Jet structure studies in small systems

(arXiv:1805.03101, 1809.10102)

Zimányi School 2018, Budapest

Zoltán Varga[ab]
in collaboration with
Róbert Vértesi[a] and **Gergely Gábor Barnaföldi**[a]

[a] Wigner RCP, Budapest, Hungary
[b] Eötvös Loránd University of Budapest (ELTE)

3 December 2018

Motivation - collectivity in small systems

- Suprise at LHC energies: v_2 and long-range correlations in high-multiplicity p+p events;
  - Long range correlations. **ATLAS, Nucl. Phys. A932, 357 (2014)**
  - Azimuthal anisotropy (v_n, flow).
    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

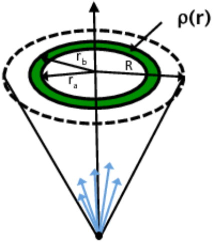
- Jet structure may be modified even in small systems without large volume of QGP.
- **We are looking for non-trivial jet shape dependence on event multiplicity.**
- We are simulating p+p collisions at $\sqrt{s} = 7$ TeV.
- Monte Carlo event generator: PYTHIA 8.2 with different PDF sets: NNPDF2.3lo for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

Different tunes and settings

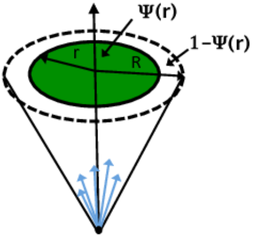
- Tunes: Monash, Monash*, 4C.
- Multi parton interactions (MPI).
- Colour reconnection (CR): In PYTHIA this is an in-built mechanism that allows interactions between partons originating in MPI and initial/final state radiations, by minimizing color string lengths.
  - 0: MPI-based scheme,
  - 1: QCD-based 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:

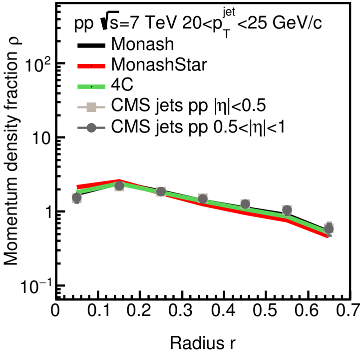


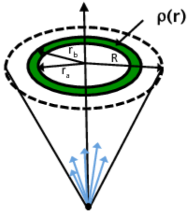
$$\rho(r) = \frac{1}{\delta r}\frac{\sum_{r_a<r_i<r_b} p_t^{(i)}}{p_t^{jet}}.$$

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

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

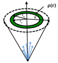
A reality check: Comparison with CMS for $\rho(r)$

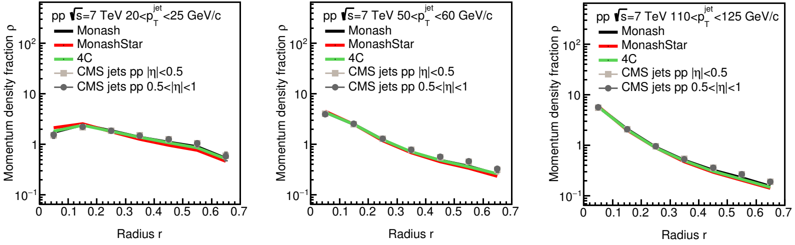




- The three different tunes reproduce the 7 TeV $|\eta| < 1$ pp CMS data within uncertainty.
- We investigated different p_T^{jet} windows between $15\ GeV/c < p_T^{jet} < 400\ GeV/c$.

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

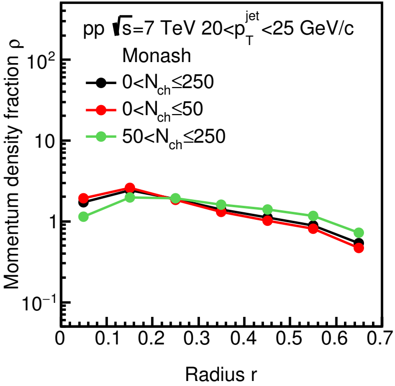


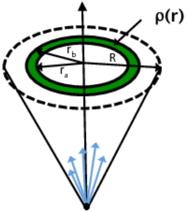


- The three different tunes reproduce the 7 TeV $|\eta| < 1$ p-p CMS data within uncertainty.
- We investigated different p_T^{jet} windows between $15\ GeV/c < p_T^{jet} < 400\ GeV/c$.

New study: Selection of jets by multiplicity!

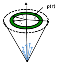
$\rho(r)$ distribution for different multiplicities

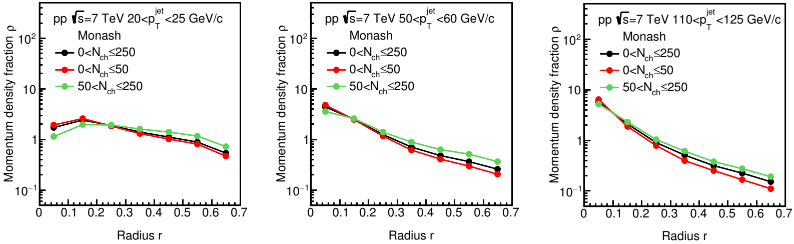




- We see a multiplicity dependence in the jet shapes,
- but it is the trivial multiplicity dependence we expected.
- Lower multiplicity jets are more collimated.

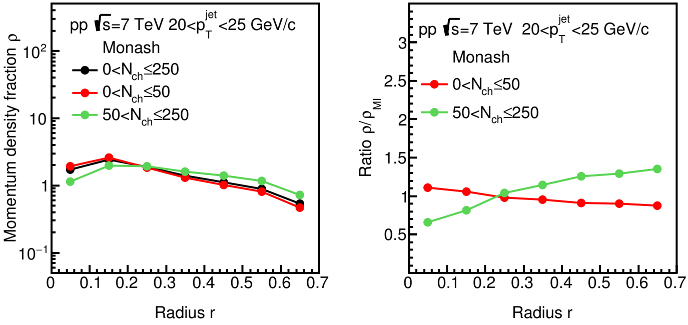
$\rho(r)$ distribution for different multiplicities





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

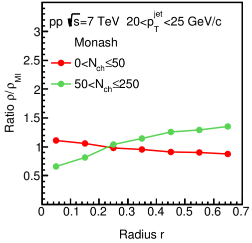
Ratio with Multiplicity Integrated (MI) $\rho(r)$

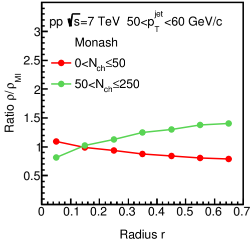


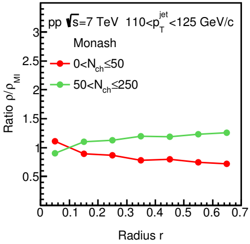
- We divide the curves in the **left** figure with the multiplicity integrated (MI) curves, so
- we gain the **right** figure.

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

 /  MI



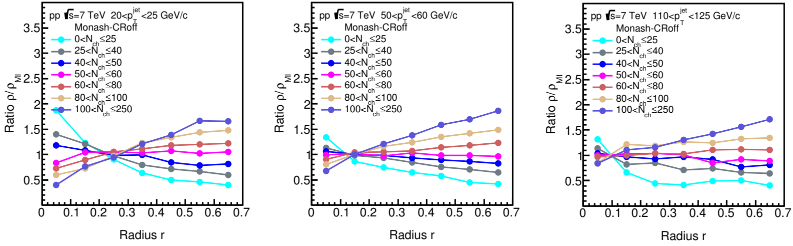




- Two curves: $\rho_{low-Nch}/\rho_{MI}$ and $\rho_{high-Nch}/\rho_{MI}$.
- The low- and high-multiplicity curves intersect each other at unity.
- The intersection point depends on the p_t^{jet} (three examples above).

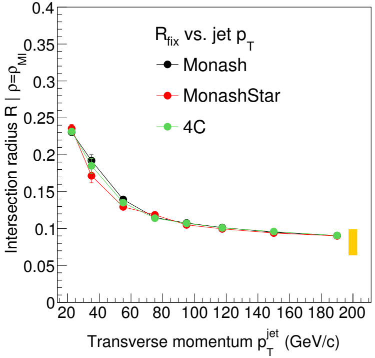
A characteristic jet size measure?

 /  MI



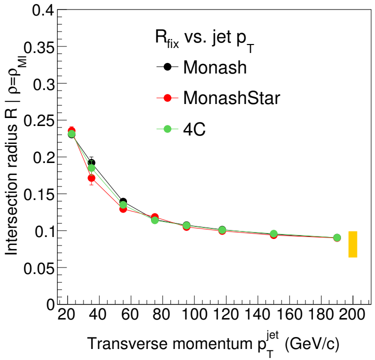
- Pythia describes the mutiplicity distributions well.
- The intersection does not depend on our multiplicity bin choice, but it depends on the p_T^{jet}.
- Our finding: a non-trivial scaling behaviour.

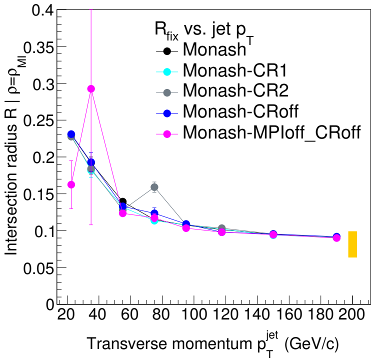
The p_t^{jet} dependence of R_{fix}



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

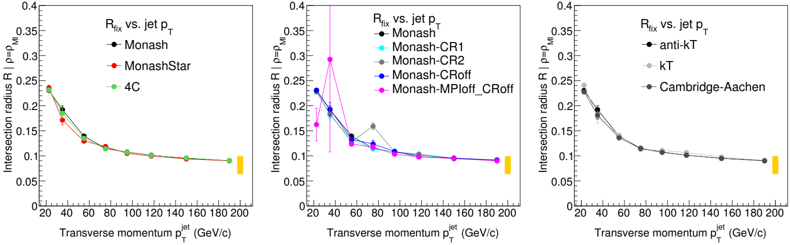
The p_t^{jet} dependence of R_{fix}





- Good agreement between tunes (left) and settings (right).

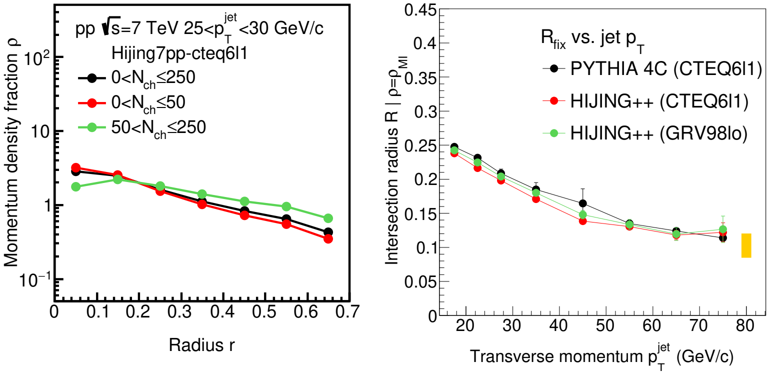
The p_t^{jet} dependence of R_{fix}



- Good agreement between tunes (left) and settings (right).
- 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}.

Let's try out a different MC generator!

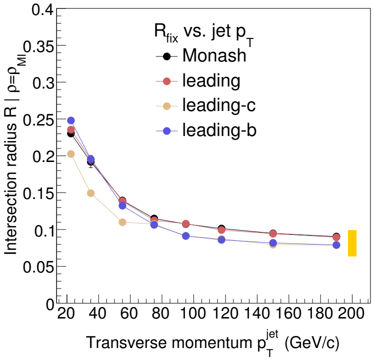
Jet structure with Hijing++



- We had a look at the new Hijing++ code.
- The R_{fix} phenomenon is visible.

Is the jet structure from Heavy Flavour any different?

R_{fix} with Heavy Flavour

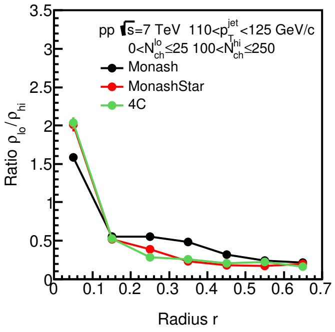


- Selection of leading jets does not make a difference.
- For smaller p_T^{jet} the charm leading jets appear narrower.
- For higher p_T^{jet} both charm and bottom jets are narrower.

Back to the question:

Does the jet shape depend on the multiplicity?

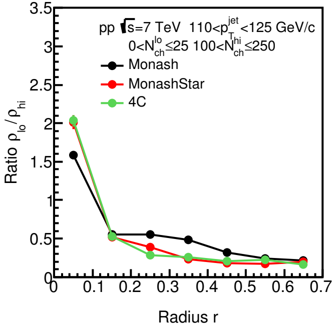
Applying a double ratio for $\rho(r)$

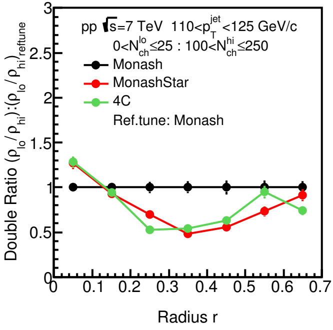


We want to apply a double ratio to cancel out multiplicity bias:

$$\frac{(\rho_{low}/\rho_{high})}{(\rho_{low}/\rho_{high})_{ref.tune}}$$

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

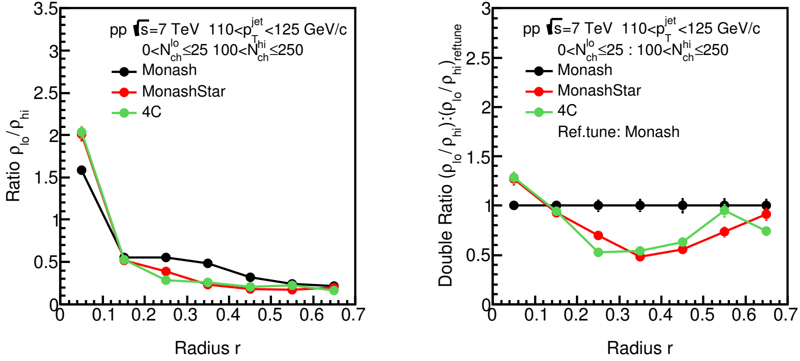




We want to apply a double ratio to cancel out multiplicity bias:

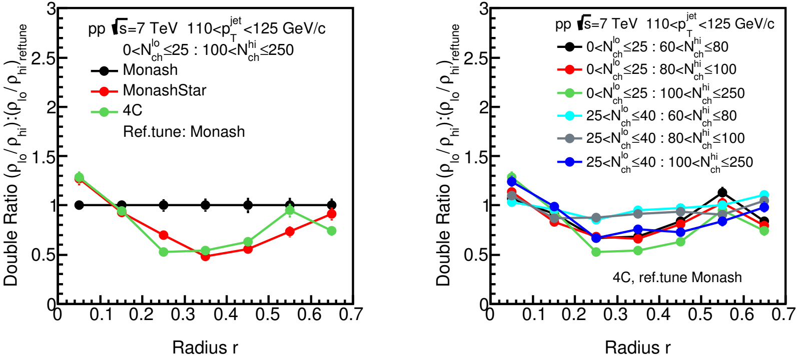
$$\frac{(\rho_{low}/\rho_{high})}{(\rho_{low}/\rho_{high})_{ref.tune}}$$

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.

Summary

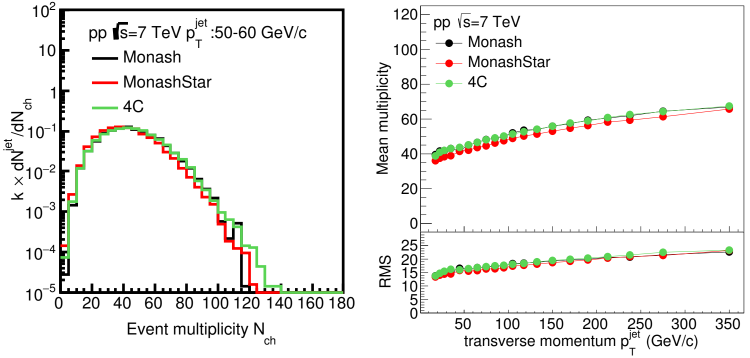
- We gave predictions for several jet structure observables in $\sqrt{s} = 7$ TeV p+p collisions using PYTHIA 8.
- Multiplicity-dependent experimental jet-structure analyses could differentiate between otherwise well-performing models.
- We suggest R_{fix} as a multiplicity-independent jet size measure.
- 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!

This work has been supported by the NKFIH/OTKA K 120660 grant, the János Bolyai scholarship of the Hungarian Academy of Sciences.
The simulations were done with the resources of The Wigner GPU Laboratory and Wigner Datacentre.

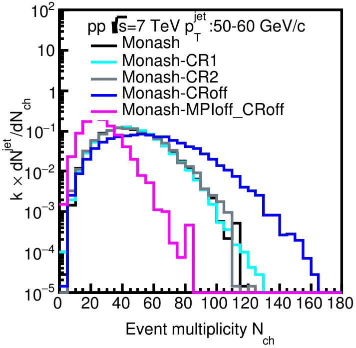
Backup

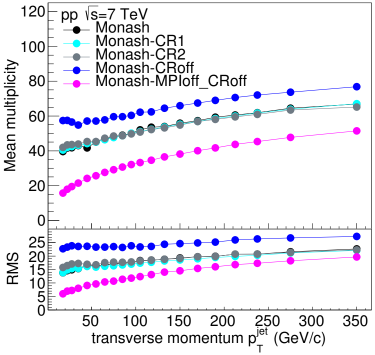
Multiplicity distribution for the tunes



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

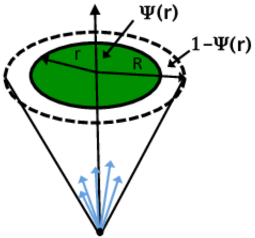
Multiplicity distribution for the settings





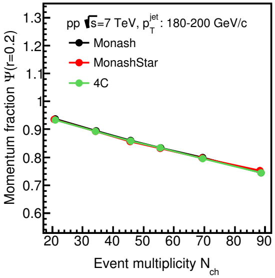
- CR schemes show similar *Nch* distributions.
- The MPI:off and CR:off settings are not physical
  - MPI:off (CR:off) → lower mean multiplicity.
  - CR:off (MPI:on) → higher mean multiplicity.

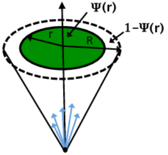
We also have the integral jet shape $\psi(r)$

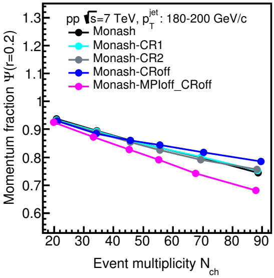


$$\psi(r) = \frac{\sum_{r_i<r} p_t^{(i)}}{p_t^{jet}}$$

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

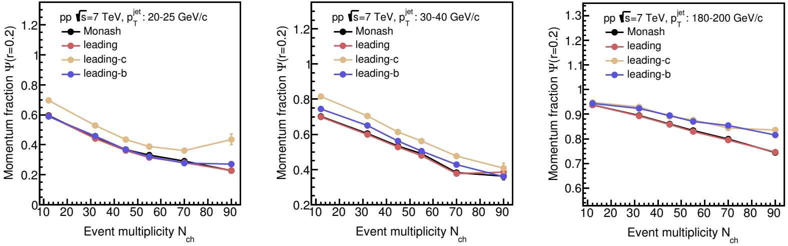






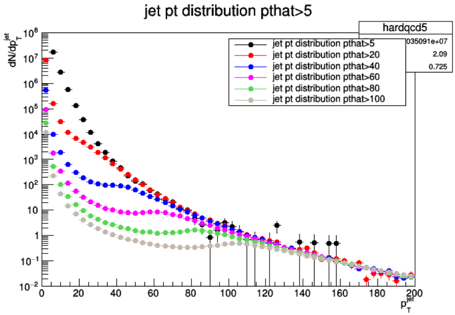
- No significant difference in integral jet structure between the three tunes and between different CR schemes.
- Turning off MPI causes significant differences for higher multiplicities, which can not be explained by bin effects.
- Observation implies MPI influence on jet structure.

Integral jet structure with Heavy Flavour



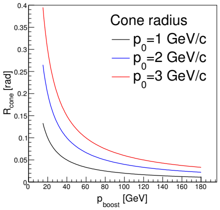
- Charm leading jets always differ (except for very low Nch).
- Bottom leading jets also differ for higher multiplicities in the case of high enough p_T^{jet}.
- For certain p_T^{jet} (depends on r) all curves differ $\rightarrow$ HF fragmentation is different $\rightarrow$ model differentiation.

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



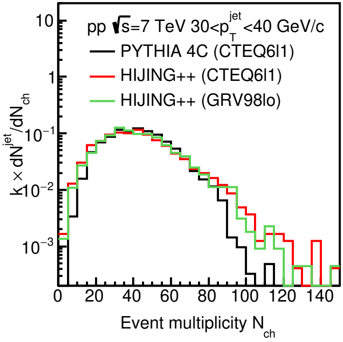
p_t^{jet}	$\hat{p}_t$
20 - 25	5 $\leq$
30 - 40	5 $\leq$
50 - 60	20 $\leq$
70 - 80	20 $\leq$
90 - 100	40 $\leq$
110 - 125	40 $\leq$
140 - 160	80 $\leq$
180 - 200	80 $\leq$
225 - 250	80 $\leq$

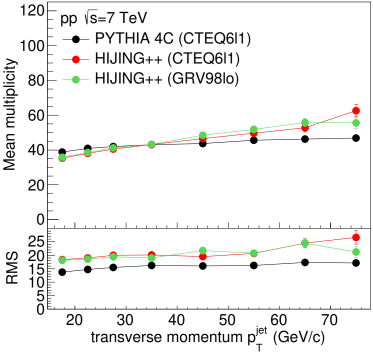
A toy model



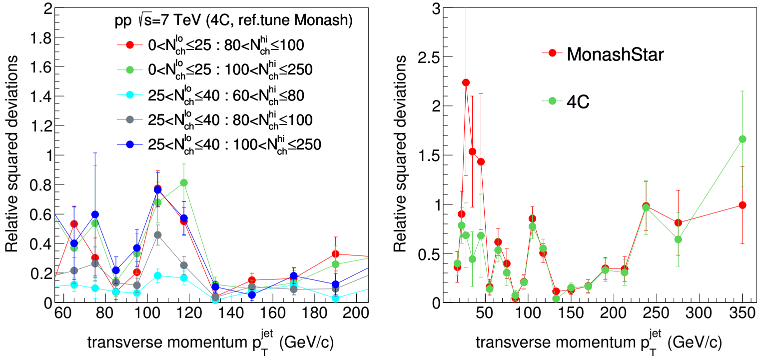
- Jet consisting of particles with equal momentum p_0.
- We boost with a certain momentum p_{boost} towards the jet axis.
- High-p_T: qualitatively similar behaviour of the characteristic jet size with respect to p_{boost}.
- Low-p_T: blow-up is not expected in data because jet rec. is limited in R and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

Multiplicity distribution for Hijing++





Relative squared deviations



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