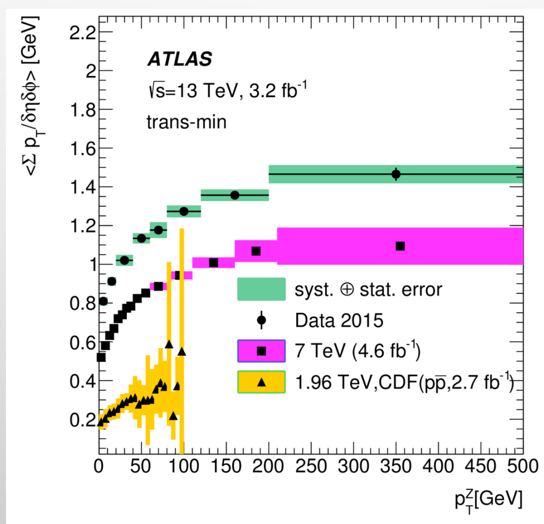
Towards Z

ttbar events





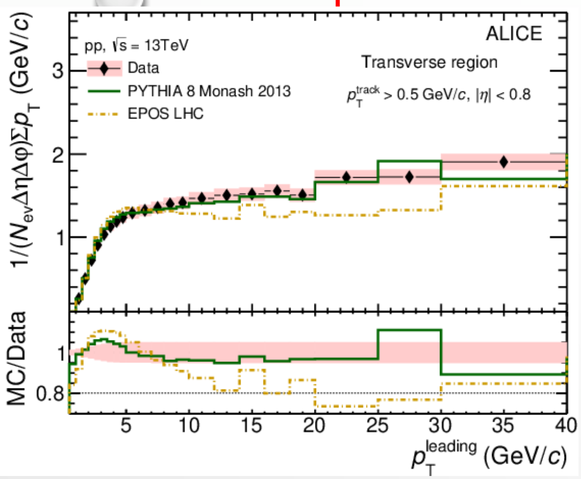




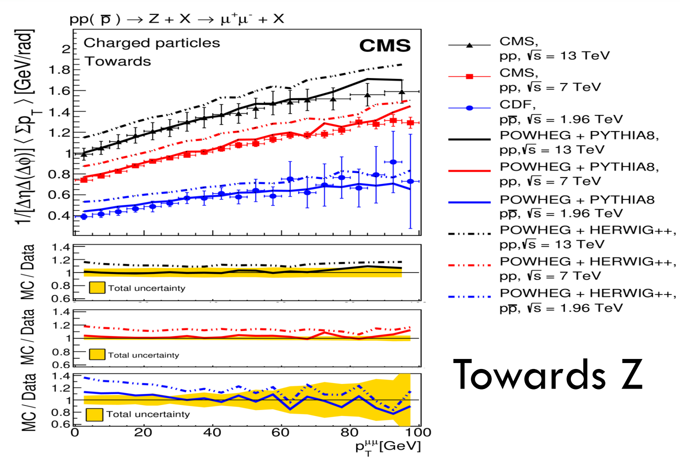
JHEP 07 (2018) 032
EPJC 79 (2019) 123
JHEP 09 (2015) 137
JHEP 03 (2017) 157
EPJC 79 (2019) 666
JHEP04 (2020) 192

Underlying events

High p_T track or Tracker jets

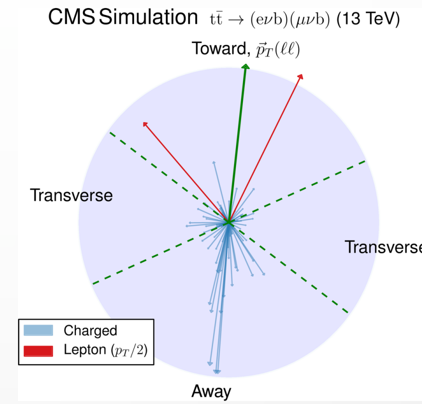


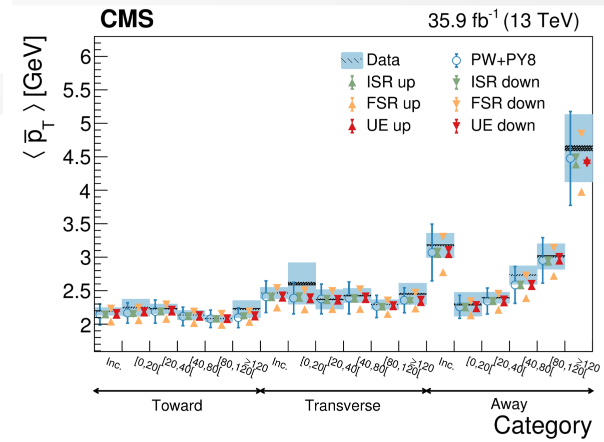
Z+jets

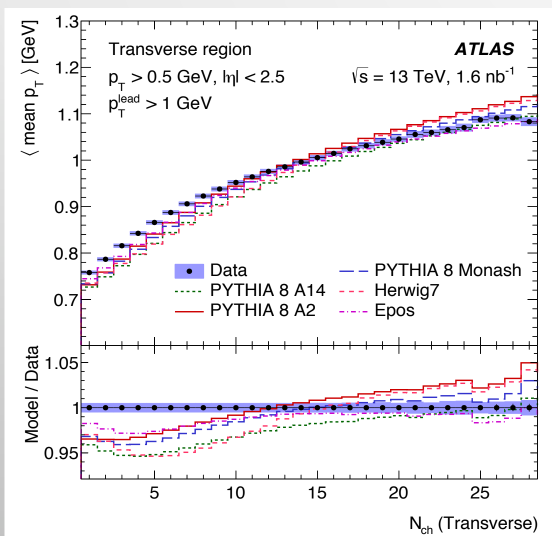


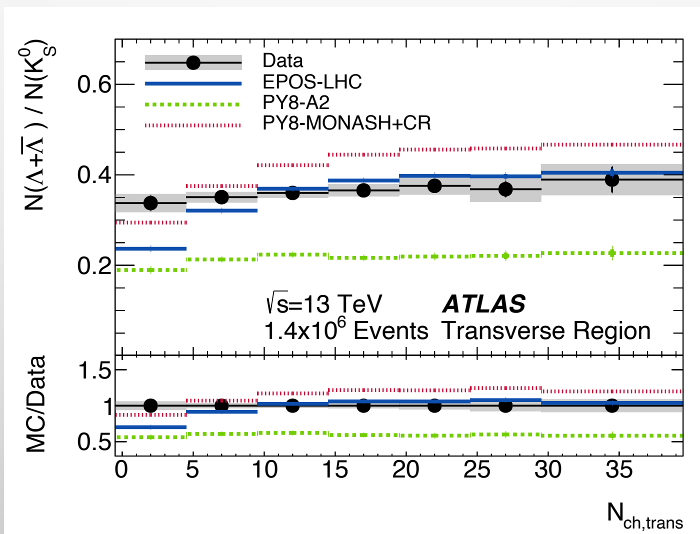
Towards Z

ttbar events









JHEP 07 (2018) 032
EPJC 79 (2019) 123
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JHEP 03 (2017) 157
EPJC 79 (2019) 666
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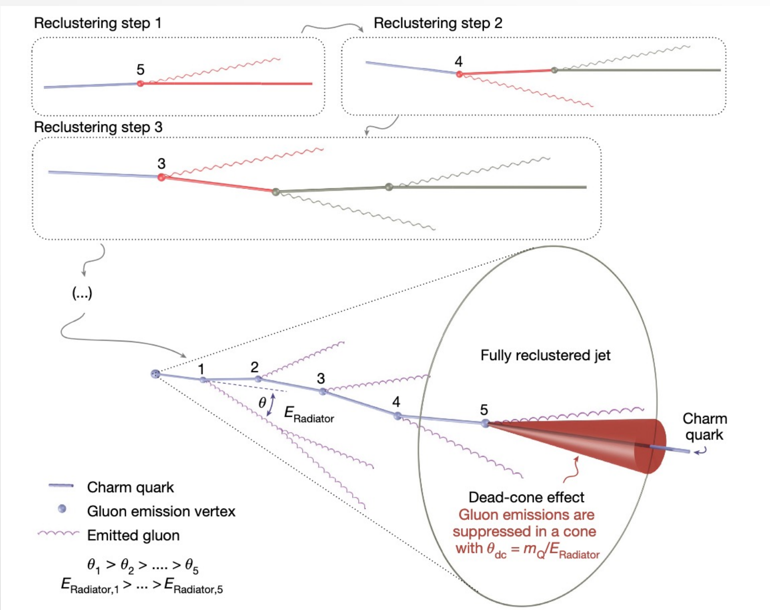
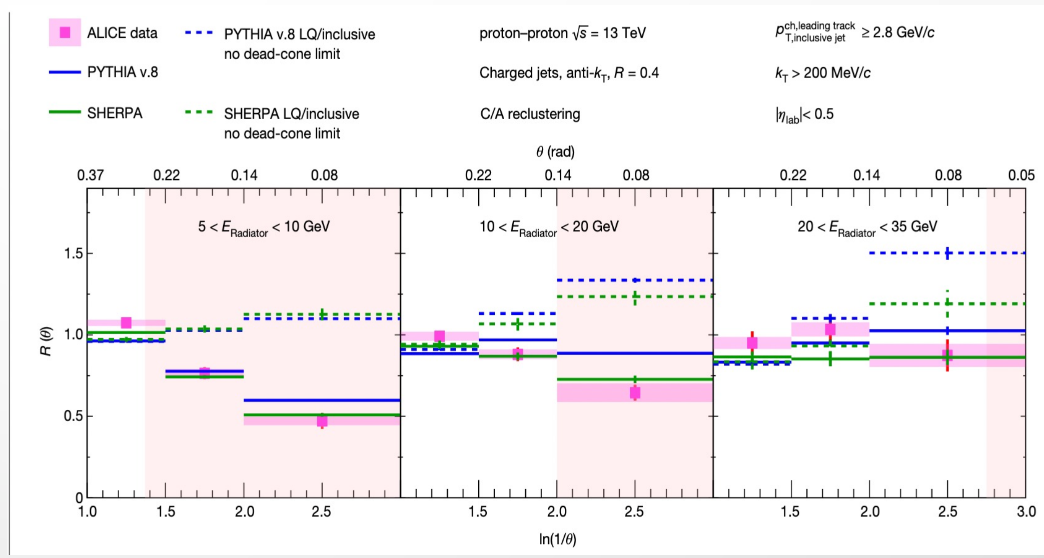
Dead cone effect for heavy quarks

- 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





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

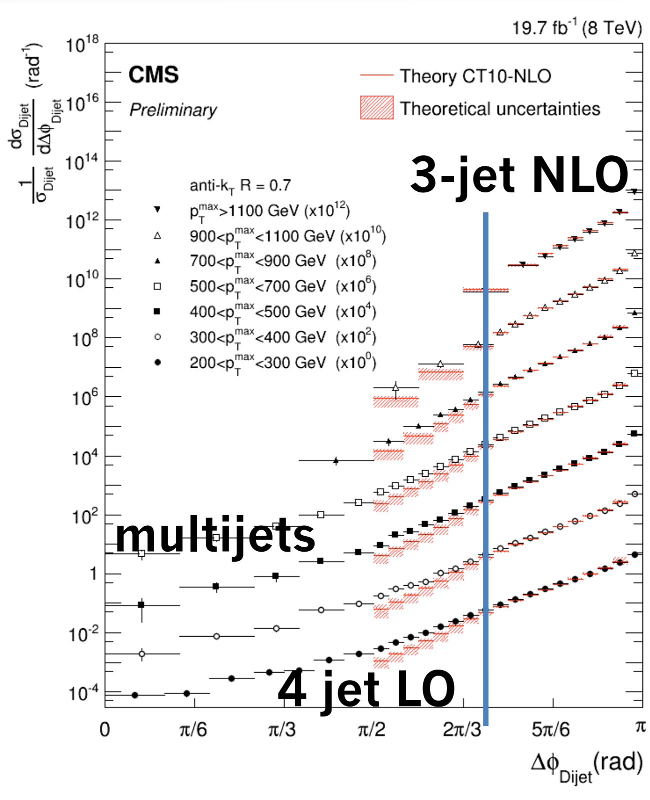
First direct observation of the dead cone effect.

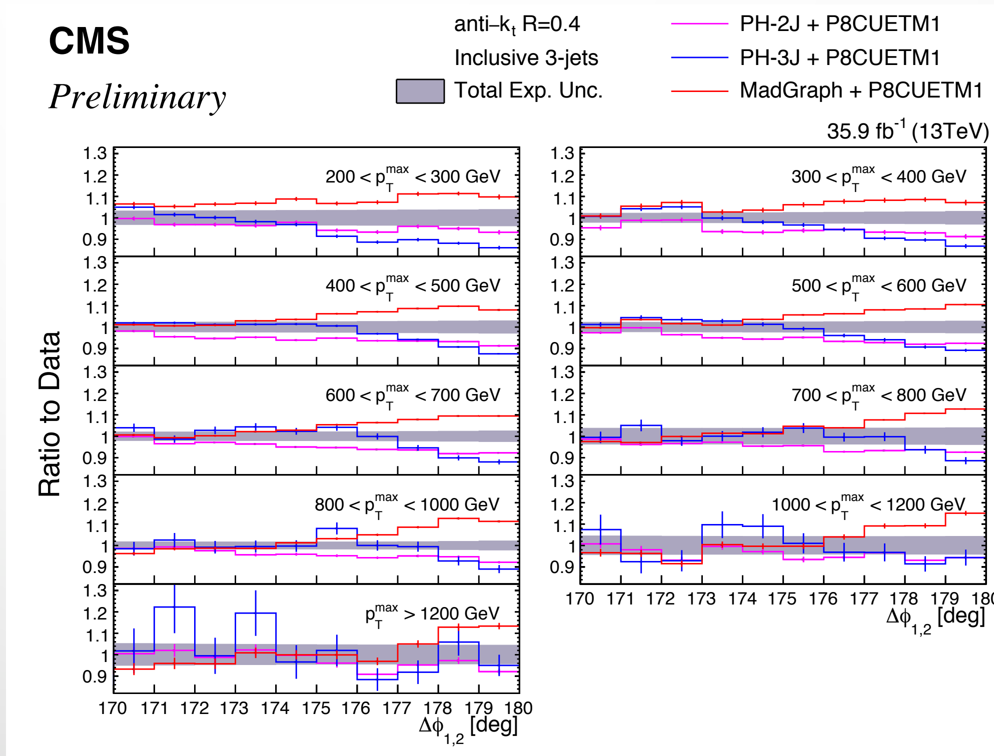
ALICE: Nature volume 605, p. 440–446 (2022)

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





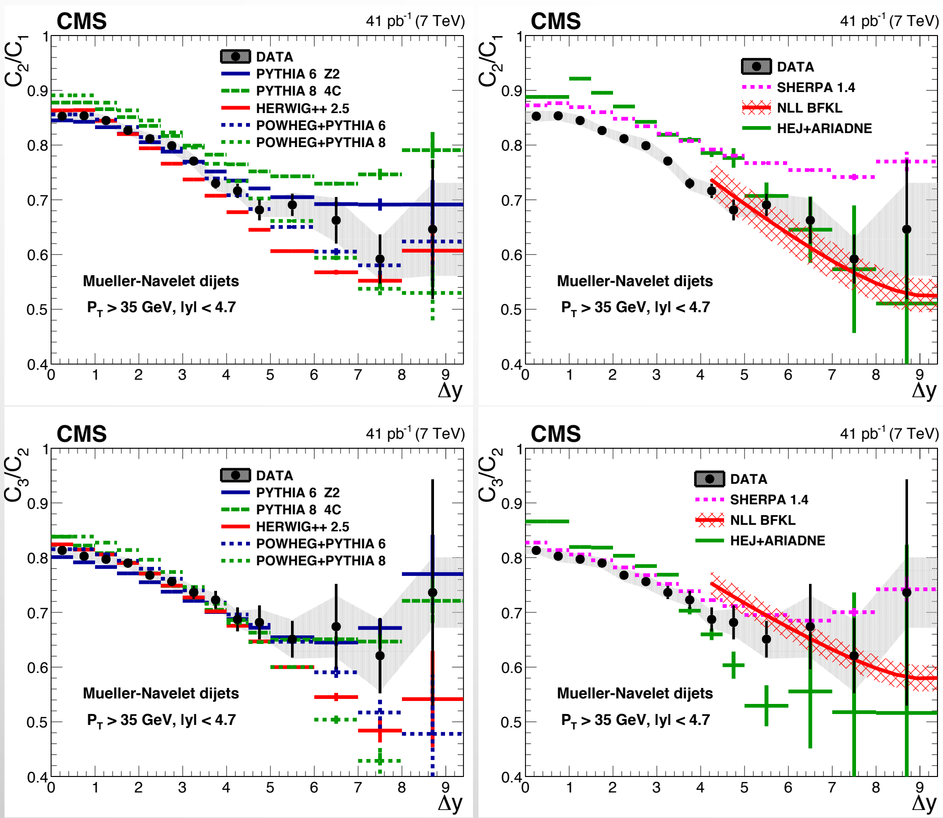
Comparison is done with fixed-order pQCD (NLO) and with LO ME+PS

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 $|\eta| < 4.7$
- For a pair of jets with the largest $\Delta\eta$ (CMS) the angular distance is calculated: $\Delta\varphi = \varphi 1 - \varphi 2$



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

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 $\Delta y > 4$

JHEP08(2016)139