DIS 2022

Santiago de Compostela
2-6 May

Measurements of untagged and HF-tagged inclusive jet distributions in proton-proton collisions by ALICE.

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on behalf of the ALICE Collaboration
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NATIONAL SCIENCE CENTRE POLAND

Motivation

Measurements of inclusive untagged and heavy-flavour tagged (HF) jets **test our understanding of strong interactions**

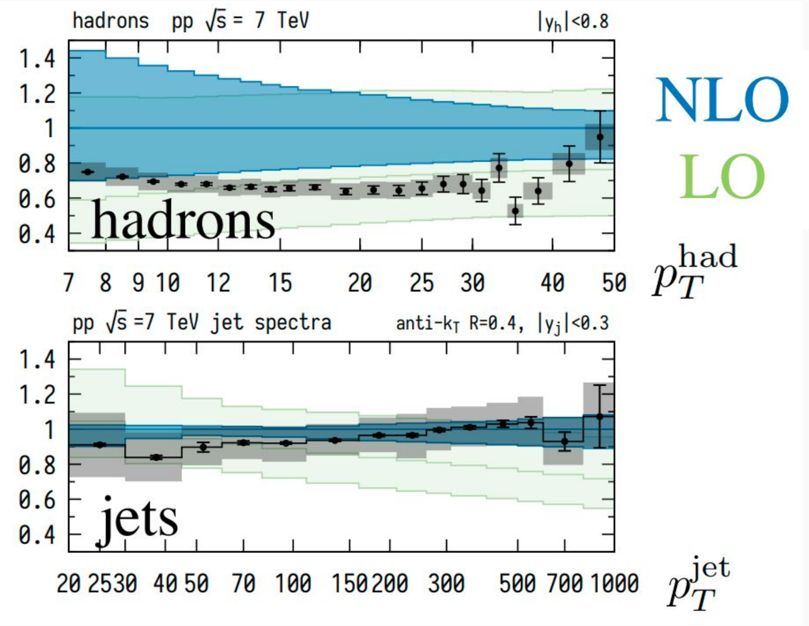
Compared to hadrons, jets are:

- not sensitive to fragmentation functions
- **under better perturbative control** ➜

HF jets allow to study:

- differences between quark and gluons fragmentation (at higher p_T)
- impact of quark mass (at lower p_T)

Ratio of pp spectra to NLO pQCD:

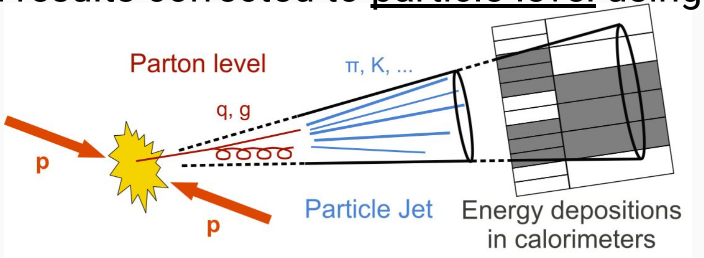


Brewer *et al.* [2108.13434]

Jet measurements in ALICE

Jet is defined by jet algorithm: usually anti-kt, parameter *R*. Various *R* show different sensitivity to perturbative effects, hadronization and UE. Taking ratio of two *R* is beneficial from both exp. and theory side (*see backup for details*).

All results corrected to <u>particle-level</u> using unfolding



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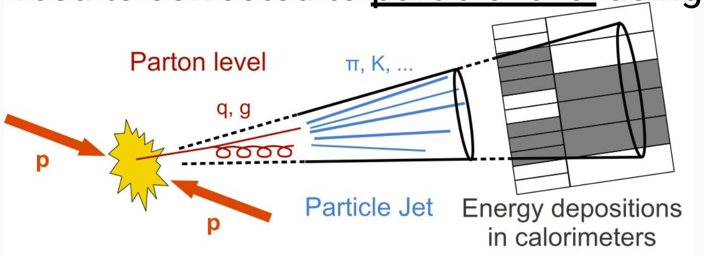

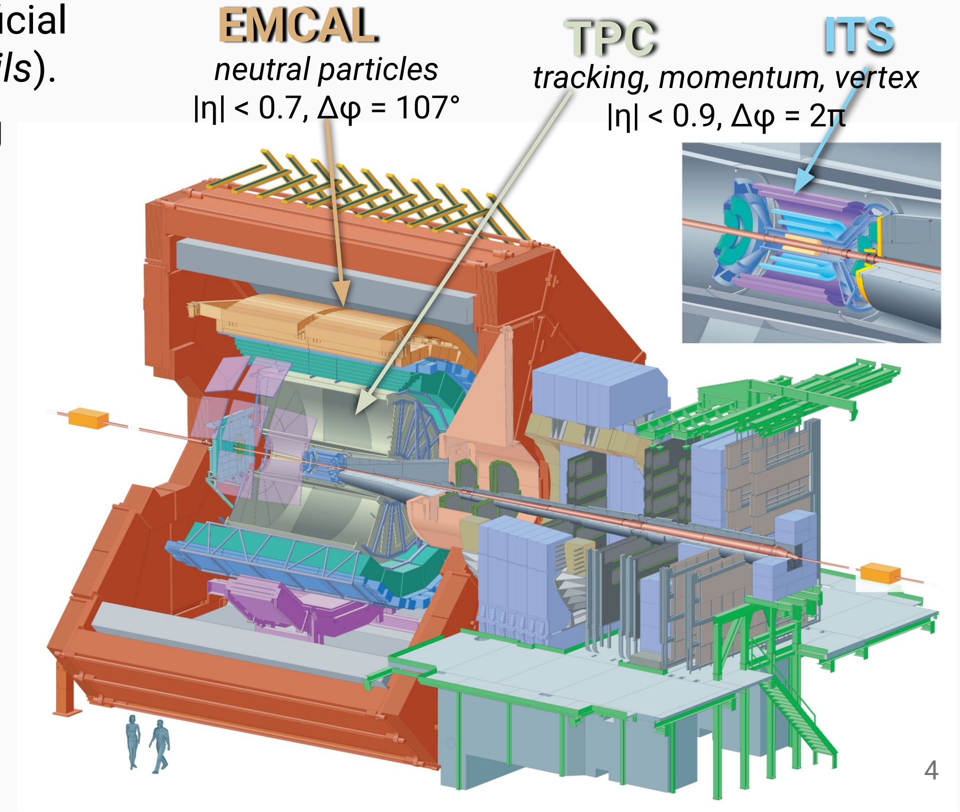

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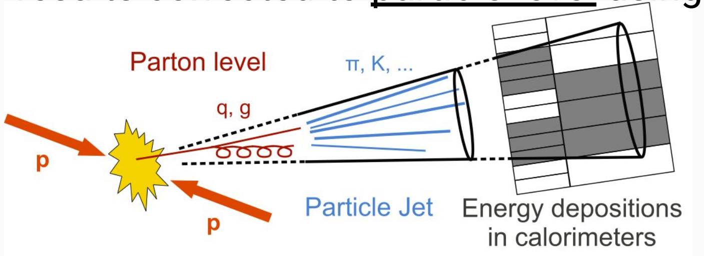
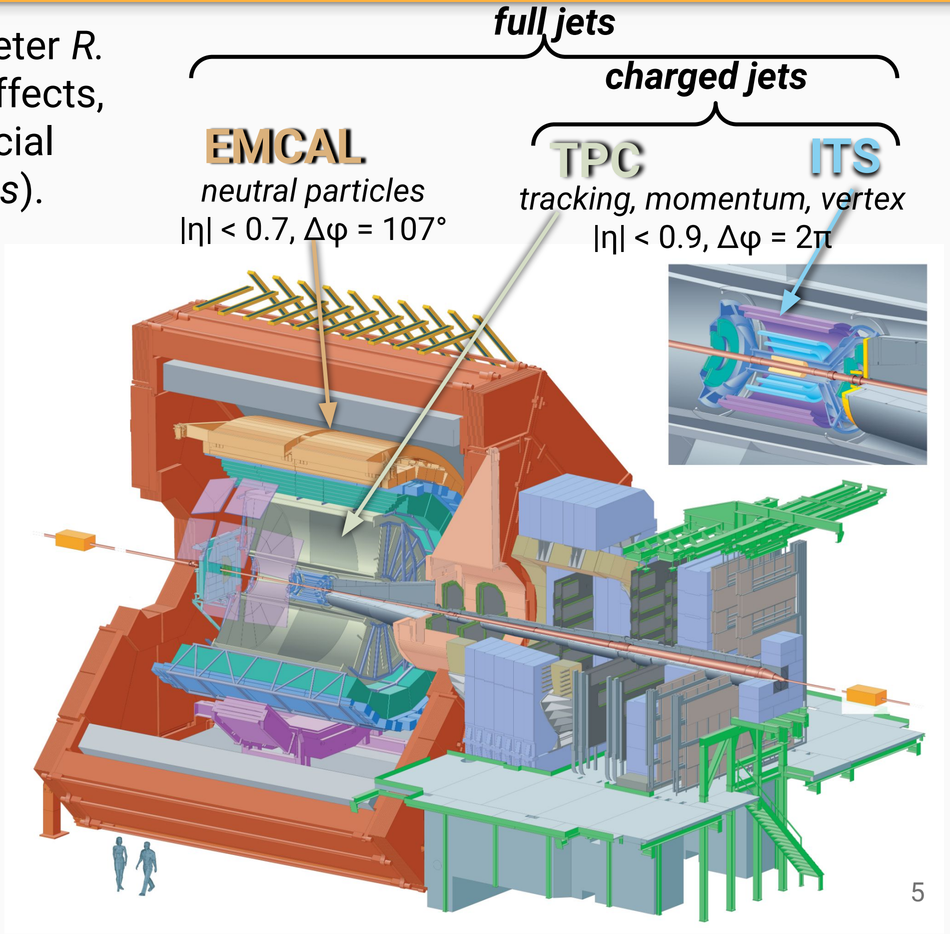


ALICE measures jets with **5 < $p_{T, jet}$** ≲ 140 GeV/*c*
Two types of jets distinguished:

"**charged**", i.e. using only charged constituents measured in ITS+TPC
better acceptance, preferred for substructure measurements

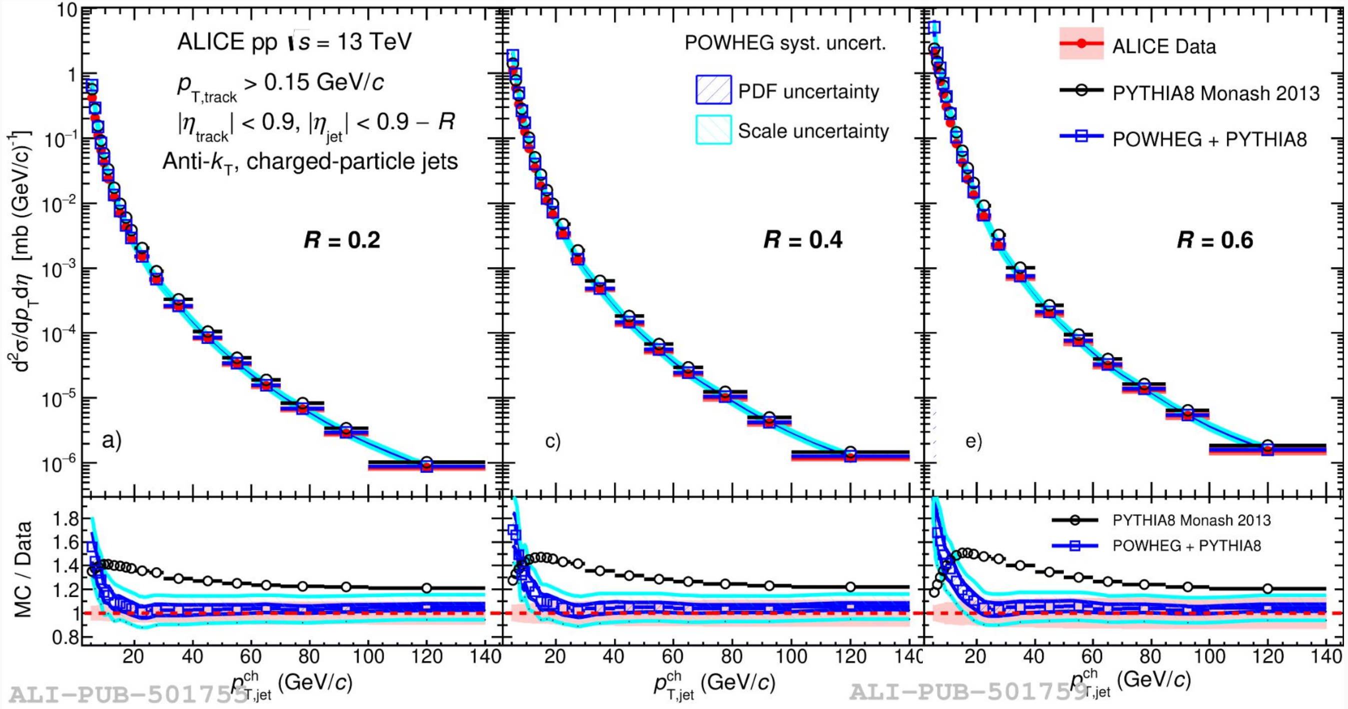
"**full**", including also neutral particles from EMCAL
more direct comparison to theoretical calculations, possible high p_T trigger



Charged jet production cross section, pp √s = 13 TeV

- **PYTHIA**: overestimates the cross section
- **POWHEG+PYTHIA**: good description above 10-20 GeV/c, below: large difference even 50-100%

arXiv:2202.01548



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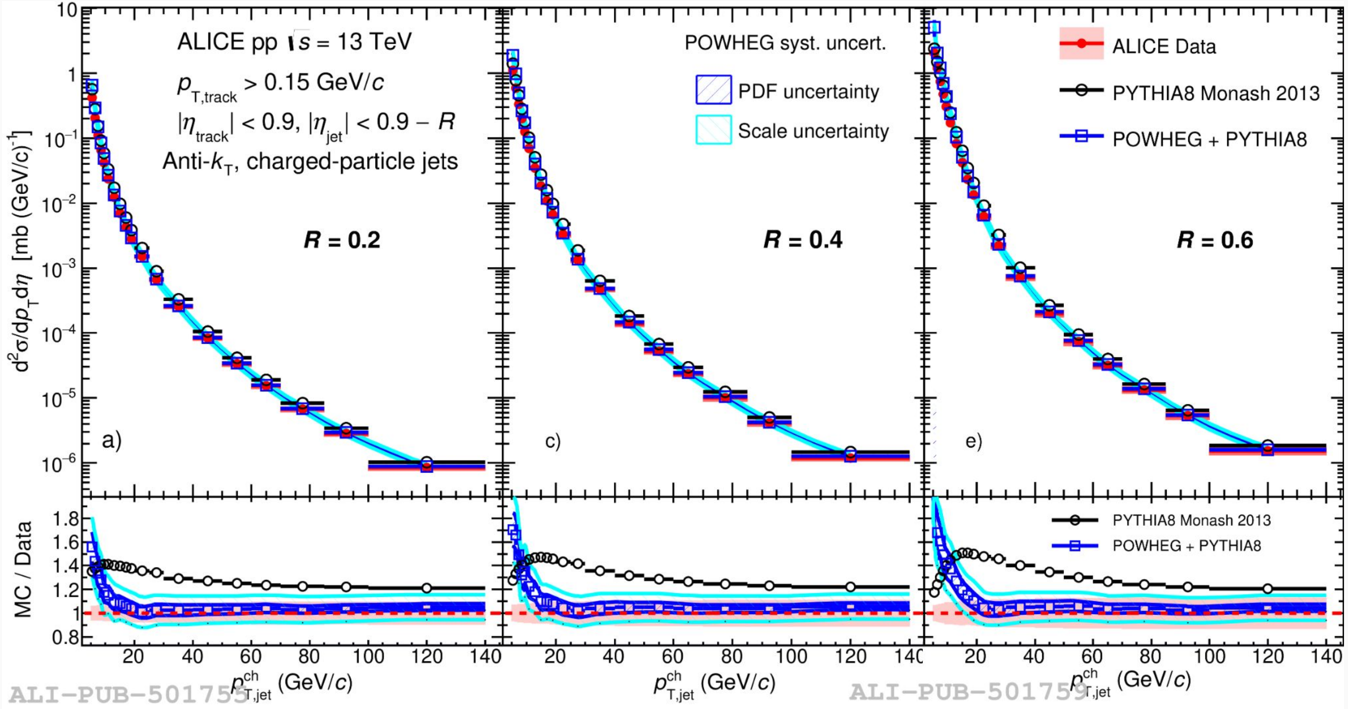
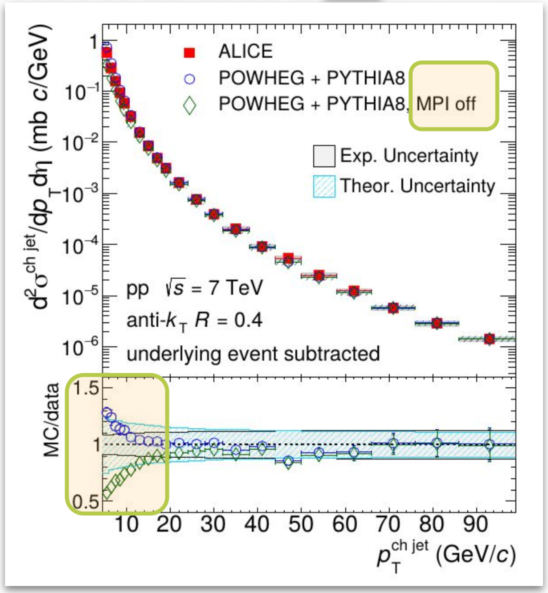


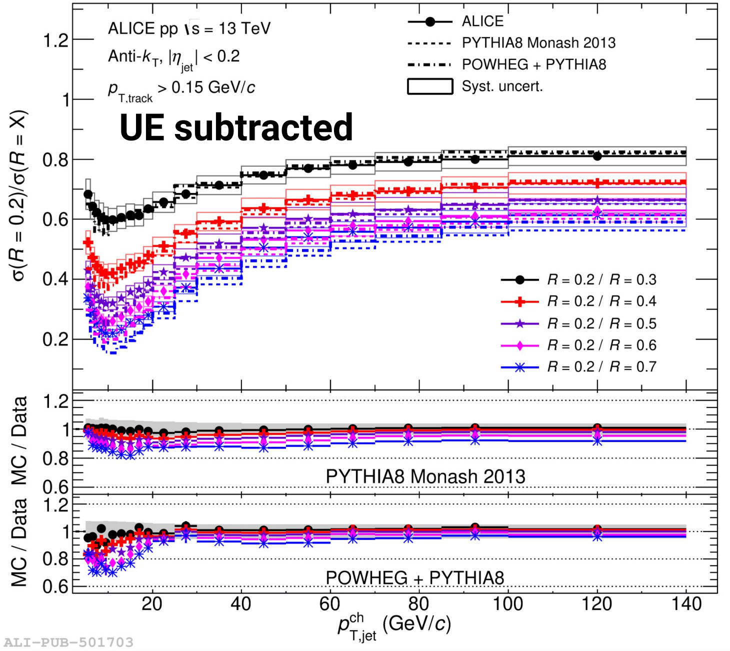
same observation for $\sqrt{s}$ = 7 TeV, could be attributed to **MPI** in PYTHIA



Phys. Rev. D 99 (2018) 012016

R – ratios

- Both PYTHIA and POWHEG+PY able to describe ratios at higher p_T
- Overestimation of cross section at low p_T increases with R => ratio underestimated
- For PYTHIA predictions: underlying event subtraction plays crucial role
- No significant dependence on collision energy (nor system) observed
- Universal behaviour: higher p_T jets are more collimated



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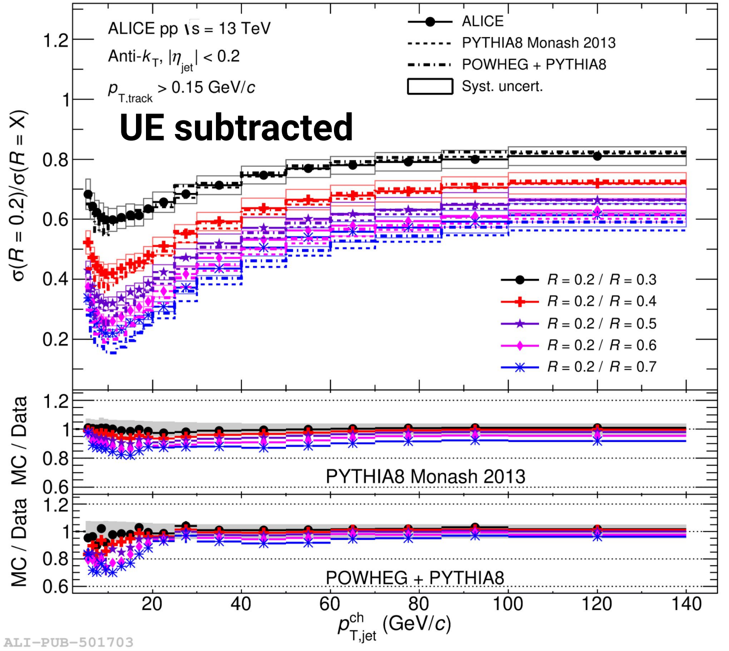

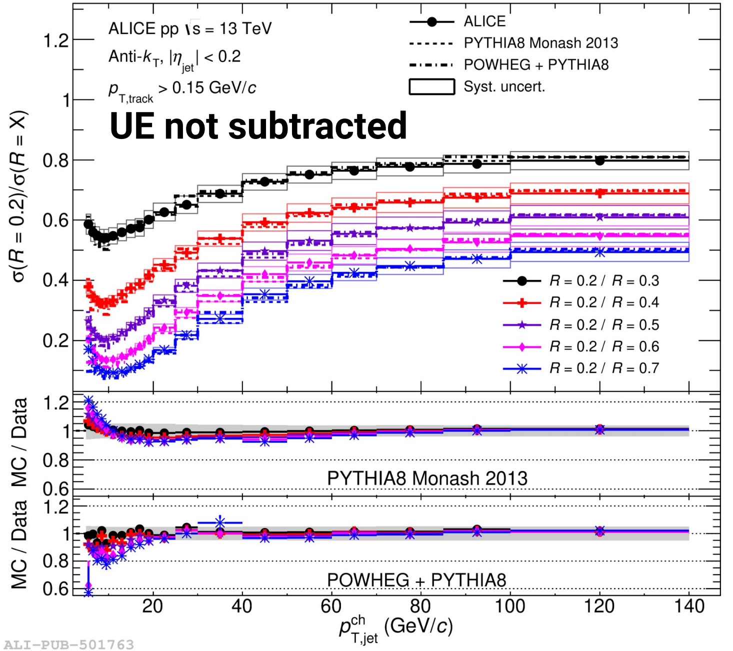

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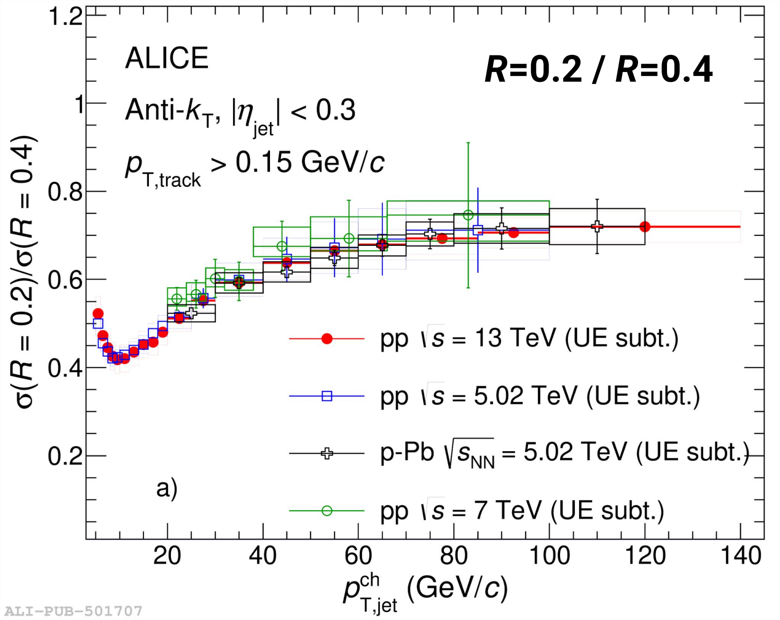
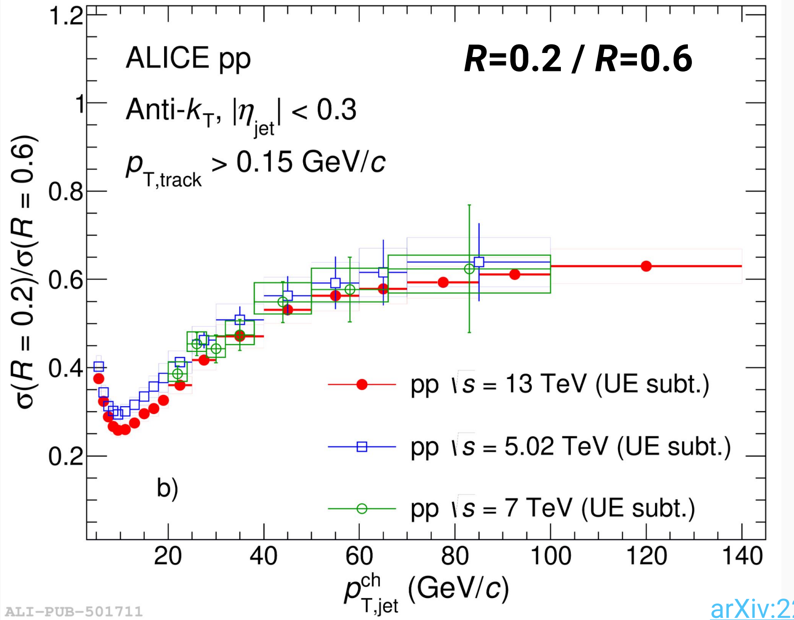
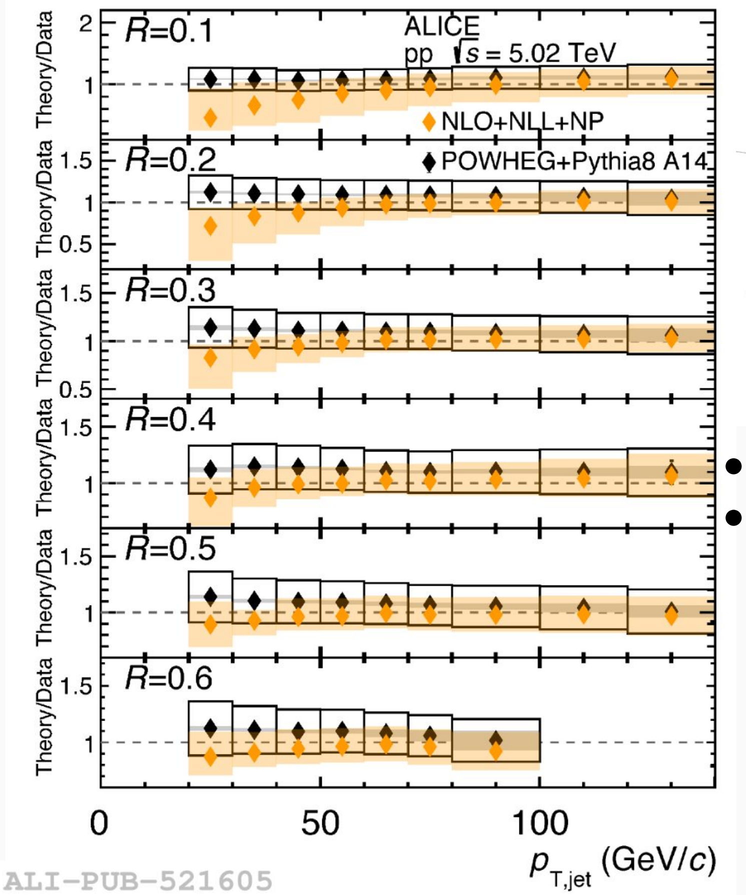


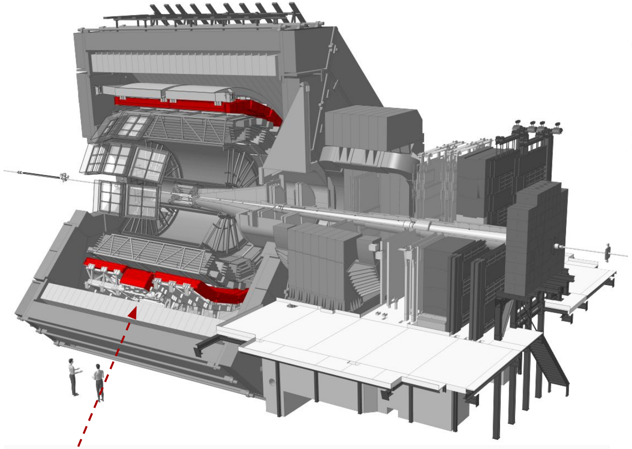


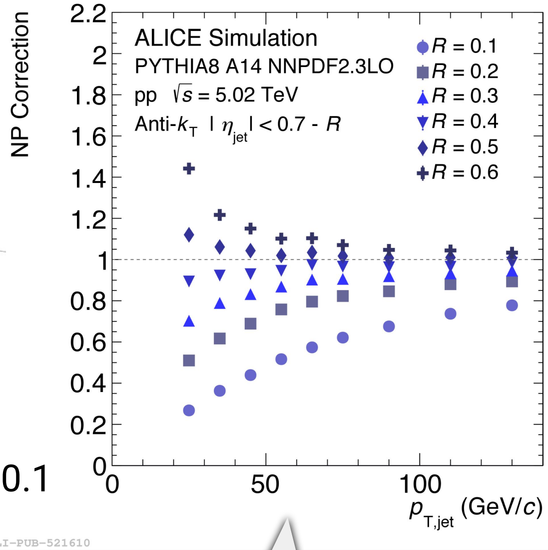
arXiv:2202.01548

Full jets and analytical calculation

PRC 101 (2020) 034911







- **Full** jets, pp at √s = 5 TeV, R down to 0.1
- Two theoretical calculations:
  POWHEG+PYTHIA8 – event generator
  NLO+NLL – **analytical calculation** + non-perturbative correction
  NP corr. = ratio of inclusive jet spectrum (PYTHIA hadron-level, MPI on) / (PYTHIA parton-lvl, MPI off)

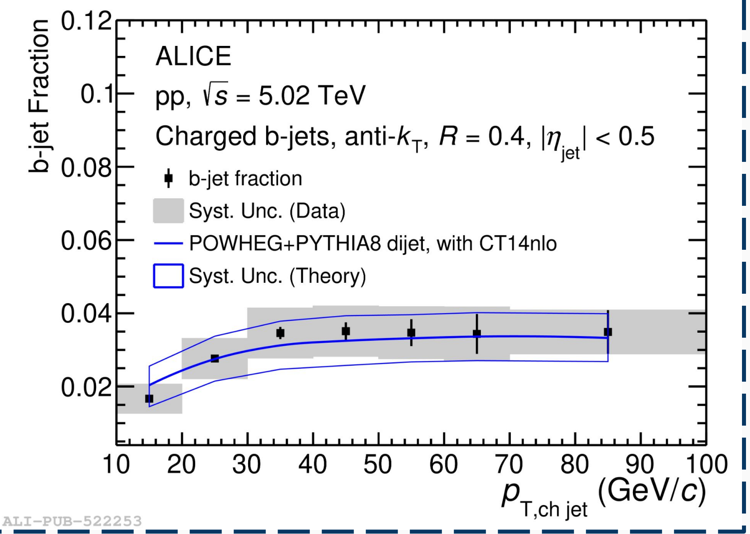
Both describe most of the data within uncertainties
Tension at low p_{T} and small R can arise from mismodelling of NP correction, which is large there

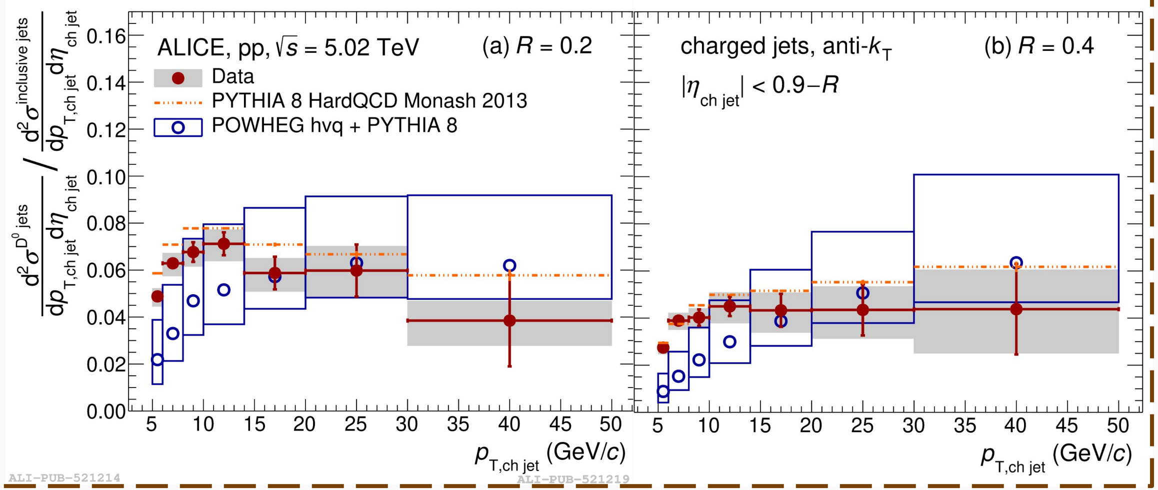
Ratio of jet cross sections: HF to untagged jets

ratio $\frac{\text{HF jets}}{\text{untagged jets}}$

for more see also:
charm jets: Ravindra on this session
beauty jets: Pietro: Wed, WG4, 12:30

JHEP 01 (2022) 178





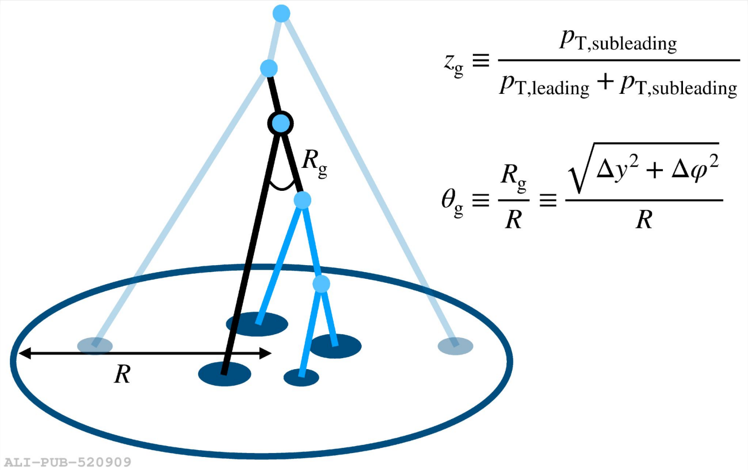
- HF fraction vs p_T: increase then flatten

arXiv:2204.10167

- tension with POWHEG hvq prediction of **D^0-tagged** jet fraction at low p_T
- **b-jet** fraction is well described by POWHEG dijet

Note the difference in $p_{T,\ ch\ jet}$ ranges and NLO calculations interfaced via POWHEG
See backup for POWHEG hvq and dijet comparison with previous measurement at √s = 7 TeV

Groomed observables



Aim of grooming: reduce impact of hadronization and UE to provide direct link with QCD calculations (z_g is Sudakov safe and θ_g collinear-infrared safe)

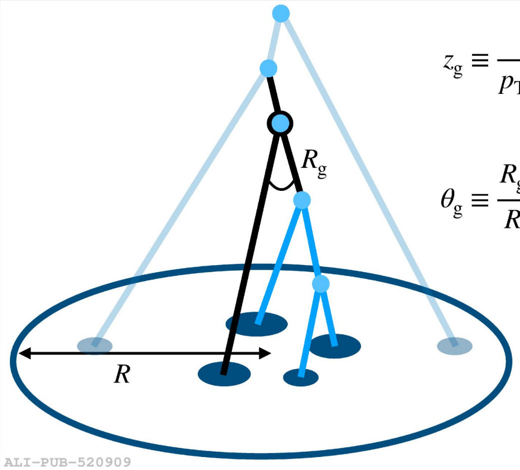
Procedure: recluster the jet with Cambridge-Aachen algorithm (angular ordered) and unwind the jet clusterization. Then iteratively remove soft branches until grooming condition is met.

For soft-drop: $z_i > z_{cut} \theta_i^{\beta}$

Soft drop removes wide-angle, soft radiation.

larger β ⇔ less grooming, particularly collinear

Groomed observables



$$z_g \equiv \frac{p_{T,subleading}}{p_{T,leading} + p_{T,subleading}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

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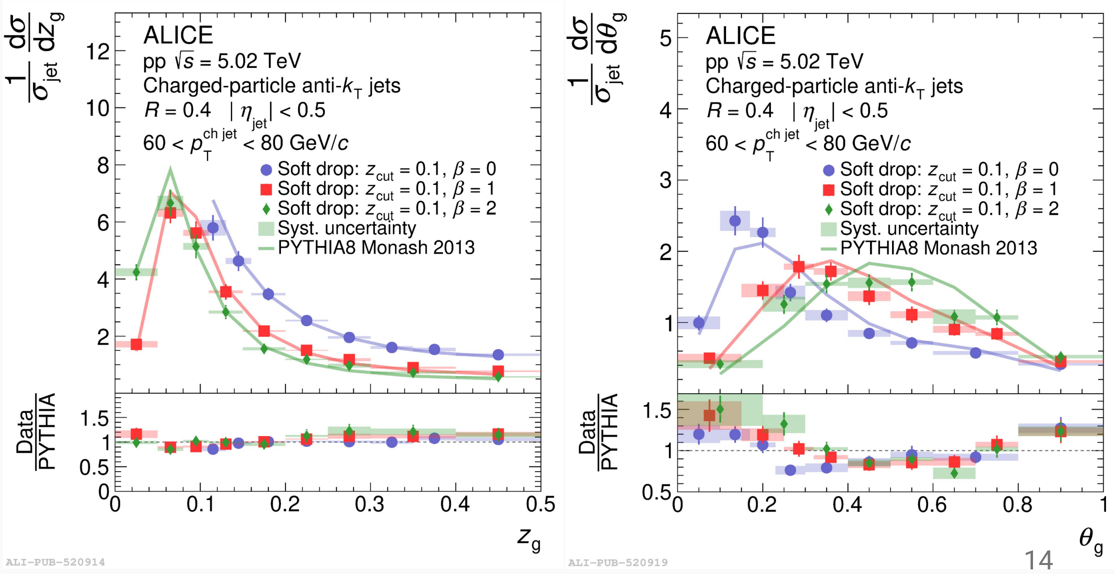
- **PYTHIA describes most of data within ~20% (except low θ_g)**
- **Jets groomed with smaller β are more collimated**
- θ_g compared with pQCD calculation: SCET (Soft-Collinear Effective Theory) framework incl. all order resummation of large logarithms
- Good agreement within uncertainties in the perturbative region

arXiv:2204.10246



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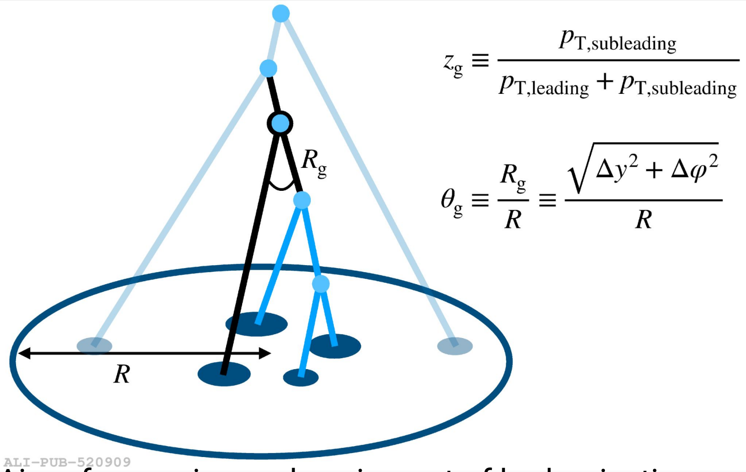

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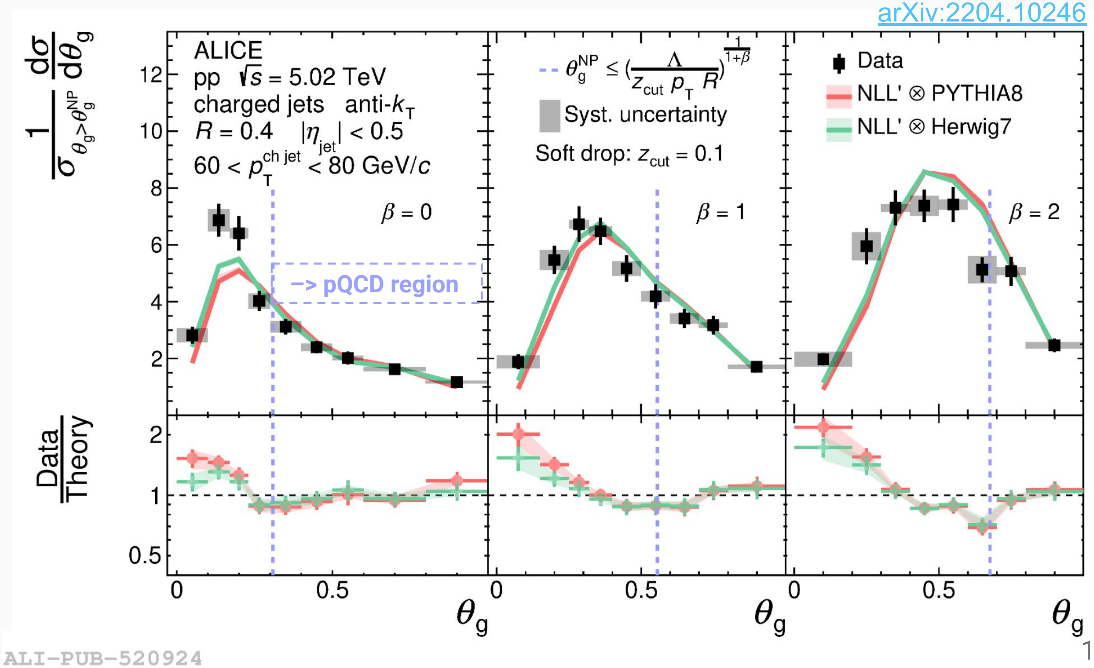
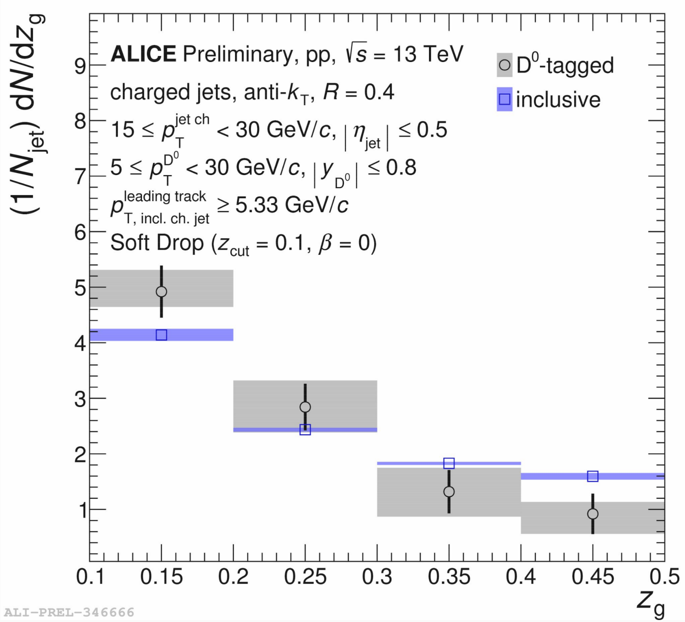


Substructure of charm jets

Soft-drop (z_{cut}=0.1, β=0)

$$z_i > z_{cut}\theta_i^\beta$$

n_{SD} = number of splittings satisfying soft-drop condition



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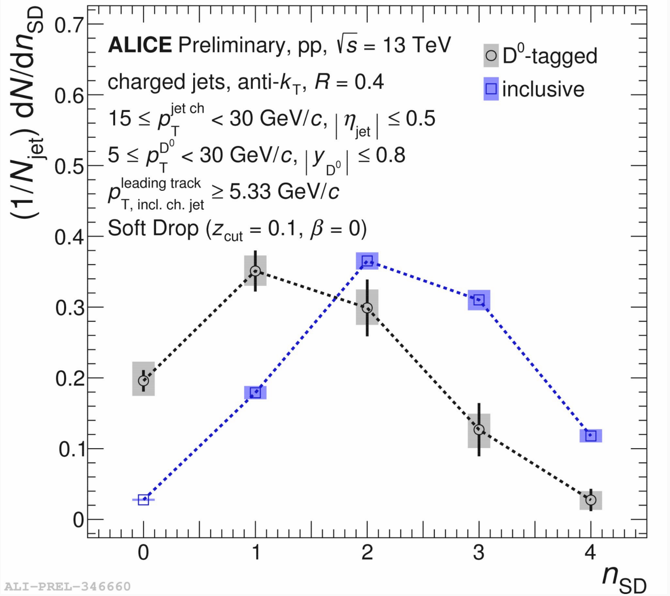


Compared to untagged jets, **D^0-tagged jets have**:

- **less symmetric splittings** ($z_g \approx 0.5$) – consistent with expected impact of mass on QCD splitting function [P. Ilten *et al.* PRD 96 (2017) 054019]
- **significantly fewer splittings satisfy grooming condition** (with high enough p_T) -> consistent w/ hardening of the fragmentation of charm quarks compared to light quarks due to presence of dead-cone (suppressed collinear splittings) (but difference in fragmentation of quarks and gluons also plays a role)

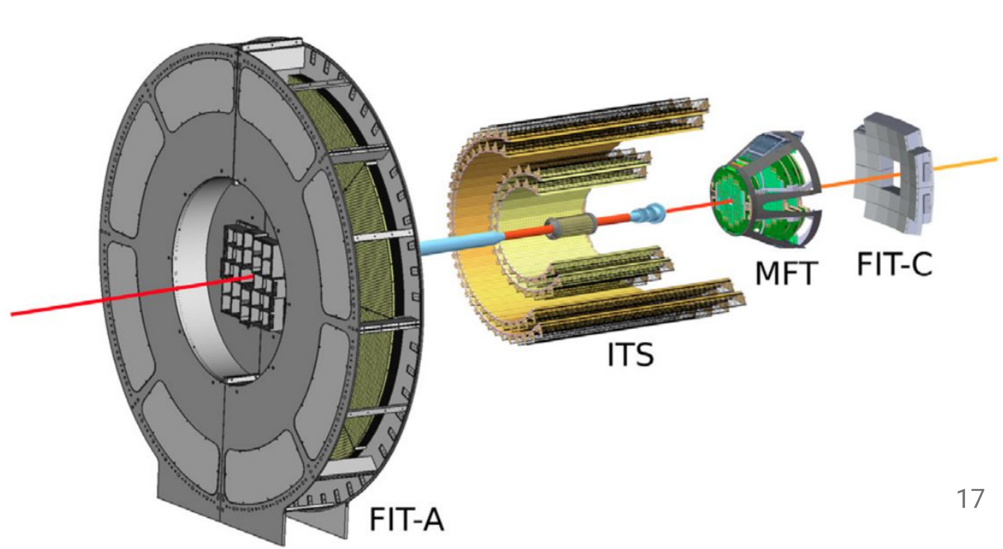
Summary and Outlook

ALICE has rich and unique jet program:

- pQCD predictions tested via cross section and substructure measurements
- Impact of non-perturbative effects studied and mitigated by variation in R and grooming techniques
- No strong tension with the calculations in their applicability region with current precision
- HF jet sector explored via production (charm and beauty) and jet substructure (charm) measurements
- … *and much more not included*

Upgraded ALICE in Run3 targets:

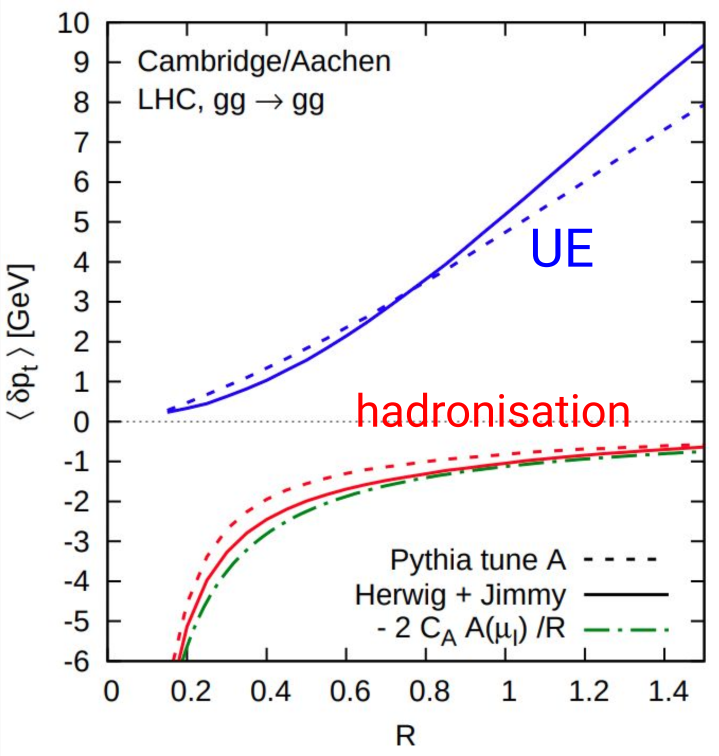
- High precision measurements in HF sector
- Substructure measurements in beauty jets
- Further nuclear modification studies



Backup

Measurement at various *R*

- anti-kt parameter ***R*** changes the relative strength of various effects on the jet transverse momentum:
  - perturbative (magnitude ↘ *R*)
  - non-perturbative: hadronisation ↘*R* and underlying event (UE)↗*R*
- sensitive to radial distribution of particles inside jet



Dasgupta *et al.* JHEP 0802 (2008) 055

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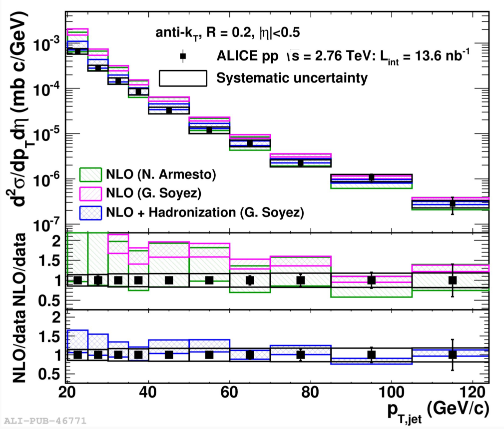
Computing the **ratio of two *R*** is beneficial from two perspectives:

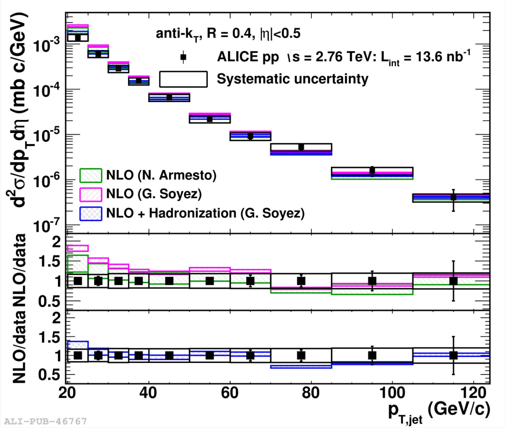
➢ *experimentally*: many uncertainties cancel out

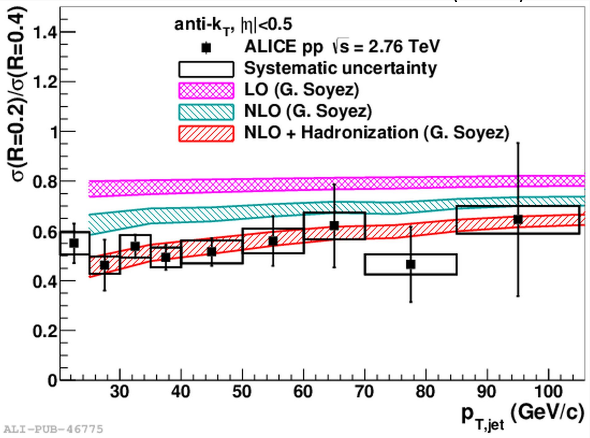
➢ *theoretically*: calculations are effectively one order higher: NLO becomes effectively NNLO

example from first ALICE jet paper, ratio much more conclusive than individual *R*:

PLB 722 (2013) 262-272

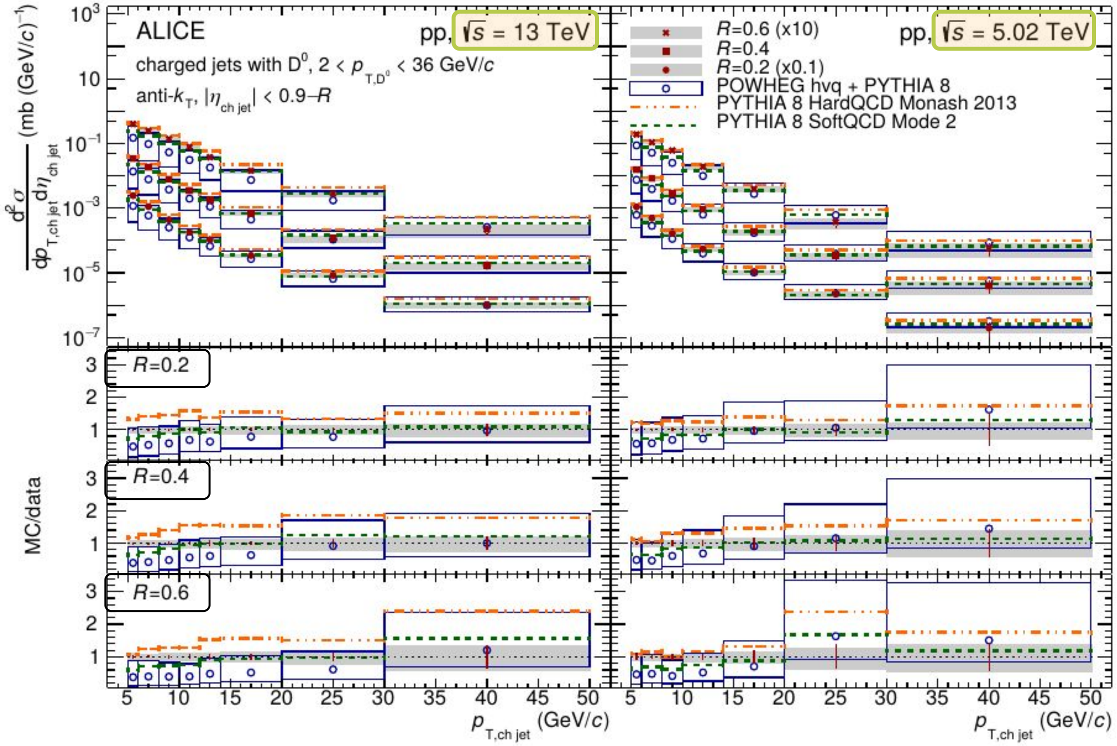


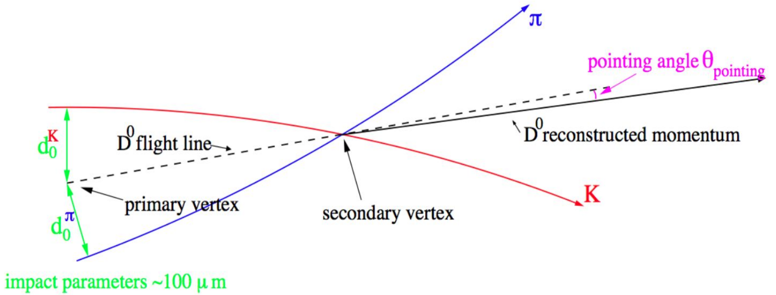




D^0-tagged jets cross section

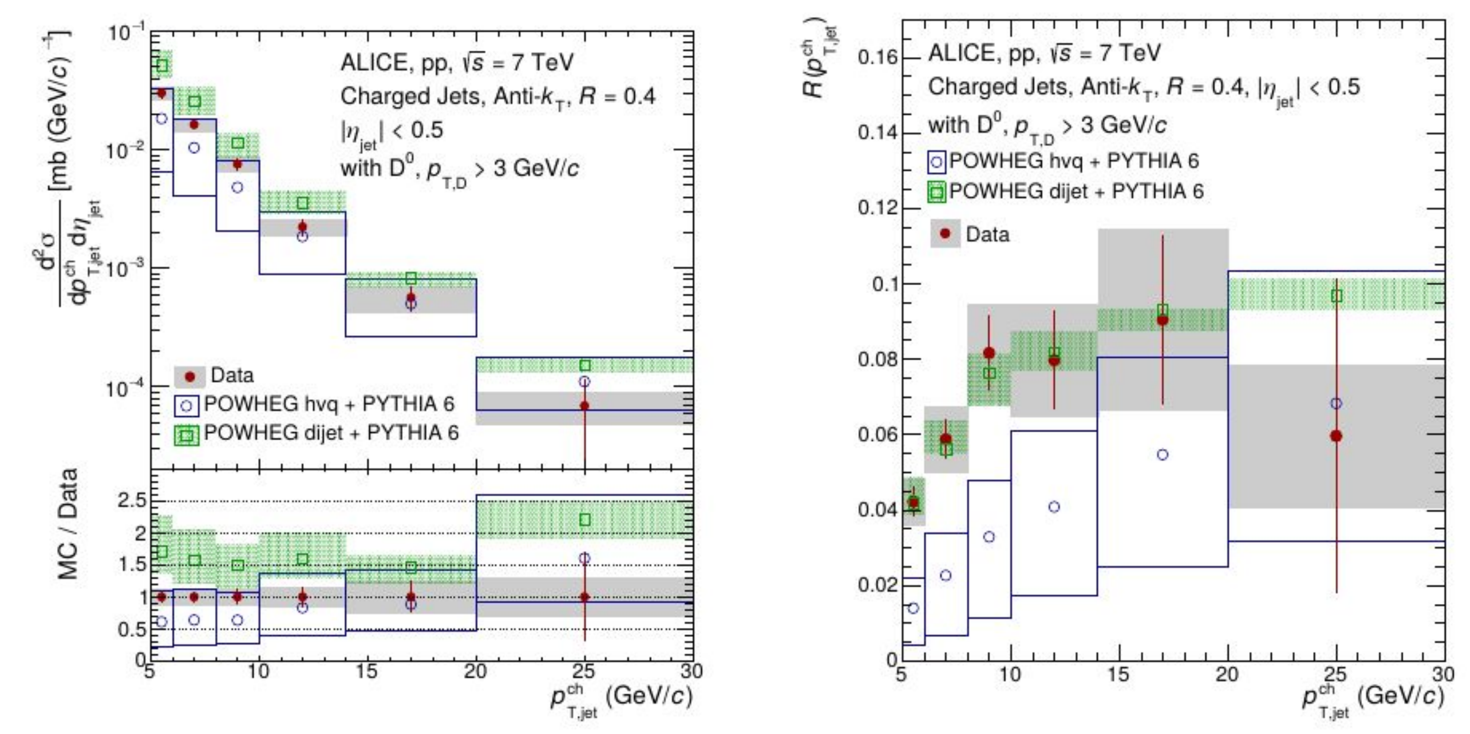
D^0 is reconstructed in hadronic channel: $D^0 \rightarrow K^-\pi^+$ using PID and topological cuts



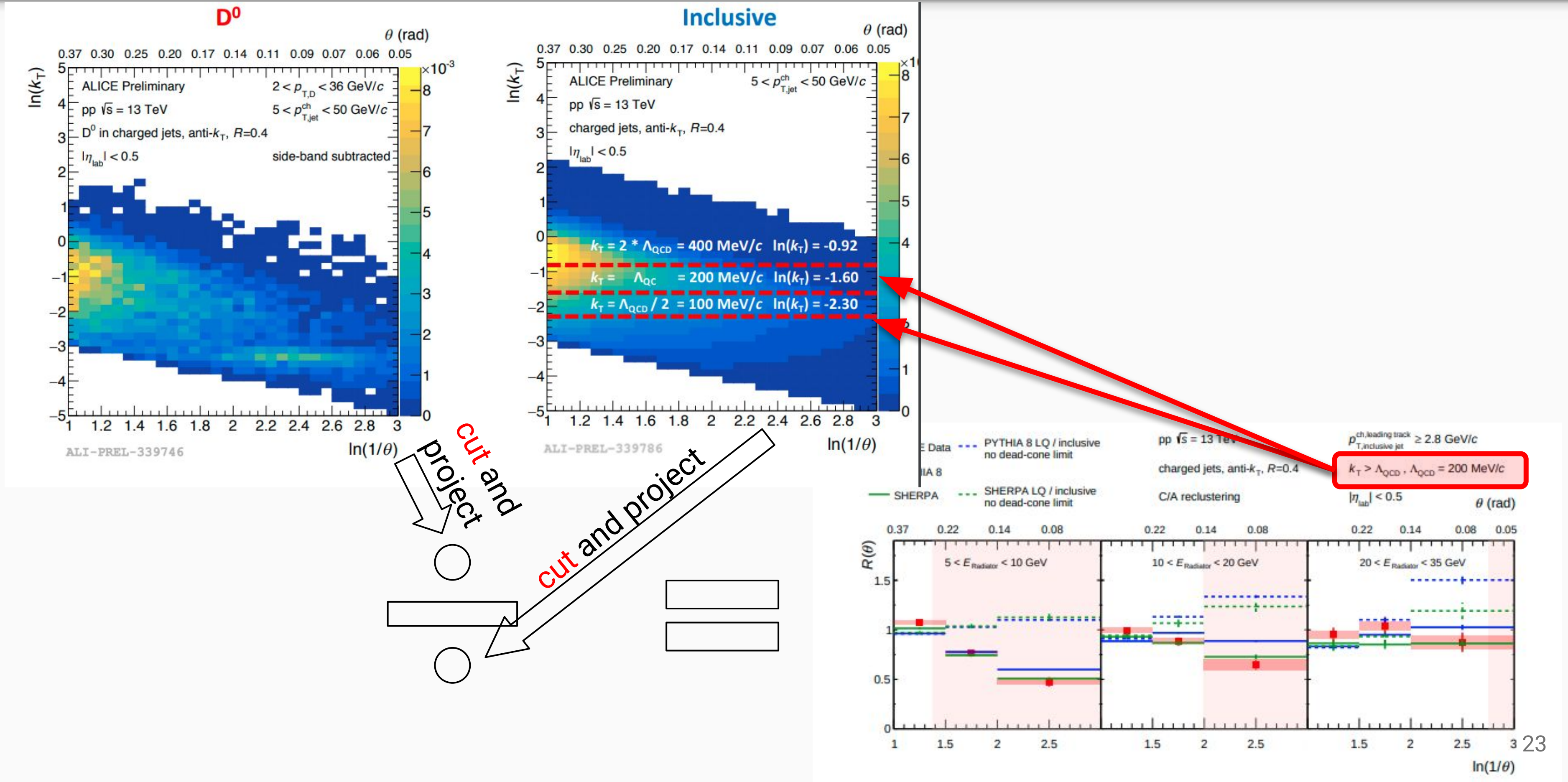


- hardening of the spectrum with √s observed
- PYTHIA Monash overestimates the cross section, SoftQCD Mode 2 works better
- POWHEG describe the higher p_T region, at lower p_T data points are at the upper band
- uncertainties in MC much larger then in data

Ratio of HF jet cross section to inclusive jets



in ratio plot (right) the inclusive jet cross section (denominator) uses POWHEG dijet in both cases



D0
ALICE Preliminary
pp √s = 13 TeV
D0 in charged jets, anti-kT, R=0.4
|ηlab| < 0.5
2 < pT,D < 36 GeV/c
5 < pch T,jet < 50 GeV/c
side-band subtracted
θ (rad)
ln(kT)
ln(1/θ)
ALI-PREL-339746
Inclusive
ALICE Preliminary
pp √s = 13 TeV
charged jets, anti-kT, R=0.4
|ηlab| < 0.5
5 < pch T,jet < 50 GeV/c
kT = 2 * ΛQCD = 400 MeV/c ln(kT) = -0.92
kT = ΛQCD = 200 MeV/c ln(kT) = -1.60
kT = ΛQCD / 2 = 100 MeV/c ln(kT) = -2.30
ALI-PREL-339786
cut and project
cut and project
Data
PYTHIA 8 LQ / inclusive no dead-cone limit
SHERPA
SHERPA LQ / inclusive no dead-cone limit
pp √s = 13 TeV
charged jets, anti-kT, R=0.4
C/A reclustering
pch,leading track T,inclusive jet ≥ 2.8 GeV/c
kT > ΛQCD , ΛQCD = 200 MeV/c
|ηlab| < 0.5
R(θ)
5 < ERadiator < 10 GeV
10 < ERadiator < 20 GeV
20 < ERadiator < 35 GeV
ln(1/θ)

Dead-cone effect

Dead-cone effect: suppression of radiation at small angles (θ < m/E) relative to the direction of emitter
It is a fundamental feature of all gauge quantum field theories

ALICE provides **first evidence of dead-cone effect** at hadronic collider:

- **significant suppression of small angle (=large ln(1/θ)) radiation**
- as expected: effect strongest for low $E_{radiator}$, suppression threshold changes with $E_{radiator}$ (shaded area)
- outlook: with same measurement for beauty, could provide constraints for quark masses