Multiplicity dependence of the jet structures in pp collisions at LHC energies

Hot Quarks 2018

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Motivation - collectivity in small systems

- Suprise at LHC energies: v_2 and long-range correlations in high-multiplicity p+p events;
  - Long range correlations. e.g. **ATLAS, Nucl. Phys. A932, 357 (2014)**
  - Azimuthal anisotropy (v_n, flow). e.g. **L. Yan, J. Y. Ollitrault, Phys. Rev. Lett. 112, 082301 (2014)**
  - Enhanced heavy quark production depending on the multiplicity. **ALICE Collaboration, JHEP 1608, 078 (2016)**
- QGP is not necessary for collectivity.
  - Vacuum-QCD effects can produce such behaviour in the soft-hard regime.
  - Multi-parton interactions (MPI) can qualitatively explain enhanced heavy flavour production.

Jet modification in small systems

- Jet structure maybe is modified even in small systems without large volume of QGP.
- **We are looking for non-trivial jet shape dependence on event multiplicity.**
- We are simulating p+p collisions at $\sqrt{s} = 7$ TeV.
- Monte Carlo event generator: PYTHIA 8.2 with different PDF sets: NNPDF2.3lo for Monash and Monash*, CTEQ6L1 for 4C.
- Jet reconstruction: Fastjet software package with anti-k_t algorithm.
- Full jet reconstruction with $R = 0.7$. $(R^2 = \Delta\phi^2 + \Delta\eta^2)$

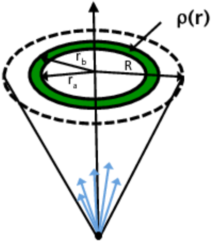
Different tunes and settings

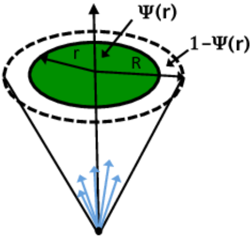
- Tunes: Monash, Monash*, 4C.
- Multi parton interactions (MPI).
- Colour reconnection (CR): In PYTHIA this is an in-built mechanism that allows interactions between partons originating in MPI and initial/final state radiations, by minimizing color string lengths.
  - 0: MPI-based scheme,
  - 1: QCD-based string length minimisation scheme,
  - 2: gluon-move scheme.
  - off: we don't use it.

Differential and integral jet shapes

Differential jet shape:

Integral jet shape:



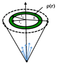


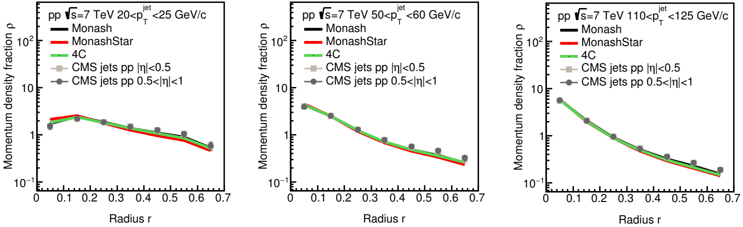
$$\rho(r) = \frac{1}{\delta r}\frac{\sum_{r_a<r_i<r_b} p_t^{(i)}}{p_t^{jet}}.$$

$$\psi(r) = \frac{\sum_{r_i<r} p_t^{(i)}}{p_t^{jet}}.$$

$$\psi(R) = \int_0^R \rho(r')dr' = 1.$$

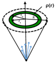
A reality check: Comparison with CMS for $\rho(r)$

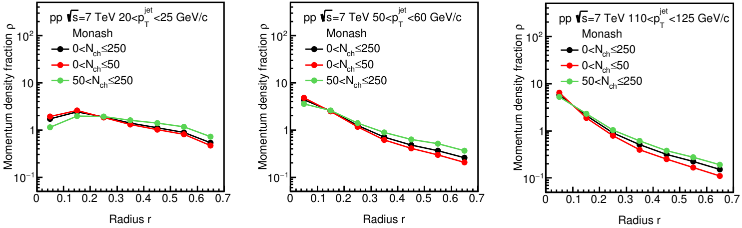




- The three different tunes reproduce the 7 TeV $|\eta| < 1$ p-p CMS data within uncertainty.
- We investigated different p_T^{jet} windows between $15\ GeV/c < p_T^{jet} < 400\ GeV/c$.

$\rho(r)$ distribution for different multiplicities

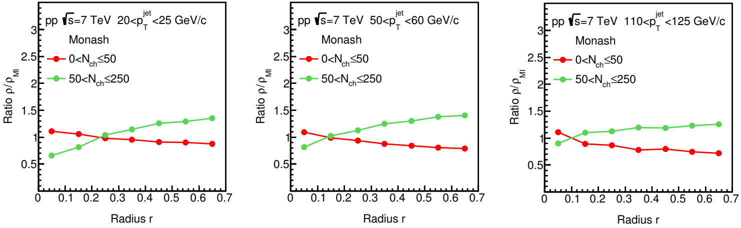




- We see a multiplicity dependence in the jet shapes,
- but it is the trivial multiplicity dependence we expected.
- Lower multiplicity jets are more collimated.

Ratio with Multiplicity Integrated (MI) $\rho(r)$

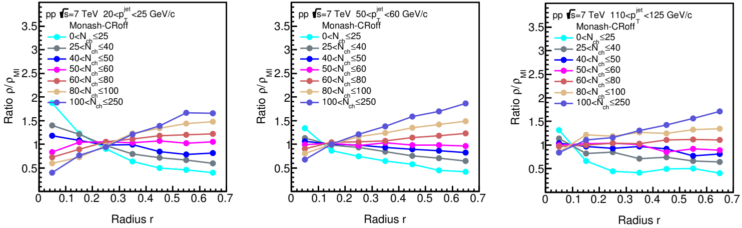
 /  MI



- Two curves: $\rho_{low-Nch}/\rho_{MI}$ and $\rho_{high-Nch}/\rho_{MI}$.
- The low- and high-multiplicity curves intersect each other at unity.
- The intersection point depends on the p_t^{jet} (three examples above).

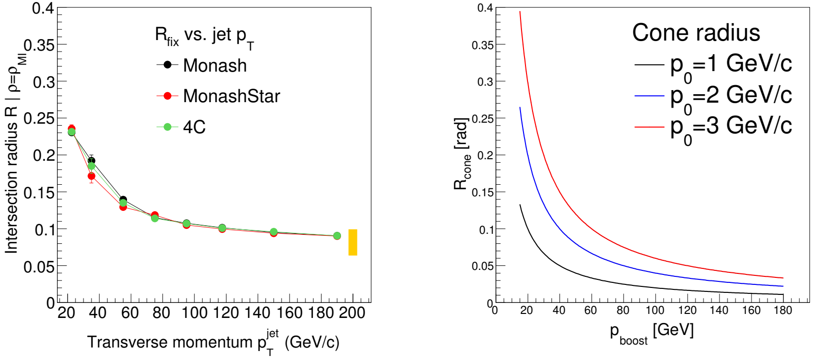
A characteristic jet size measure?

 /  MI



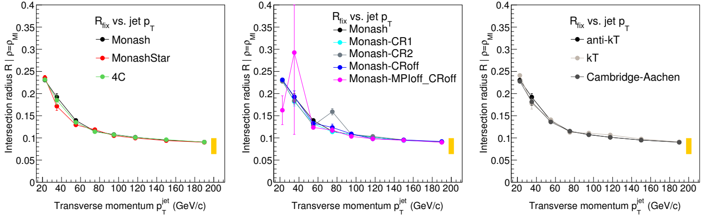
- Pythia describes the mutiplicity distributions well.
- The intersection does not depend on our multiplicity bin choice, but it depends on the p_T^{jet}.
- Our finding: a non-trivial scaling behaviour.
- What happens for different tunes and settings?

The p_t^{jet} dependence of R_{fix}



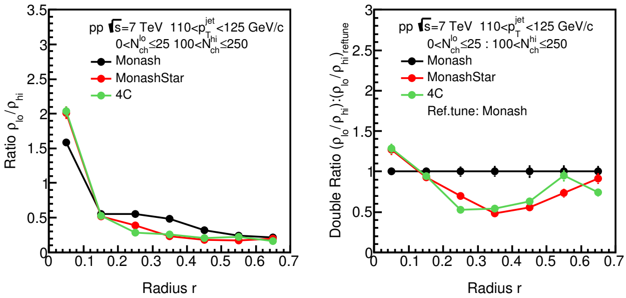
- The R_{fix} depends on the p_T^{jet}.
- The shape of the curve can be qualitatively explained by a Lorentz boost.

The p_t^{jet} dependence of R_{fix}



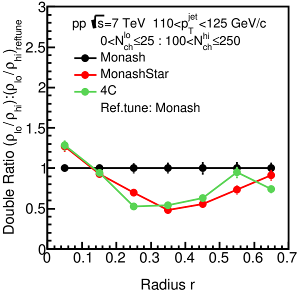
- Good agreement between tunes (left) and settings (middle).
- The R_{fix} does not depend on the three jet reconstruction algorithms (right).
- R_{fix} is a **characteristic jet size** at a given p_t^{jet}.

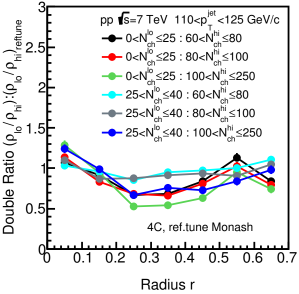
Applying a double ratio for $\rho(r)$



- Cancelling out trivial multiplicity bias: $\frac{(\rho_{low}/\rho_{high})}{(\rho_{low}/\rho_{high})_{ref.tune}}$.
- We find a significant effect at given p_t^{jet} windows.
- Non-trivial dependence on p_t^{jet}, origin of the effect needs further investigation.

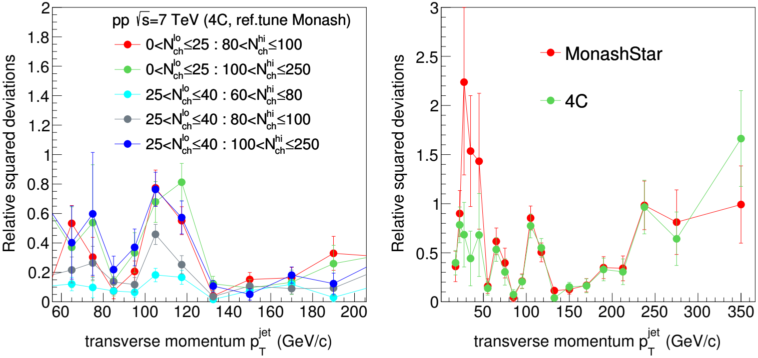
Double ratio for different multiplicity bins





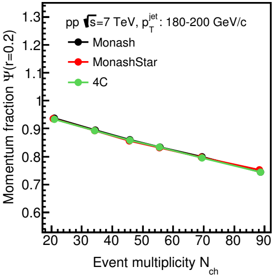
- Same calculations for several different multiplicity bins.
- The effect is larger as the separation in multiplicity is larger.
- Statistically independent samples → not fluctuations.

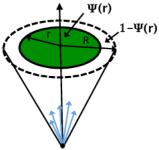
Relative squared deviations

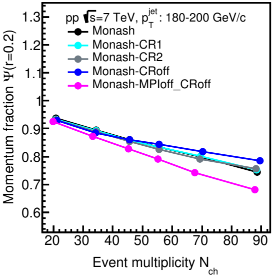


- $RSD = \sqrt{\sum_{0<r_i<R} \left(DR(r_i) - 1\right)^2}$
- The nature of the p_T^{jet} dependence is independent of the chosen multiplicity bin.

$\psi(r = 0.2)$ dependence on multiplicity

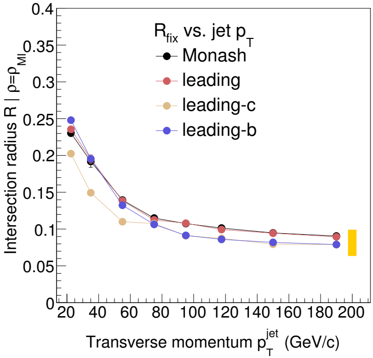






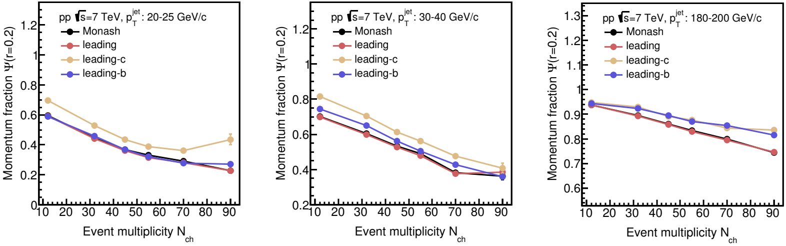
- No significant difference in integral jet structure between the three tunes and between different CR schemes.
- Turning off MPI causes significant differences for higher multiplicities, which can not be explained by bin effects.
- Observation implies MPI influence on jet structure.

R_{fix} with Heavy Flavour



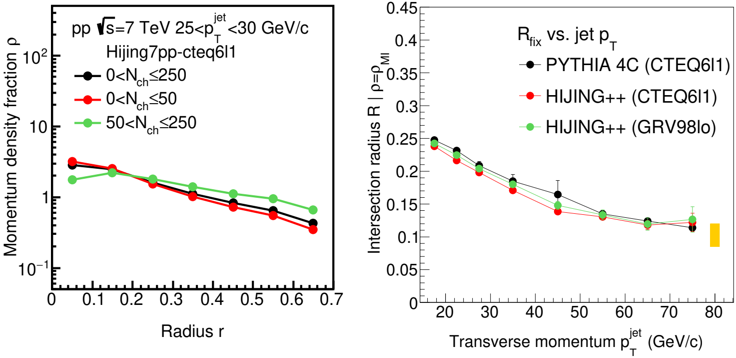
- Selection of leading jets does not make a difference.
- For smaller p_T^{jet} the charm leading jets appear narrower.
- For higher p_T^{jet} both charm and bottom jets are narrower.

Integral jet structure with Heavy Flavour



- Charm leading jets always differ (except for very low Nch).
- Bottom leading jets also differ for higher multiplicities in the case of high enough p_T^{jet}.
- For certain p_T^{jet} (depends on r) all curves differ → HF fragmentation is different → model differentiation.

Jet structure with Hijing++



- We had a look with the new Hijing++ code (see Gábor Bíró's talk).
- The R_{fix} phenomenon is visible.

Summary

- We gave predictions for several jet structure observables in $\sqrt{s} = 7$ TeV p+p collisions using PYTHIA 8.
- Multiplicity-dependent experimental jet-structure analyses could differentiate between otherwise well-performing models.
- We suggest R_{fix} as a multiplicity-independent jet size measure.
- R_{fix} is present in Hijing++, even with different PDF sets.
- Multiplicity-dependent jet stuctures of Heavy Flavor jets are sensitive probes of flavor-dependent fragmentation.

Thank you for your attention!

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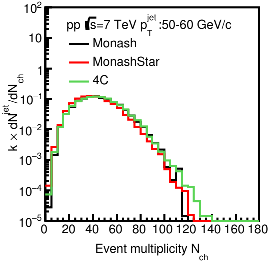
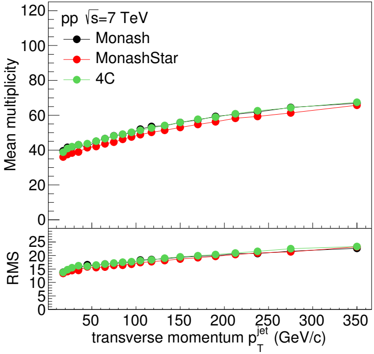
Backup

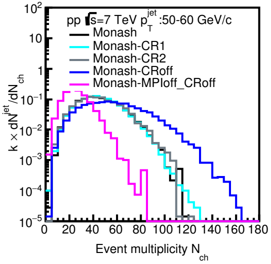
Event Nch multiplicity distribution for the tunes

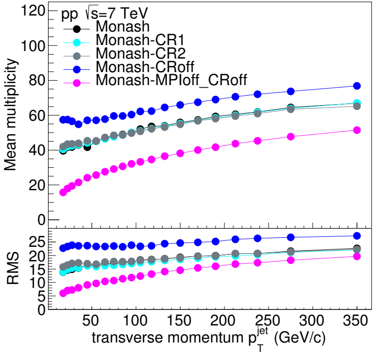




- All three tunes show similar event Nch distributions (they were calibrated for real data).
- The mean multiplicity increases with the p_T^{jet}.

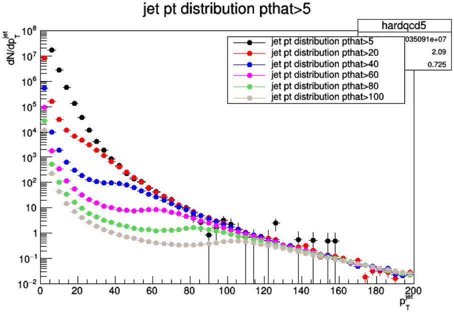
Event Nch multiplicity distribution for the settings





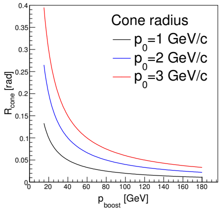
- CR schemes show similar *Nch* distributions.
- The MPI:off and CR:off settings are not physical
  - MPI:off (CR:off) → lower mean multiplicity.
  - CR:off (MPI:on) → higher mean multiplicity.

p_t^{jet} distributions for different $\hat{p}_t$



p_t^{jet}	$\hat{p}_t$
20 - 25	$5 \leq$
30 - 40	$5 \leq$
50 - 60	$20 \leq$
70 - 80	$20 \leq$
90 - 100	$40 \leq$
110 - 125	$40 \leq$
140 - 160	$80 \leq$
180 - 200	$80 \leq$
225 - 250	$80 \leq$

A toy model



- Jet consisting of particles with equal momentum p_0.
- We boost with a certain momentum p_{boost} towards the jet axis.
- High-p_T: qualitatively similar behaviour of the characteristic jet size with respect to p_{boost}.
- Low-p_T: blow-up is not expected in data because jet rec. is limited in R and because of angular cut-off in splitting.

Multiplicity distribution for Hijing++