Investigating jet modification in high multiplicity proton-proton collisions at 13 TeV using PYTHIA 8 event generator

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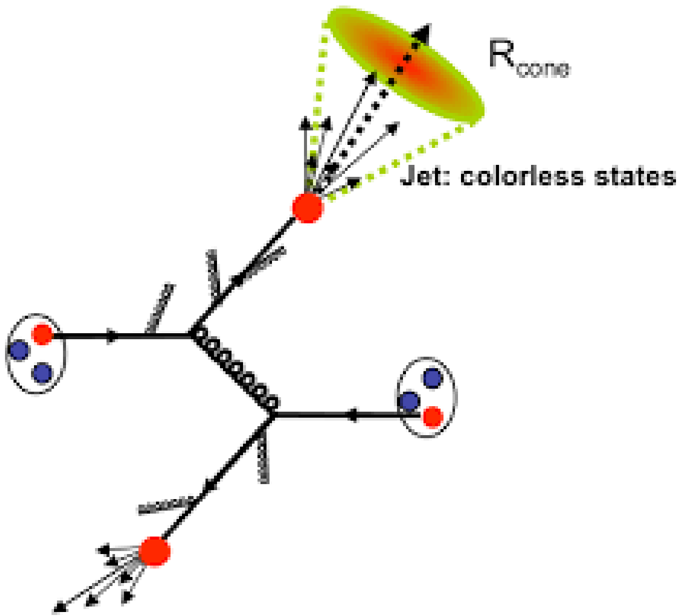
Outlines

- Motivation
- Analysis details
- Results and discussion
- Summary

Jets

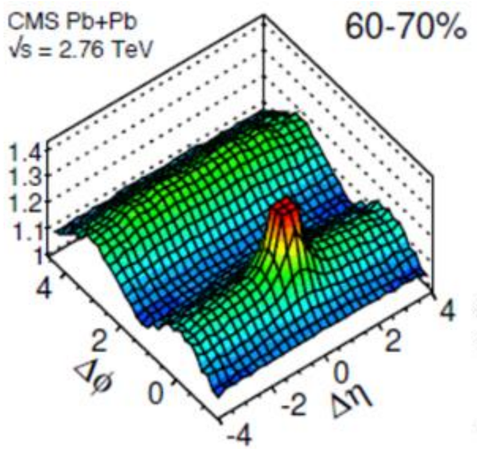
- <u>Jets</u>
  - Collimated showers of particles produced from the fragmentation and hadronization of hard-scattered (large Q^2) partons
  - Considered as the proxy to the initial hard-scattered partons and are expected to reflect the parton properties
  - <u>In heavy-ion (AA) collisions</u>
    - Serve as calibrated probes for modification in QGP medium through jet-medium interaction and partonic energy loss (jet quenching)
  - <u>In proton-nucleus (pA) collisions</u>
    - Test the impact of Cold Nuclear Matter (CNM) effects
  - <u>In proton-proton (pp) collisions</u>
    - Test perturbative QCD (pQCD) calculations
    - Provide reference measurements for pA and AA collisions



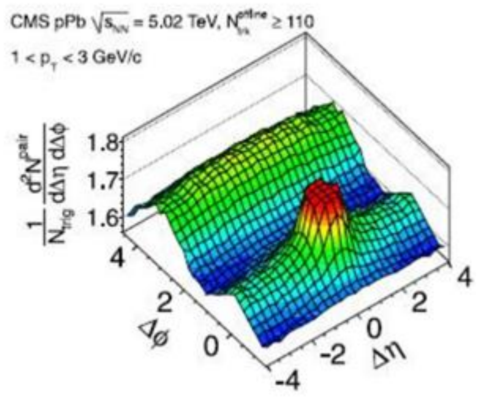
Picture courtesy: link

Collective behaviour observed in small collision systems (pp and p-Pb)

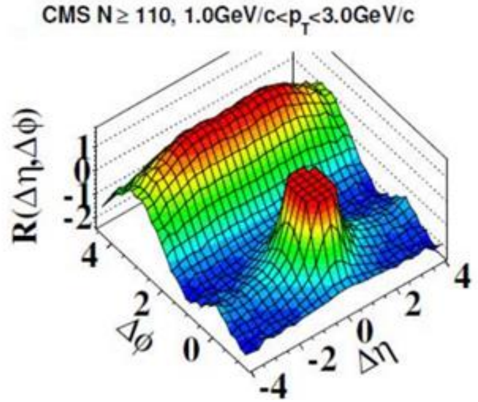
Pb-Pb and **small systems** behave **similarly**



CMS, Eur. Phys. J. C72, 2012 (2012)

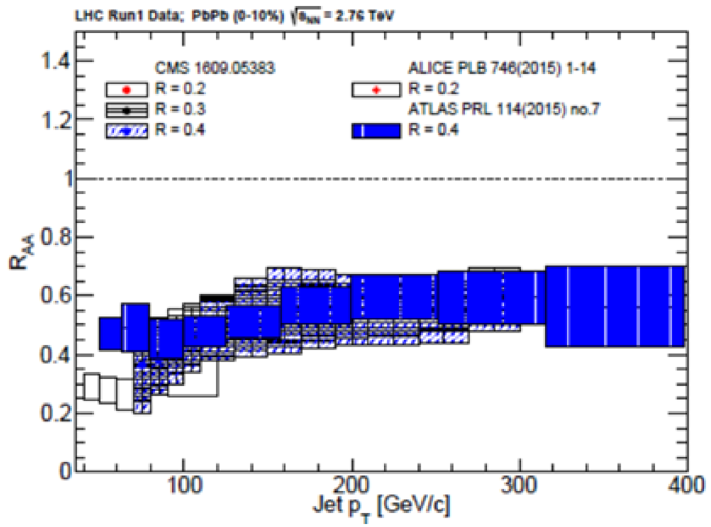


CMS, Phys.Lett. B718, 795 (2013)

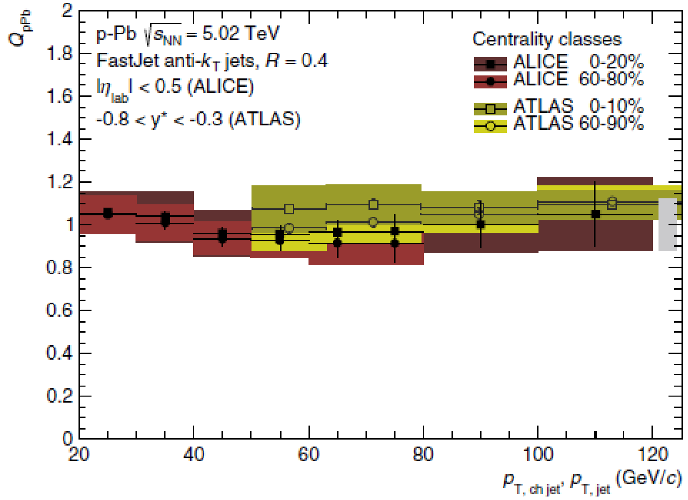


JHEP 09 (2010) 091

Pb-Pb and **small systems** behave **differently**



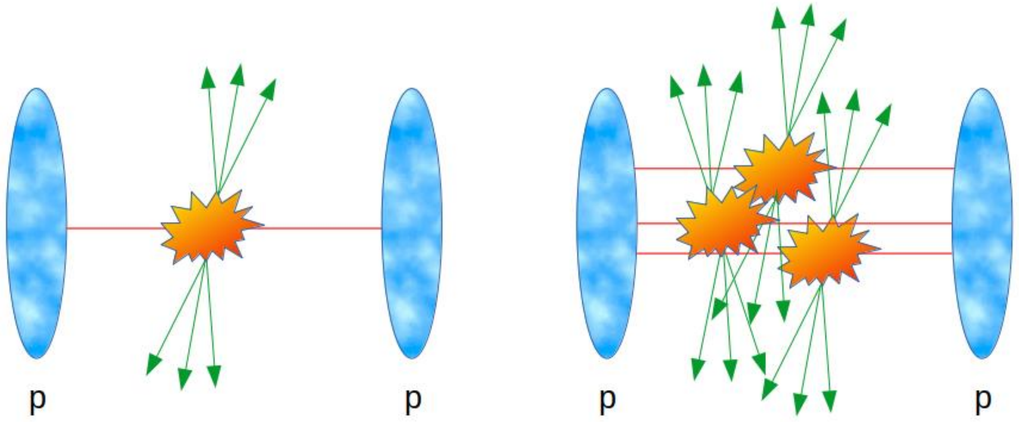
Review of Jet Measurements in Heavy Ion Collisions, arXiv:1705.01974v1

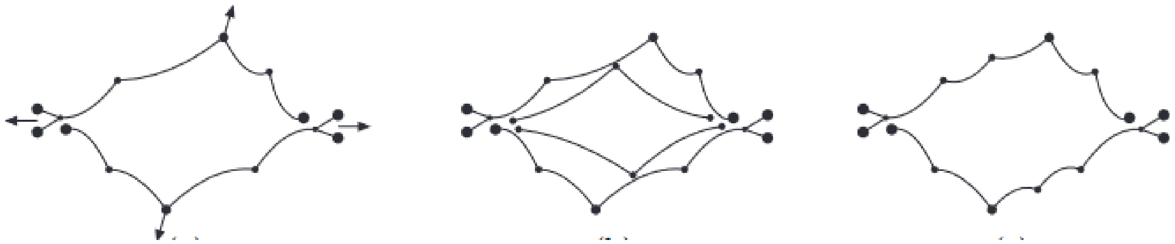


Eur. Phys. J.C. 76 (2016) 271

Open questions: **Medium formation** in **small systems**? Or some **other source(s)** playing a role here?

Multiparton interaction and color reconnection





❖ **Multiparton interaction (MPI):** multiple partonic hard scatterings occurring in a single event (proton-proton collision)

❖ **Color reconnection (CR):** final outgoing partons from MPIs are connected via color strings so as to minimize the total length of the strings

❖ MPI and CR mechanisms in PYTHIA 8 can explain some of the collective behaviours observed in high multiplicity pp collisions

❖ In this work, we investigate the effects of MPI and CR on the modification of transverse momentum distribution inside jets in high multiplicity pp collisions using PYTHIA 8 simulation

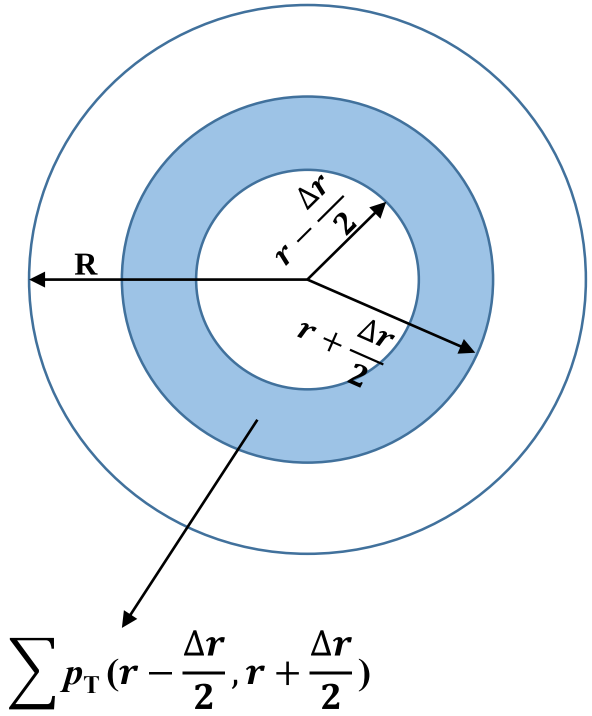
Picture courtesy: G. Gustafson, Acta Phys. Polon. B40, 1981 (2009)

Jet observable

❖ Radial distribution of transverse momentum density inside the jet cone about the jet axis is defined as

$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N_{\text{jets}}} \sum_{i=1}^{N_{\text{jets}}} p_{\text{T}}^{i} \left(r - \frac{\Delta r}{2}, r + \frac{\Delta r}{2}\right) / p^{\text{ch}}_{\text{T, jet}}$$

where r is the distance from the jet axis and $p_{\text{T}}^{\text{i}} \left(r - \frac{\Delta r}{2}, r + \frac{\Delta r}{2}\right)$ denotes summed p_{T} of all particles of i-th jet, inside the annular ring between $r - \frac{\Delta r}{2}$ and $r + \frac{\Delta r}{2}$



Analysis details

Data generation
- Collision system: pp
- Center-of-mass energy ($\sqrt{s}$): 13 TeV
- PYTHIA 8.219 Monash 2013
- 3 Configurations (500 M events each):
  1. MPI: OFF, CR: OFF
  2. MPI: ON, CR: OFF
  3. MPI: ON, CR: ON

Event classes
- Minimum bias (MB)
- High multiplicity (HM): 0-5% highest multiplicity events**

Track selection
- Charged tracks
- $p_{\mathrm{T,\,track}} > 0.15$ GeV/c
- $|\eta_{\mathrm{track}}| < 0.9$

Jet reconstruction
- FastJet anti-k_{T} algorithm
- Jet resolution parameter, $R^{*} = 0.4$
- $p^{\mathrm{ch}}_{\mathrm{T,\,jet}} > 5$ GeV/c
- $|\eta^{\mathrm{ch}}_{\mathrm{jet}}| < 0.5$

* $R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$

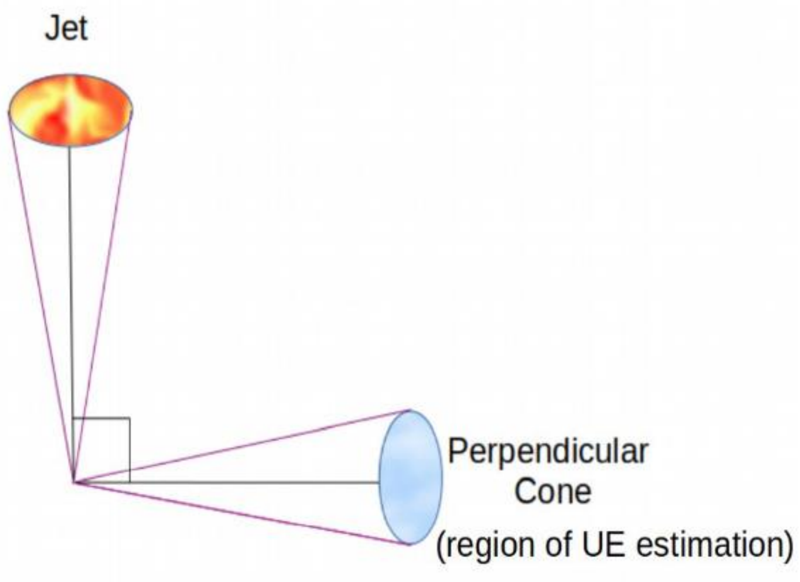
** High multiplicity events are selected based on charged-particle multiplicity at forward rapidity (same coverage as V0A and V0C detectors in ALICE)

Underlying event

- Underlying event (UE): consists of particles produced from sources other than the hard-scattered partons

- Perpendicular cone method:
  - UE is estimated event-by-event based on circular regions perpendicular to the jet cones.
  - The circular cones have the same size as the jet resolution parameter and placed at the same η but offset at an azimuthal angle $\Delta\varphi = \pi/2$ relative to the jet axis

- UE subtraction: performed on a statistical basis



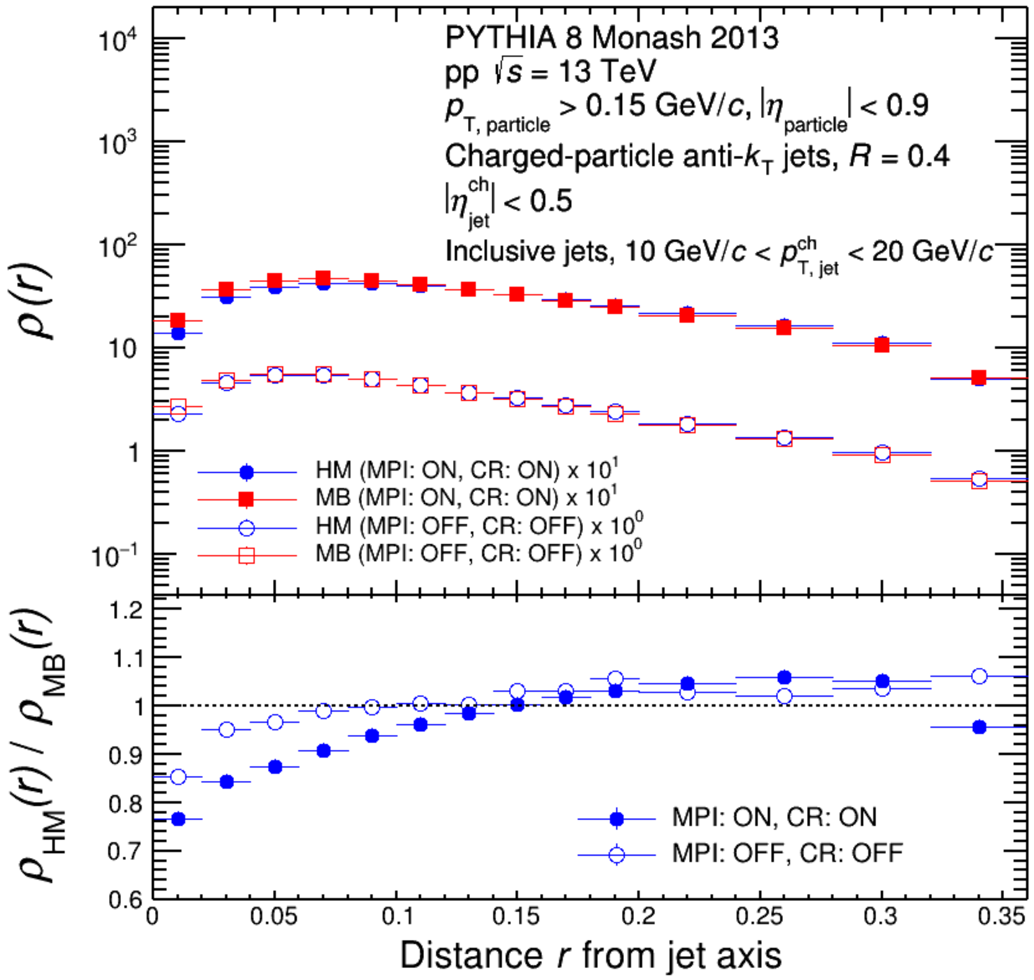
Matching: jet and parton

- Hard-scattered partons in an event need to be matched to reconstructed jets

- <u>'Distance of closest' approach:</u>
  - geometrically closest jet is matched to the parent parton
  - One-to-one correspondence between the matched parton and jet
  - Jets having p_T less than 20% of the matched parton p_T are rejected to avoid fake jets

Results and discussion

ρ distribution: Inclusive jets (p_T = 10 - 20 GeV/c)



- Significant modification observed in HM events compared to MB events for inclusive jets of 10 < $p^{ch}_{T,\,jet}$ < 20 GeV/c
- Energy is redistributed away from the jet axis, resulting in enhancement in $\rho(r)$ at larger r (> 0.15)
- In presence of MPI & CR:
  - the core of the jet in HM event class is depleted by about 23%
- In absence of MPI & CR:
  - the amount of modification is significantly reduced
  - a small depletion of the jet core and enhancement at larger r is still present

e-Print: 2209.00972 [hep-ph]

Gluon fraction

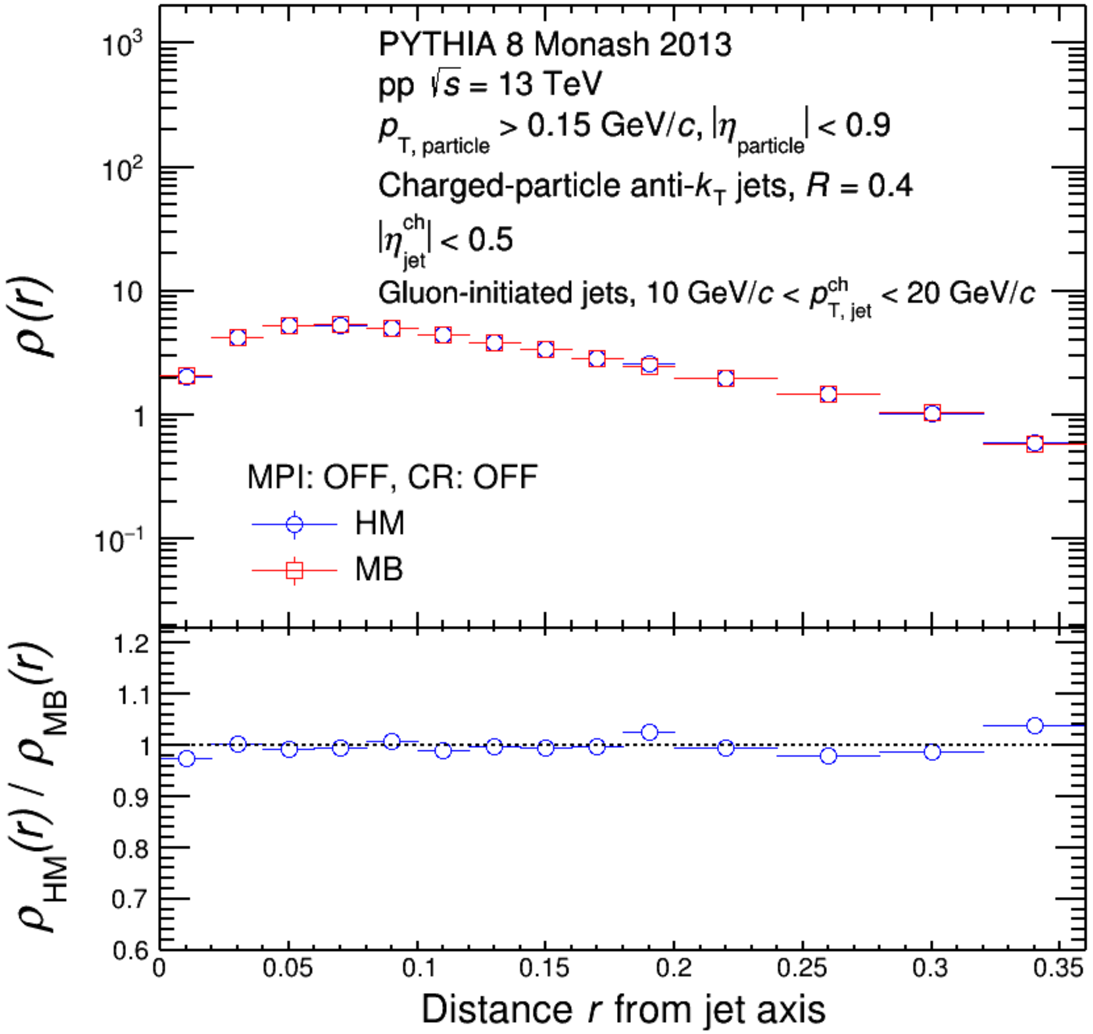
- Gluon-initiated jets are expected to be softer and broader compared to quark-initiated jets

- **Gluon fraction** = $\frac{No.\, of\ jets\, matched\, with\, gluons}{No.\, of\ all\, matched\ jets}$

- Gluon fraction is **0.89** and **0.78** in the HM and MB event classes respectively when both MPI and CR are switched OFF

- A difference in the ratio ($\rho_{\mathrm{HM}}/\rho_{\mathrm{MB}}$) is expected due to this enhanced gluonic contribution

ρ distribution: Gluon-initiated jets (p_T = 10 - 20 GeV/c)

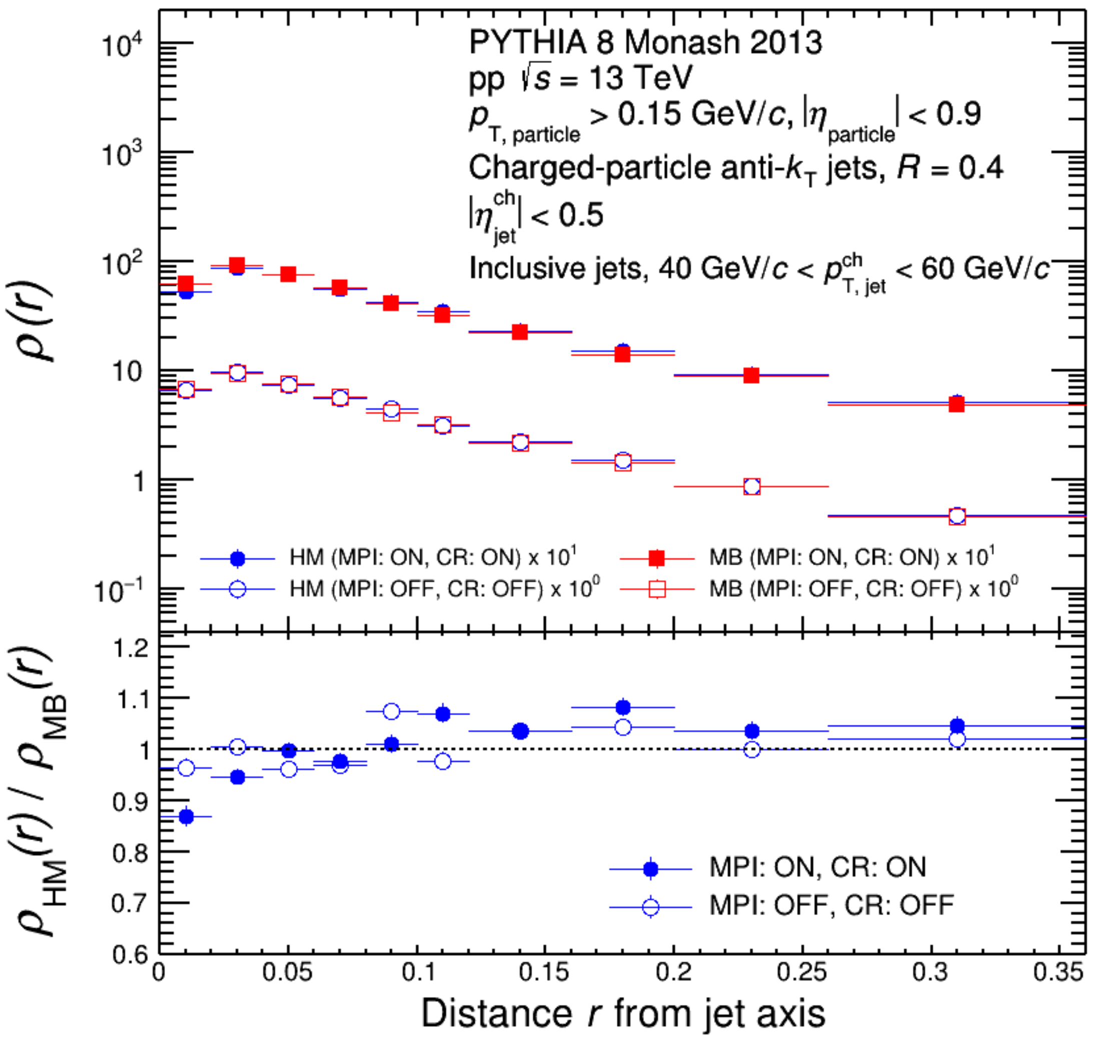


❖ No modification in $\rho(r)$ is observed in HM event class compared to MB event class for gluon-initiated jets of 10 < $p^{ch}_{T,jet}$ < 20 GeV/c

➢ ***Conclusion:*** MPI, CR and enhanced gluonic contribution are the main sources of modification in $\rho(r)$ in high multiplicity pp events in PYTHIA 8

e-Print: 2209.00972 [hep-ph]

ρ distribution: Inclusive jets (p_T = 40 - 60 GeV/c)

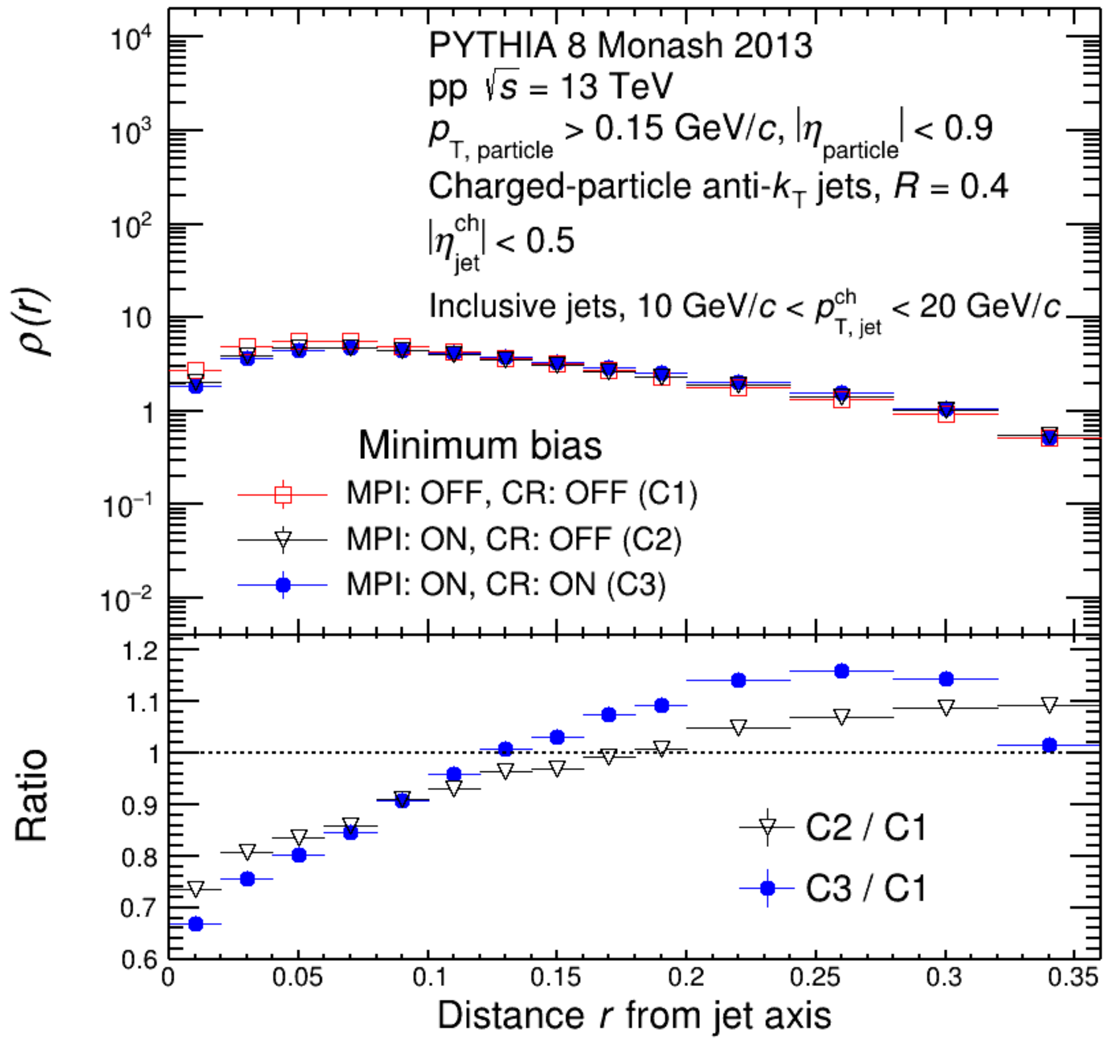


- ❖ At higher jet p_T, the modification is significantly reduced

- ❖ The effect of MPI and CR is expected to be dominant in low p_T region

e-Print: 2209.00972 [hep-ph]

Individual effects



❖ MB event class

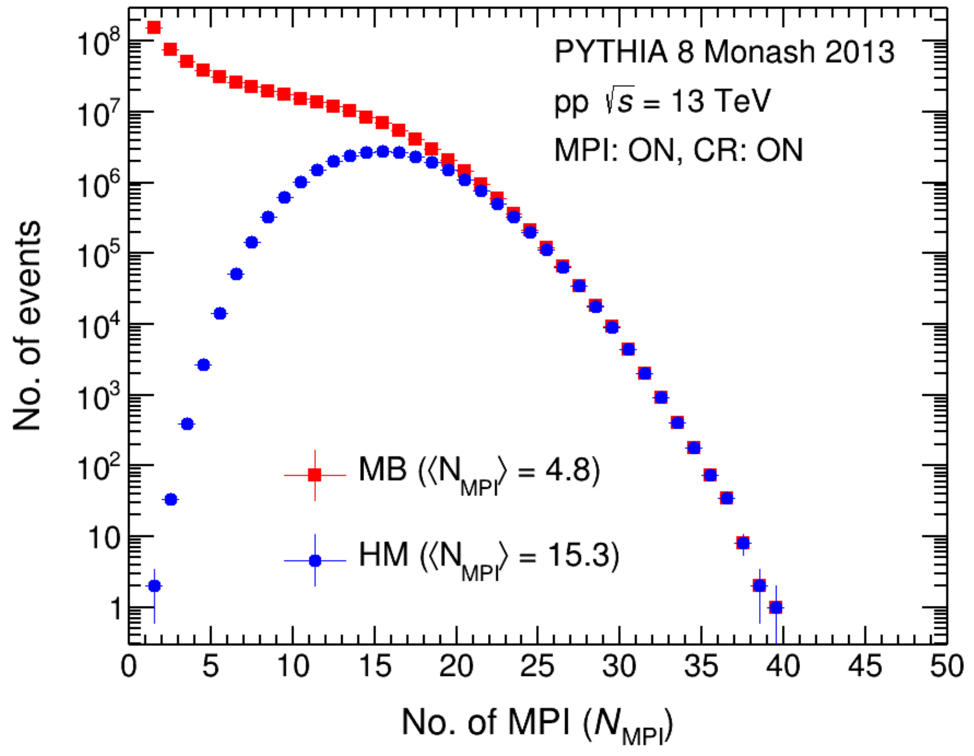
❖ Compared to 'MPI: OFF, CR: OFF' configuration,

❑ About 26% modification of jet core observed when only MPI is switched ON

❑ The modification increases to 33% when both MPI and CR are switched ON

e-Print: 2209.00972 [hep-ph]

Possible relation between amount of modification and $<N_{MPI}>$



Values of $<N_{MPI}>$

	MB	HM
MPI: OFF, CR: OFF	1	1
MPI: ON, CR: ON	4.8	15.3

- ❖ An increase of $<N_{MPI}>$ by a factor of 4.8 from 'MPI: OFF, CR: OFF' to 'MPI: ON, CR: ON' leads to 33% modification in $\rho(r)$
- ❖ If a proportional relation exists between the amount of modification at jet core and $<N_{MPI}>$, then an increase by a factor of 3.2 (from 4.8 to 15.3) should amount to about 22% modification in $\rho(r)$ at jet core in HM event class compared to MB event class
- ❖ The amount of modification in $\rho(r)$ at jet core in HM event class compared to MB event class is about 23%... ***Interesting*!!!**

e-Print: 2209.00972 [hep-ph]

Summary

- The effects of MPI and CR on the jet observable $\rho(r)$ are studied in pp collisions at 13 TeV using PYTHIA 8 MC simulation

- Significant modification in $\rho(r)$ observed for jet p_T = 10 – 20 GeV/c at high multiplicity pp collisions

- Amount of modification reduced in absence of MPI and CR in PYTHIA 8

- Enhanced $\langle N_{MPI} \rangle$ along with CR and enhanced gluonic contribution are the main sources contributing to modification of $\rho(r)$ in high multiplicity pp events in PYTHIA 8

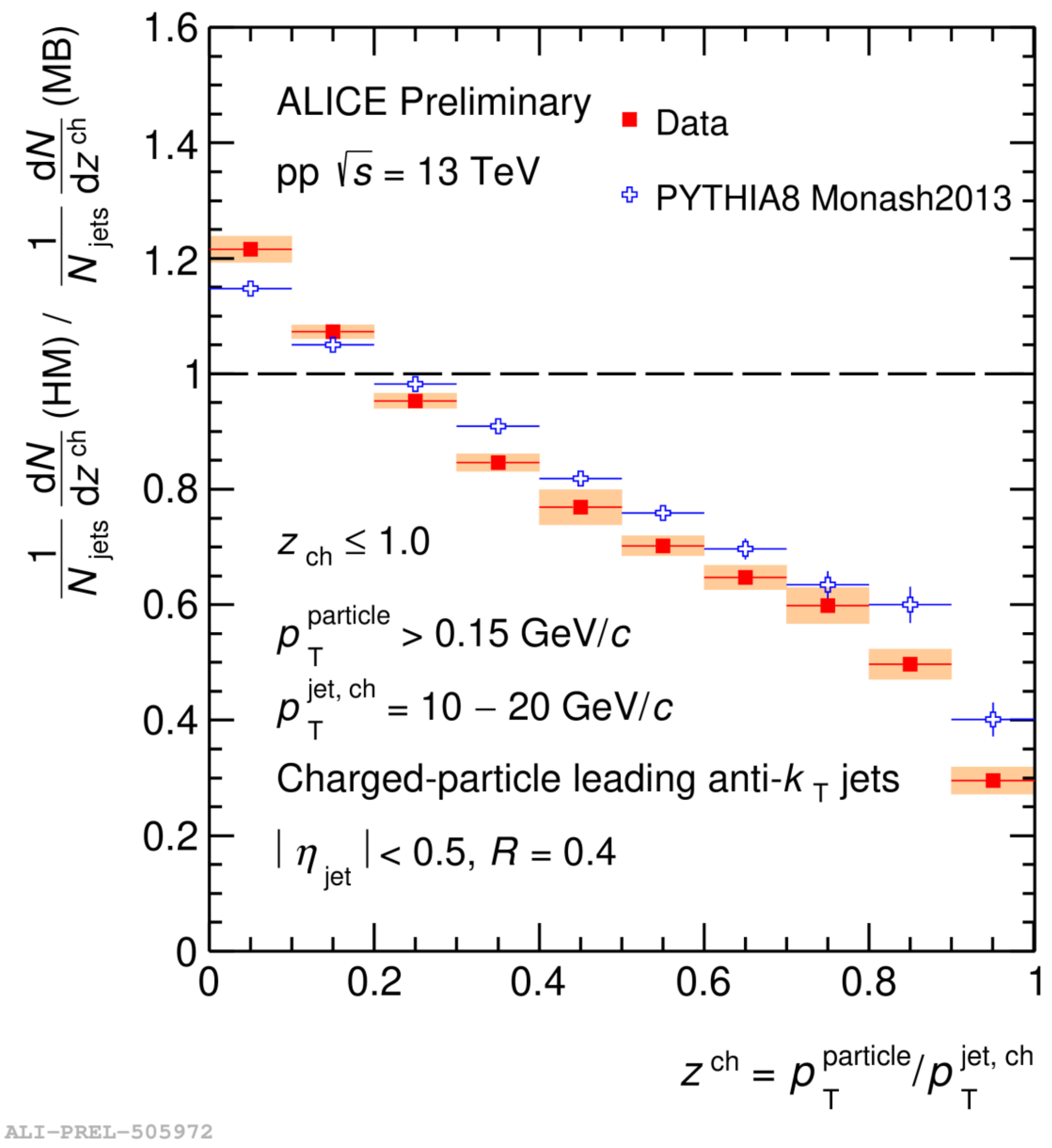
- Amount of modification significantly reduced for higher jet p_T

- Possibility of direct relation between amount of modification in $\rho(r)$ at jet core and $\langle N_{MPI} \rangle$ - needs further investigation

Thank you

Back up

ALICE preliminary result



- Jet modification observed in high multiplicity pp collisions at 13 TeV
- Qualitatively reproduced by PYTHIA

e-Print: 2210.04511 [hep-ex]

Jet finding algorithms

- Experimentally jets can be defined as a set of collimated particles which are clustered as a single entity as they are subjected to certain algorithms known as jet finding algorithms.
- Jet algorithms are nothing but a set of rules advocated in order to make groups of particles together (each group is entitled as a single 'jet') and can have one or more parameters.
- Two important types of jet algorithms are:
  - (a) Cone algorithms
  - (b) Sequential recombination algorithm
- We have used anti-k_T algorithm for jet finding ,which is a sequential recombination algorithm.

Anti-k_T Algorithm

(i) For each pair of particles the distance

$$d_{ij} = min(p_{ti}^{-2}, p_{ti}^{-2})\frac{\Delta R_{ij}^2}{R^2} \tag{1}$$

is measured where

$$\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \tag{2}$$

is the distance between two particles (i-th and j-th) in (η - ϕ) plane, R = jet radius and p_{ti} and p_{tj} are the transverse momentum of the i-th and j-th particles respectively.

(ii) Additionally, particle-beam distance for each particle, given by

$$d_{iB} = p_{ti}^{-2} \tag{3}$$

is also measured.

(iii) The minimum of d_{iB} with d_{ij} is found out.

(iv) If it is a d_{ij}, i-th and j-th particles are recombined into a single new object whose momentum is (p_{ti} + p_{tj}) and it is often called a "pseudojet", since it is neither a particle nor yet a full jet.

(v) Otherwise, if the minimum is a d_{iB}, i-th particle is considered to be part of "beam" jet and it is removed from the list.

CR models in PYTHIA 8

- **<u>The MPI-based model:</u>** the original and default option, wherein all the gluons of a lower-$p_\perp$ interactions can be inserted onto the colour-flow dipoles of a higher-$p_\perp$ one, in such a way as to minimise the total string length
- **<u>The QCD-based model:</u>** alternative coherent parton–parton states beyond leading colour are identified based on the multiplet structure of SU (3)C , and reconnections are allowed to occur when the total string length can be reduced. Particular attention is given to the formation of junctions, i.e. where three string pieces form a Y-shaped topology, which provides an additional source of baryon formation in this model.
- **<u>The gluon-move model:</u>** individual gluons are moved from their current location, on the colour line in between two partons, to another such location if that results in a reduction of the total string length. An optional "flip" step can reconnect two different string systems, such that a quark end becomes connected with a different antiquark one.