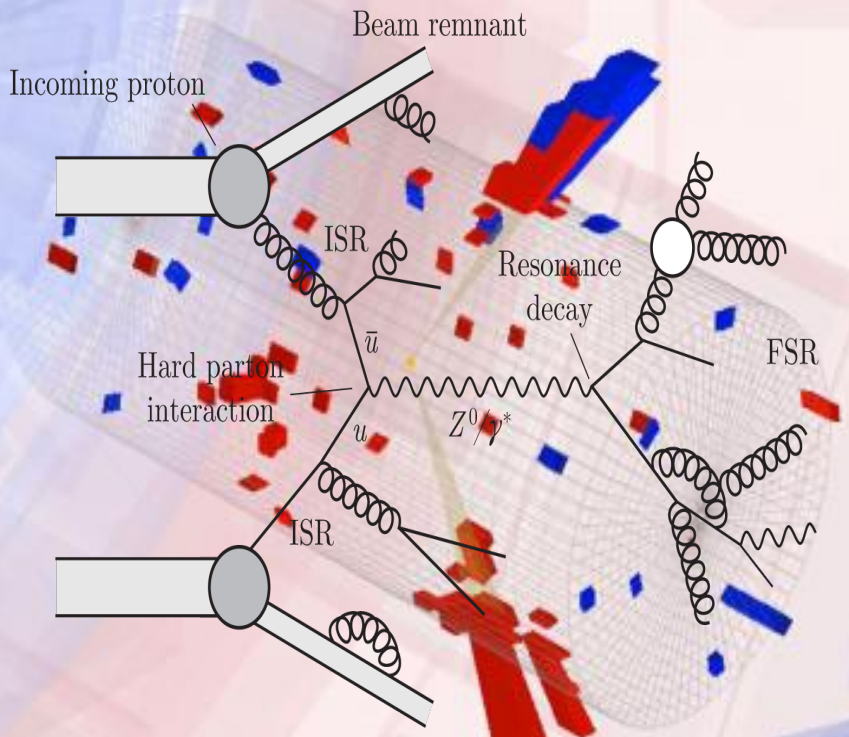
Precision QCD Measurements from CMS



Salim CERCI
Adiyaman University
On behalf of the CMS Collaboration
10/6/2021

LHCP2021
The Ninth Annual Conference on Large Hadron Collider Physics
Online
7-12 June 2021 Paris (France), Sorbonne Université
9th Edition of the Large Hadron Collider Physics Conference

Outline

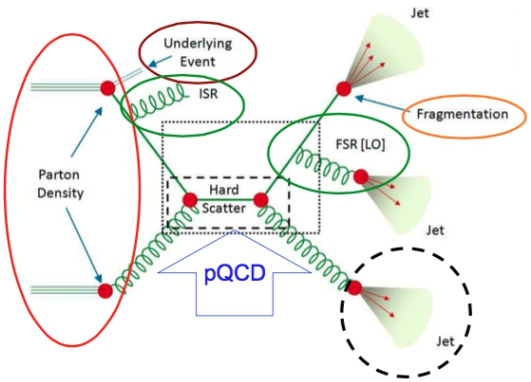
- Introduction
  - QCD at LHC
- QCD measurements
  - 3-jet/Z+2jet angular+momentum (SMP-17-008 submitted to EPJC)
  - Radius scan for inclusive jets (SMP-19-003, JHEP12(2020)082)
  - Differential Z/gamma jets (SMP-19-010, submitted to JHEP)
  - Differential Z+c jet cross section (SMP-19-011, JHEP04(2021)109)
  - Azimuthal correlations (SMP-17-009, EPJC 79 (2019) 773)
- Summary
  - ★ **Many more results exist and and are discussed in details in the other talks.**

QCD @ LHC

- The main goal of QCD studies is to improve our detailed description of the SM physics.
- QCD is the theory of strong interaction describing the interactions between quarks & gluons

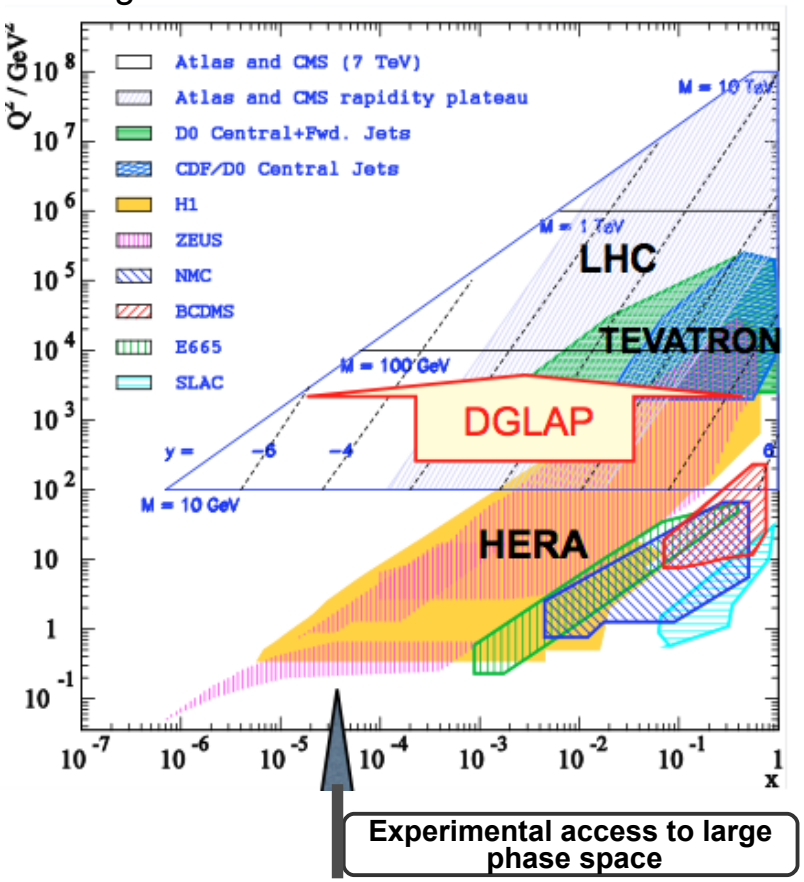
Hard QCD

- Perturbation theory pQCD
- PDFs
- Initial & final state radiation (ISR, FSR)
- Parton shower & hadronization



Soft QCD

- Multiparton scattering
- UE activity
- Fragmentation



- QCD events are immensely complicated
  - theoretical predictions very hard
  - Experimental challenges
- Studies of QCD are key to understand production of all (B)SM signals & backgrounds at the LHC.

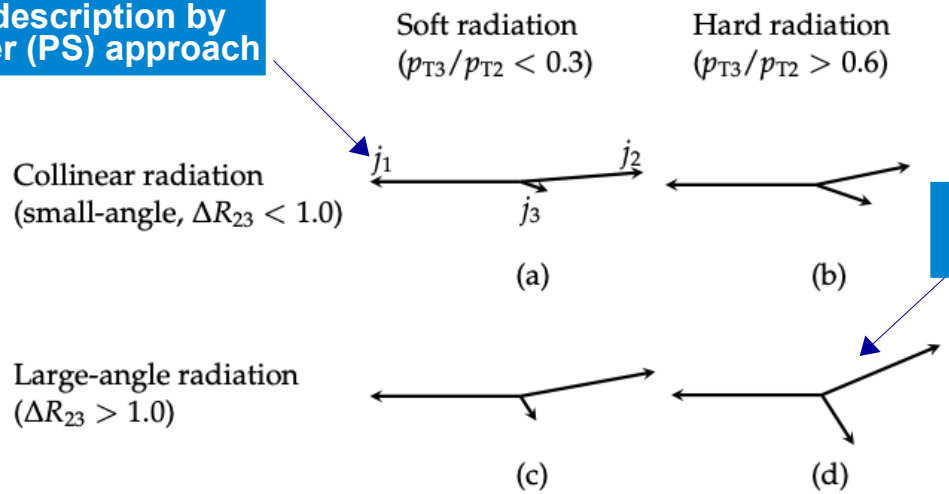
Multi-jet Correlations

SMP-17-008
(submitted to EPJC)

- Multi-jet correlations are sensitive to the modeling of radiative processes.
- Goal : study to probe large or small angle, soft and hard radiation.
- Measure two observables of sub-leading jets in 3-jet events (8 & 13 TeV) & Z+2-jet events (8 TeV) :
  - **Transverse momentum ratio** (p_{T3} / p_{T2}) and **angular separation** (ΔR_{23})
- Split events into categories of interest

Expect good description by Parton Shower (PS) approach

j_1, j_2, j_3: p_T-ordered jets (Z boson is j_1)

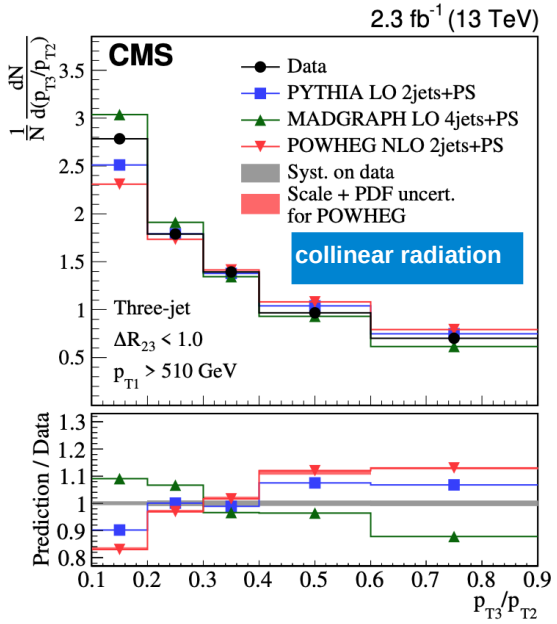


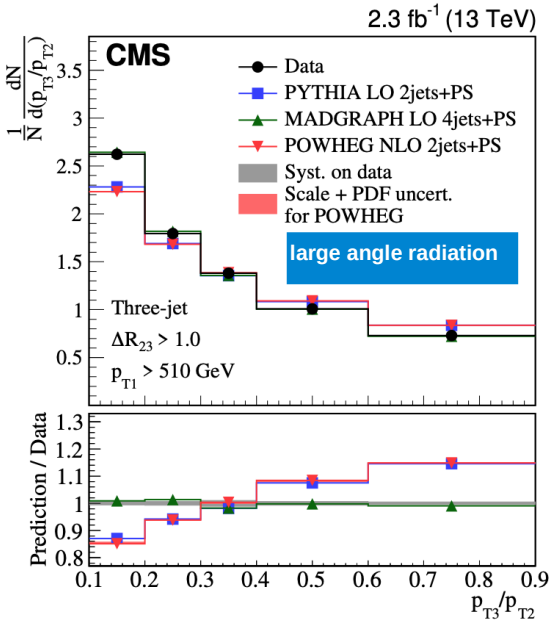
Expect good description by matrix Element (ME) calculation

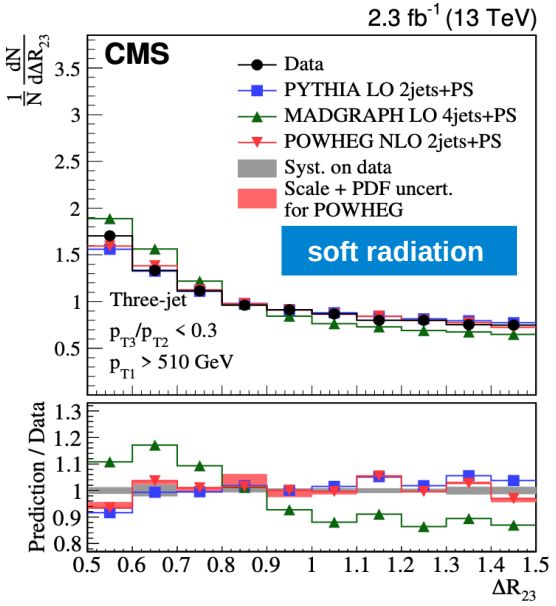
Multi-jet Correlations

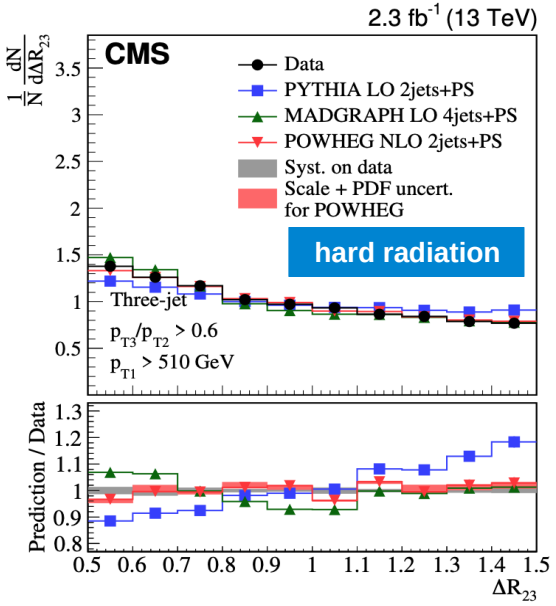
SMP-17-008
(submitted to EPJC)

- Large-angle and hard radiation well described by calcuations using higher order ME (LO 4j+PS).
- Soft region well described by PS approach (LO 2j+PS and NLO 2j+PS).
- Collinear region not well described by either.







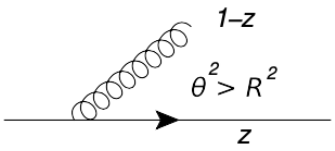


Radius scan of inclusive jet cross section

JHEP 12 (2020) 082
SMP-19-003

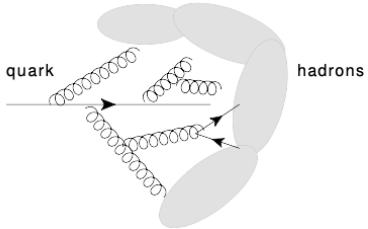
- Double differential (p_T, y) jet cross sections are sensitive to PDFs over a wide (x,Q^2) range, in particular high-x gluon and valence
- R is sensitive to various processes in the evolution of parton into jet (radiation & PS, hadronization, UE)
- δp_T ≡ "lost" transverse momentum → calculated using a QCD splitting function, with LO in the small-R approx. (R<<1)

Parton shower:
$(\delta p_T)_{PS} \sim \ln(1/R)$

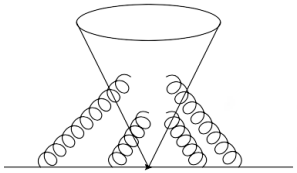


Suggests to use large R

Hadronization:
$(\delta p_T)_{HAD} \sim R^{-1}$



Underlying event activity:
$(\delta p_T)_{UE} \sim R^2$



warns to use small R

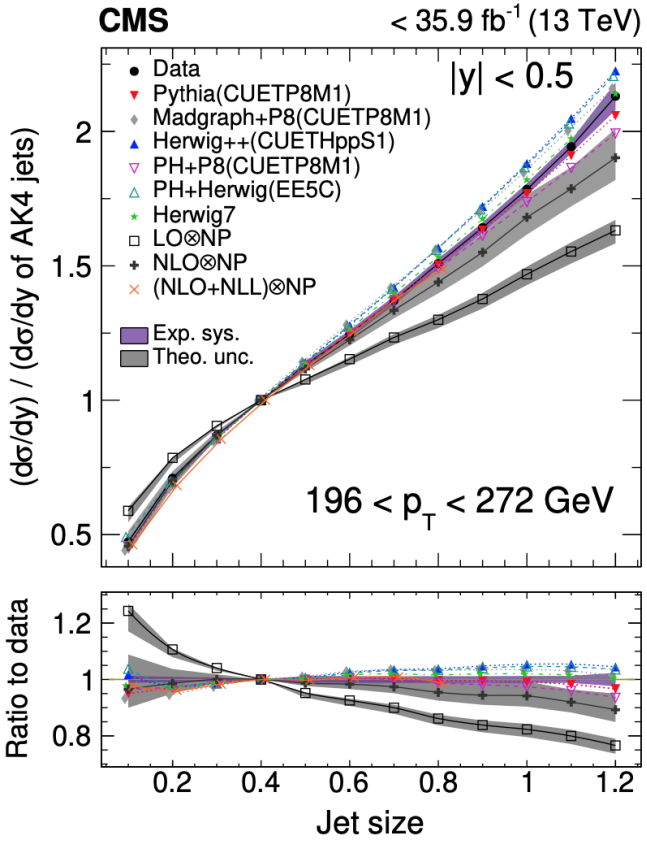
Measurement

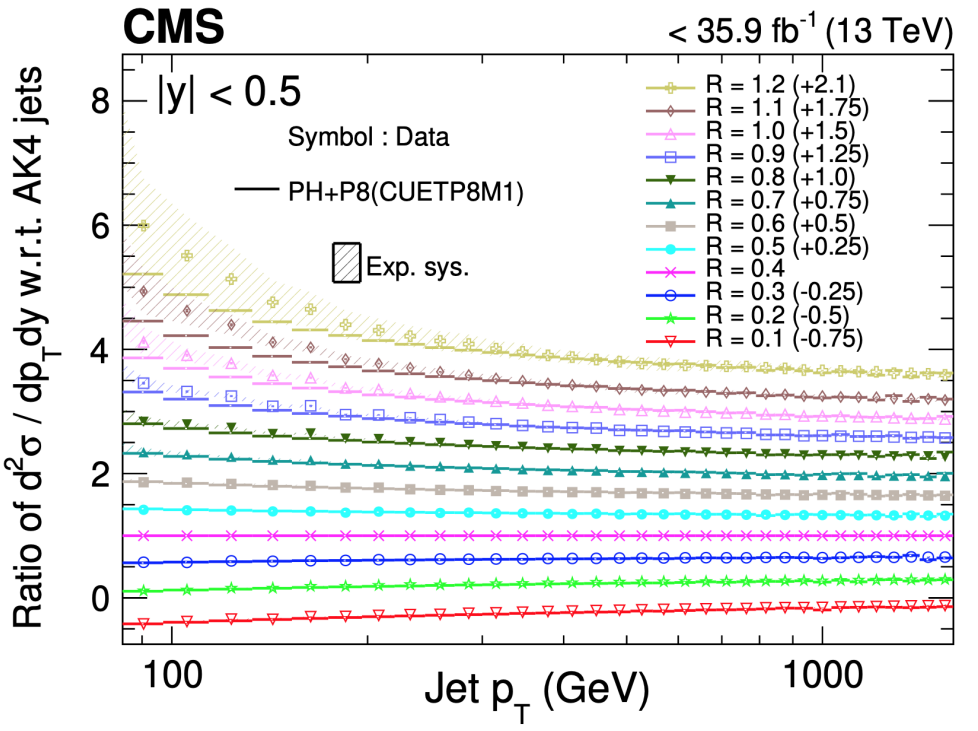
- 2016 data used
- PF jets (p_T> 84 GeV; |η| < 2.5); 0.1 < R <1.2
- Double-differential inclusive jet cross section ratio
- Unfolding to particle level
- Comparisons to LO and NLO predictions

Radius scan of inclusive jet cross section

JHEP 12 (2020) 082
SMP-19-003

- Inclusive jet cross sections are determined in p_T and y bins for all the jet sizes
- Ratio is taken with respect to AK4 inclusive jet cross section in the same p_T and y bin





- NLO+PS calculations agree well with for high jet p_T (all R) data.
- NLO corrections on fixed-order LO are needed.
- Accurate modeling of non-perturbative (UE, hadronization) effects is essential.

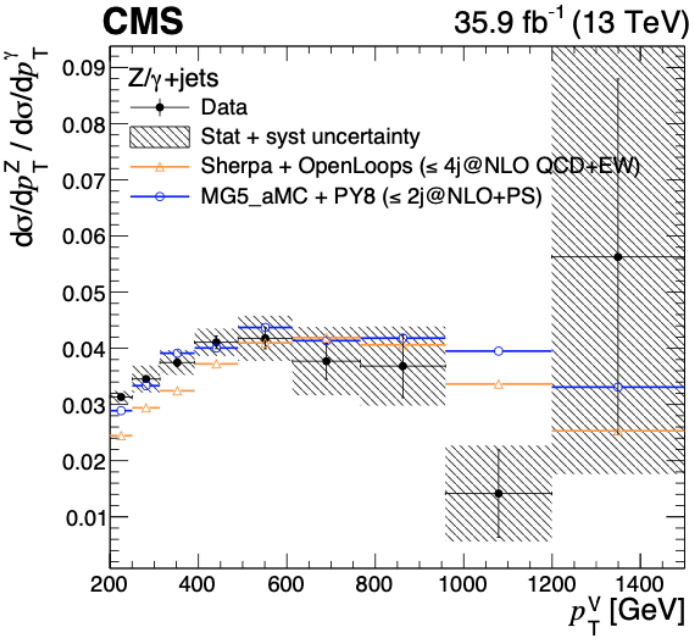
Z/γ + jets differential cross section

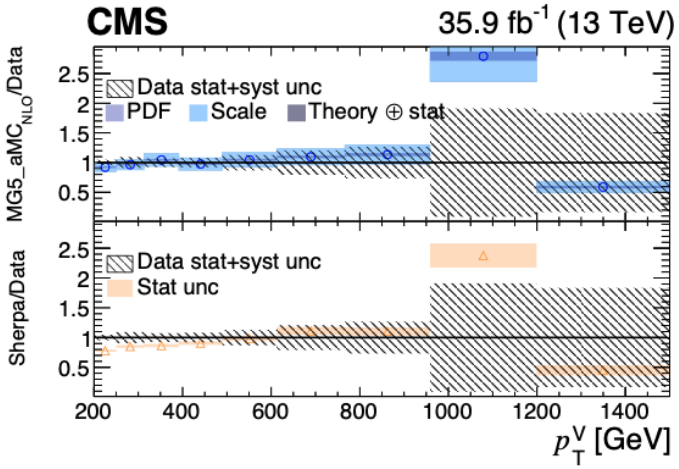
SMP-19-010 (submitted to JHEP)

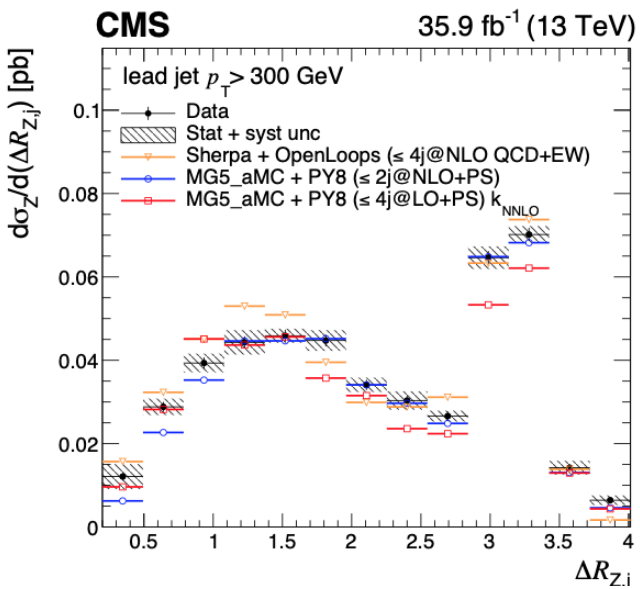
- Z/γ ratio is sensitive to higher order EW corrections at high p_T
- Precision test of pQCD
- Important input to constrain backgrounds in searches
- First measurement of collinear emission of a Z + high p_T jet!

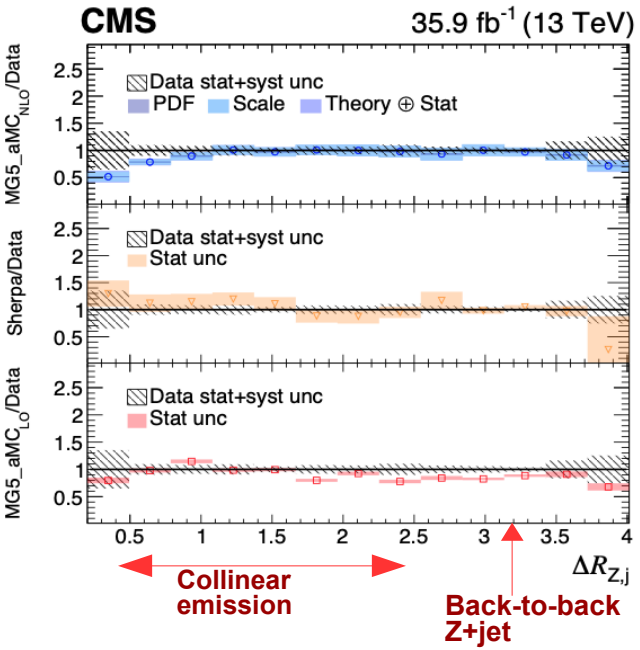
Measurement

- Differential cross sections & ratio presented vs p_T & $\Delta R_{Z,jet}$
- 2016 data, Z bosons reconstructed from muons (p_T>100 GeV; |η|<2.4)
- Requires lead jet (p_T>100 GeV |η|<2.4), and photons (p_T >200 GeV; |η|<1.4) , testing bosons p_T up to 1.5 TeV.
- Comparison with LO+ NLO predictions
- Consistency within the uncertainties across the entire p_T range







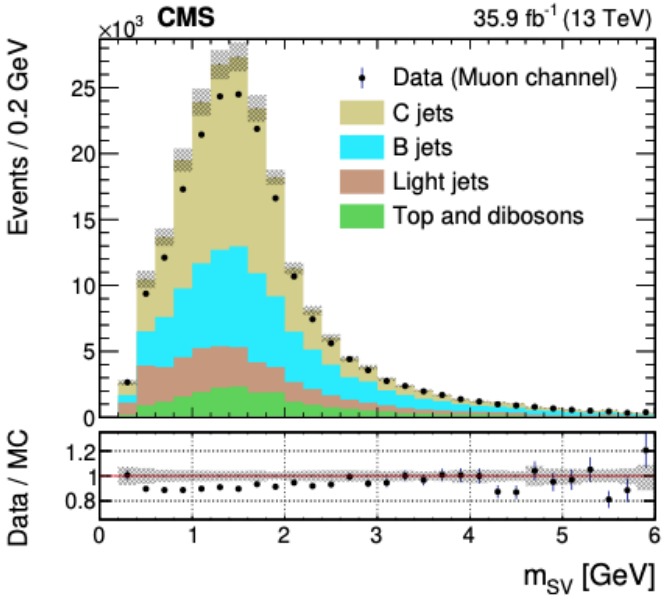


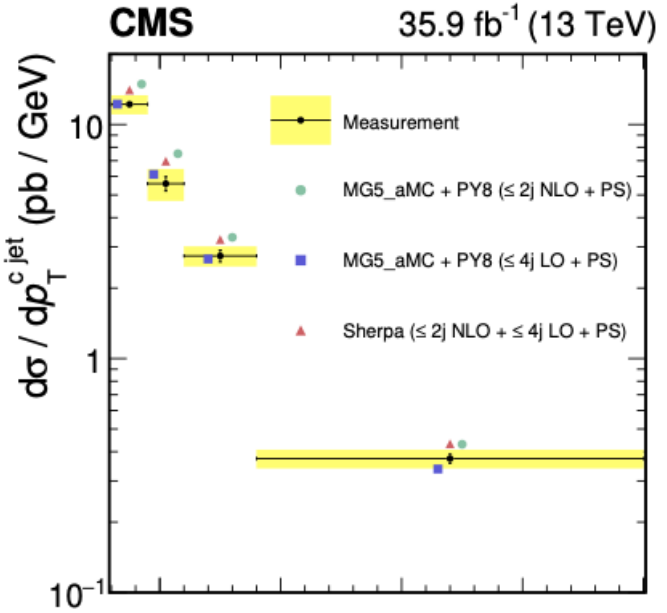
Z+c jet production

JHEP04(2021)109
SMP-19-011

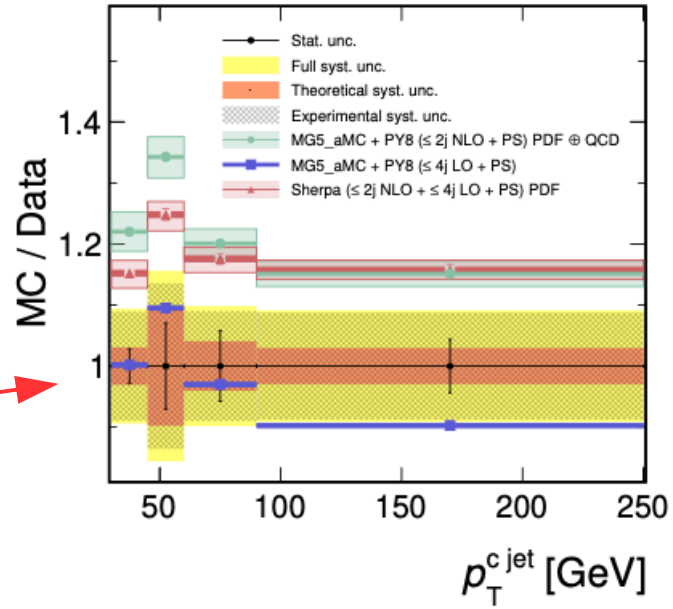
- Z+c is sensitive to charm content: perturbative and NP (i.e. intrinsic charm)
- important background in BSM searches

- Extract Z+c components with fit to the invariant mass of tracks m_{SV} associated with secondary vertex.





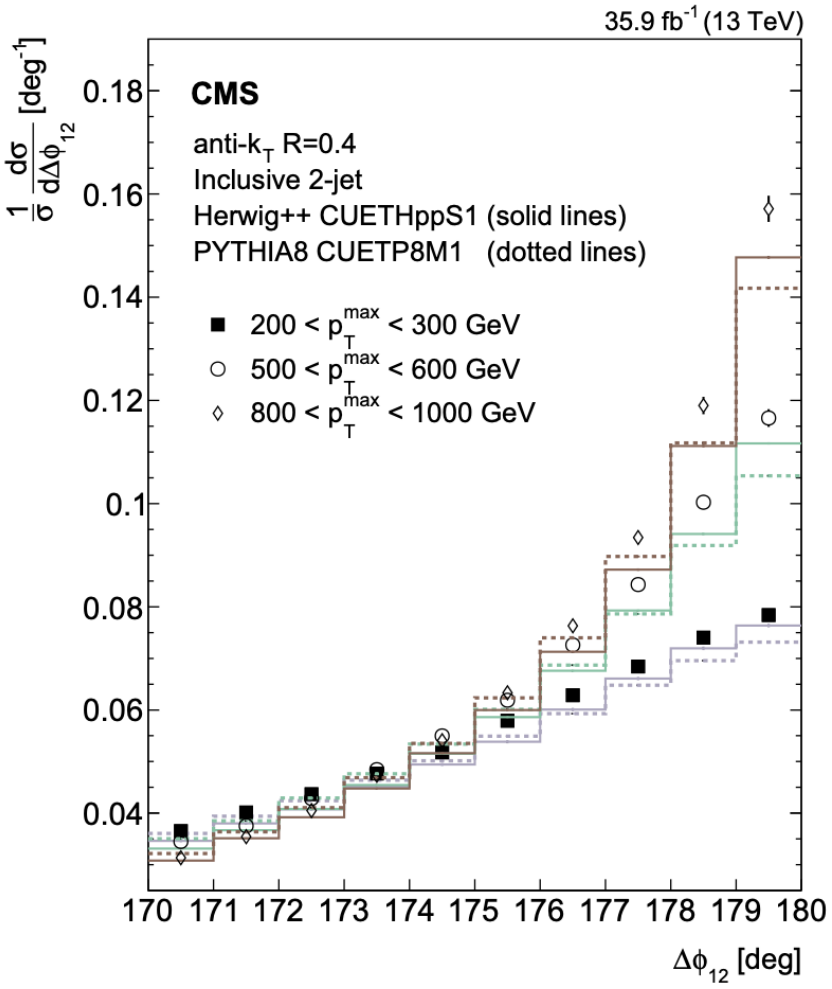
- Madgraph LO agrees well within uncertainties
- Sherpa (NLO) and Madgraph NLO overestimate the data.
- Inclusive Z+jets agrees better with NLO - PDFs may overestimate charm quark content in the proton.

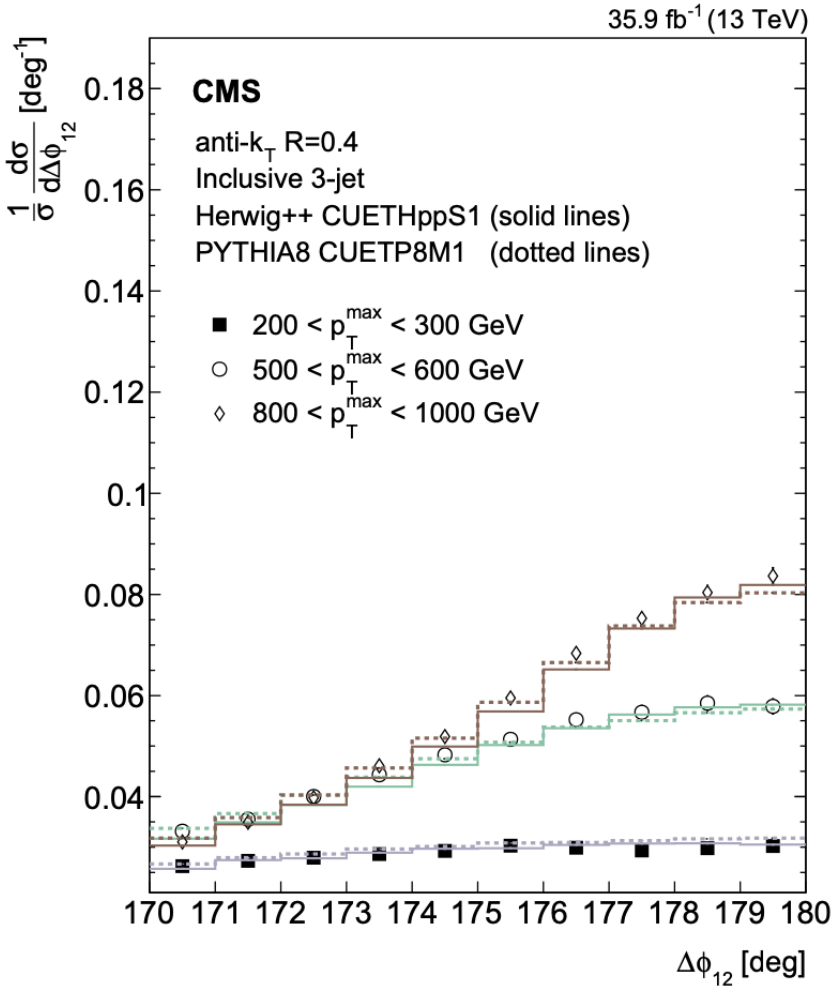


Azimuthal correlations

EPJC 79 (2019) 773
SMP-17-009

- Measurement for inclusive 2- and 3-jet events of the azimuthal correlation between the two jets with the largest p_T : $\Delta\varphi$
- Allows a more precise test of different resummation strategies
- Consider events: the two leading jets are nearly collinear ("back-to-back") $\Delta\varphi \sim 180^\circ$

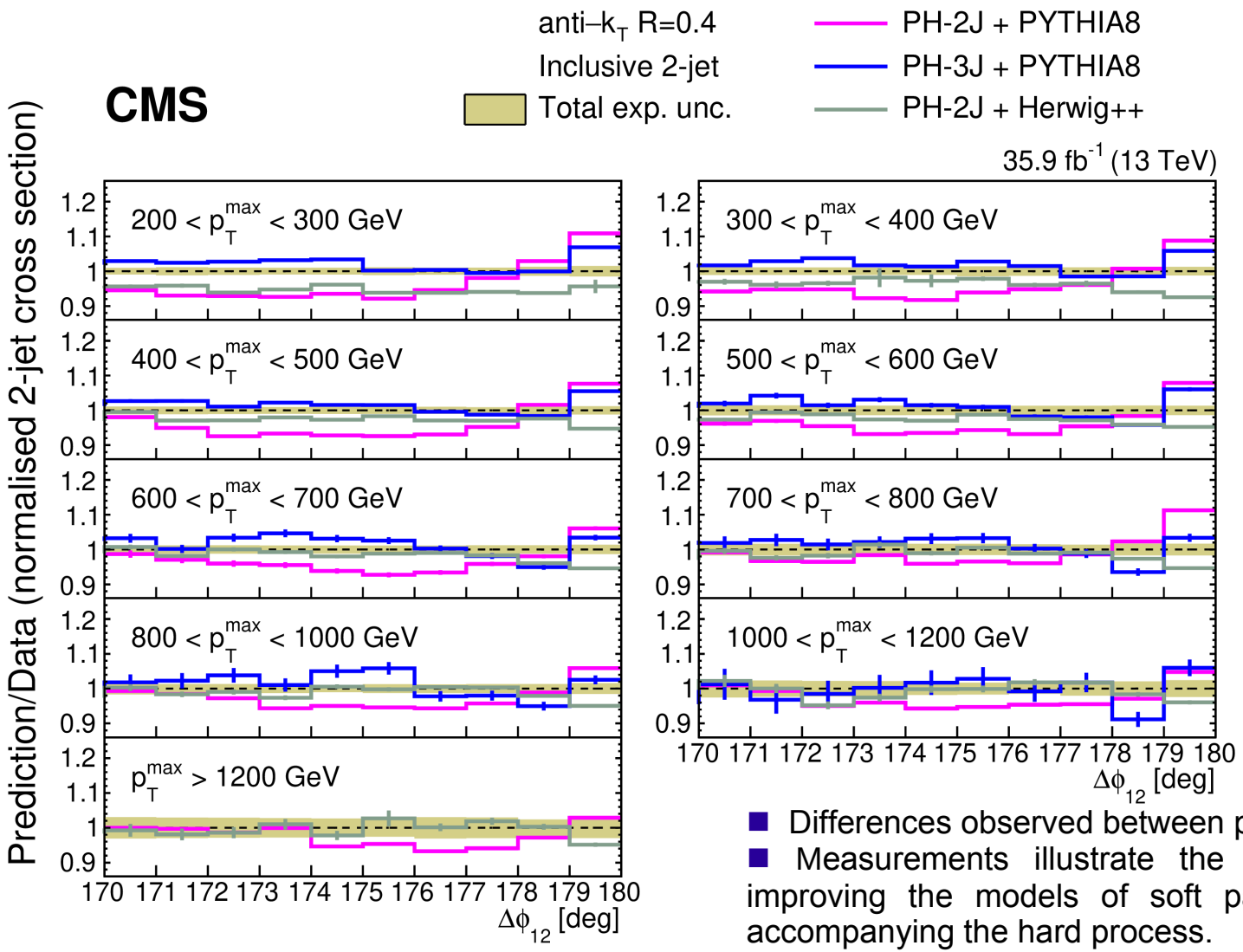




Azimuthal correlations

EPJC 79 (2019) 773
SMP-17-009

- MC@NLO method of combining PS with the NLO parton level calculations has advantages compared to the POWHEG method



- Differences observed between predictions
- Measurements illustrate the importance of improving the models of soft parton radiation accompanying the hard process.

Summary

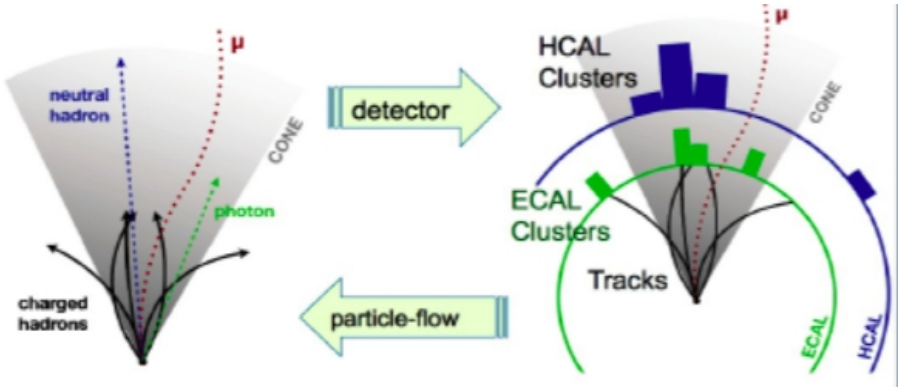
- Broad range of physics results to deepen our understanding of QCD
  - Investigation on modelling of soft, collinear, hard and large-angel QCD phase space with multijet correlation measurements
  - NLO modelling doing well with Z/γ +jets
  - Z+c measurement shows PDFs may overestimate charm content
- New measurements are still to come to be used in precision QCD analyses and to improve the understanding of the proton structure

THANKS FOR YOUR ATTENTION!

BACKUP

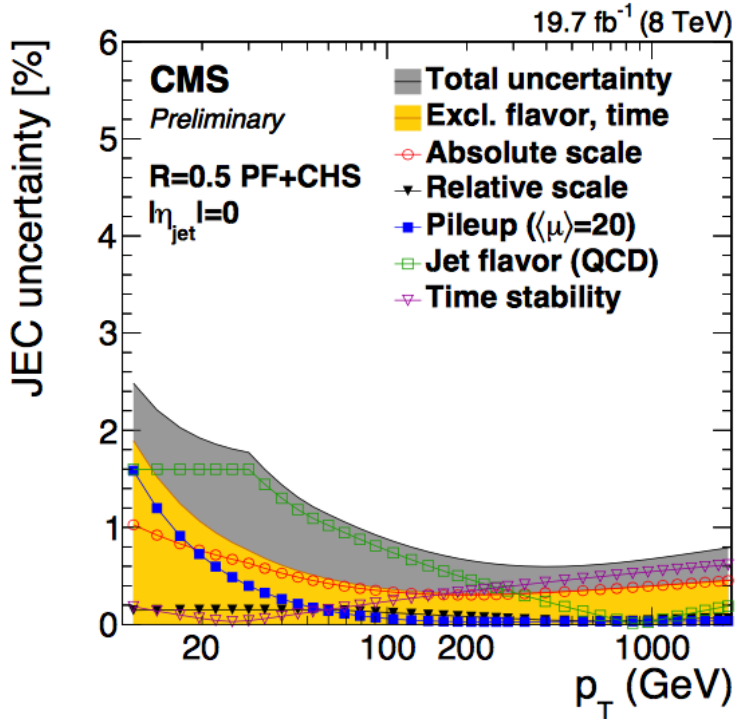
Jet reconstruction and jet calibration @ CMS

- Jet reconstruction procedure:
  input objects (e.g. particles) → apply jet finding algorithm → jet reconstruction



- Particle Flow (PF) is an event reconstruction technique which attempts to reconstruct and identify all stable particles in the event, through the optimal combination of all CMS sub-detectors.

- PF Jets are the output of the jet algorithm on the reconstructed particles (e, μ, γ, charged and neurtal hadrons)



CMS DP-2015/044

- Anti-k_T jet clustering algorithm is used by CMS measurements

- Factorized Jet Energy Correction approach in CMS:

Calibrated Jet = Raw Jet × Offset Correction (pile-up) × Relative Correction (vs η) × Absolute Correction (vs pT)