Jets in Small Systems

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Motivation

Surprise 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 (vn, 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.

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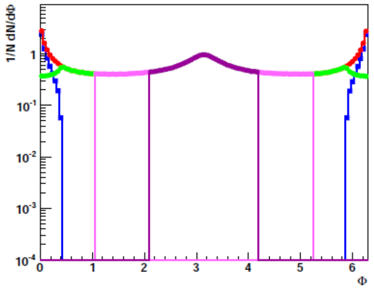
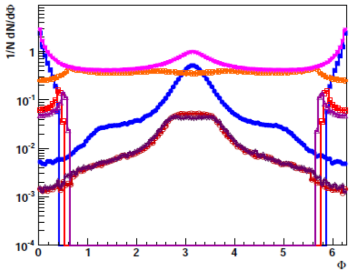
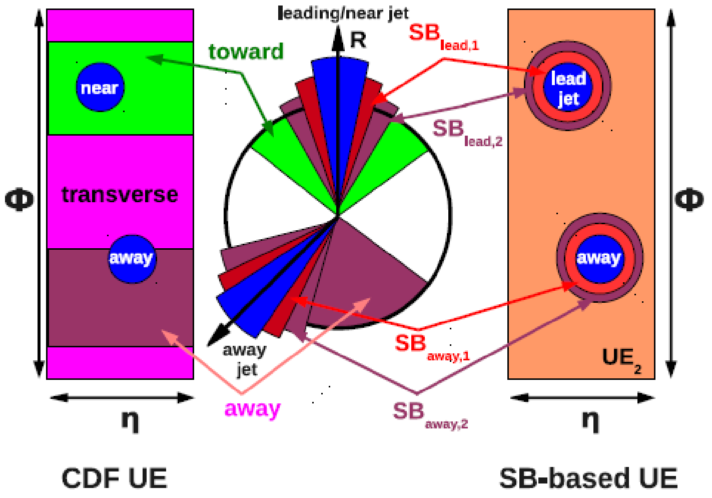
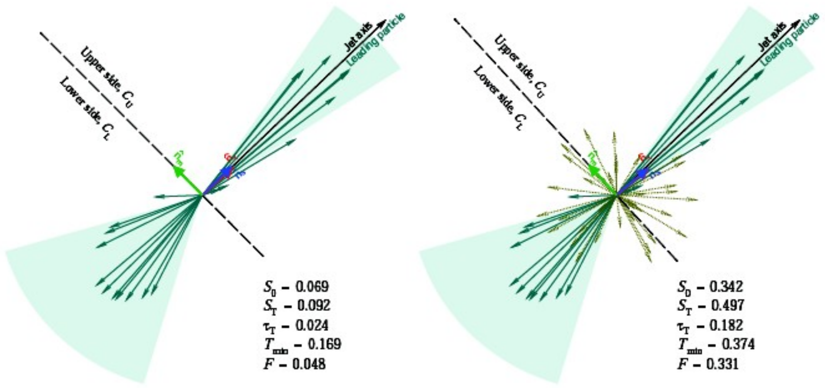
- The better understanding of the jet-matter interaction requires more precise separation of the jet and the underlying event
- Need to find a better measure → multiplicity can help?
  - Subcone methods A. Agocs, P. Levai, GGB (2011)

  - Spherocity, Thust A. Ortiz, G. Paic (2017)

$$S_0 = \frac{\pi^2}{4}\left(\frac{\sum_i |\vec{p}_{\mathrm{T}i} \times \hat{\mathbf{n}}|}{\sum_i p_{\mathrm{T}i}}\right)^2 \qquad T_{\min} \equiv \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}_m|}{\sum_i p_{\mathrm{T},i}}$$





Jet-modification in Small Systems

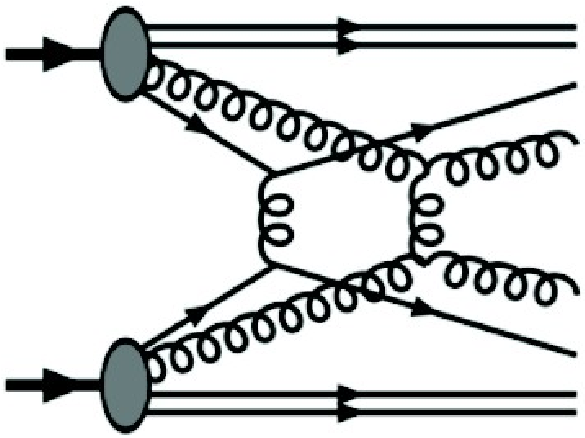
- Jet structure maybe is modified even in small systems without large volume of QGP.
  - We are looking for non-trivial jet shape dependence on event multiplicity.
  - Monte Carlo event generator:
    - PYTHIA 8.2 with different PDF sets: NNPDF2.3lo for Monash and Monash*, CTEQ6L1 for 4C.
    - HIJING++,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

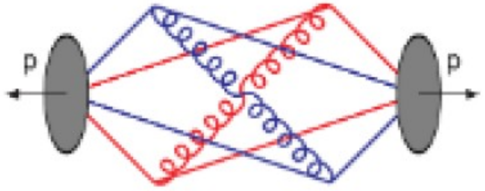
Jet distribution in small system

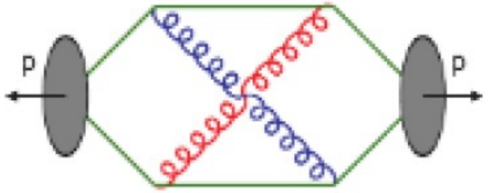
Z. Varga, R. Vértesi, GGB: Adv. High. En. Phys. 6731362 (2019), Universe 5 (2019) 132, MDPI Proc 10 (2019) 3

Different Tunes & Settings

- We have used the following settings in our analysis
  - 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 minimalization scheme,
    - 2: gluon-move scheme.
    - off: we don’t use it.
  - HIJING++ simulation with CR and no MPI (but minijets)

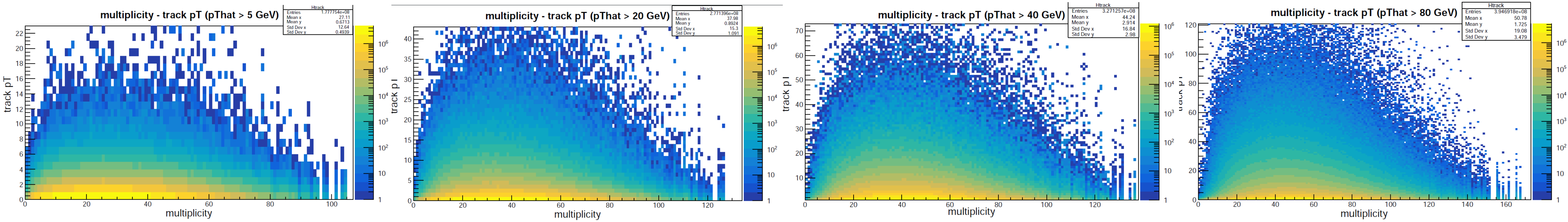






Meet the data: jets in pp collisions at 7 TeV

- p_T^{track} - multiplicity map, with various cuts of 2→ 2 hard reactions



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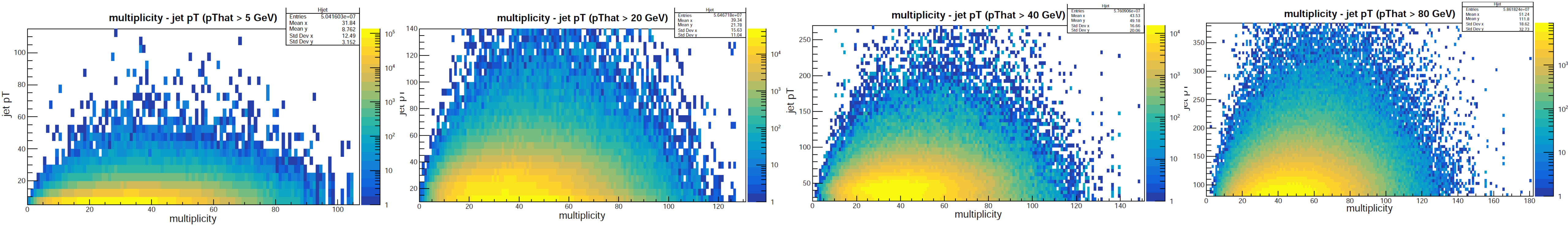

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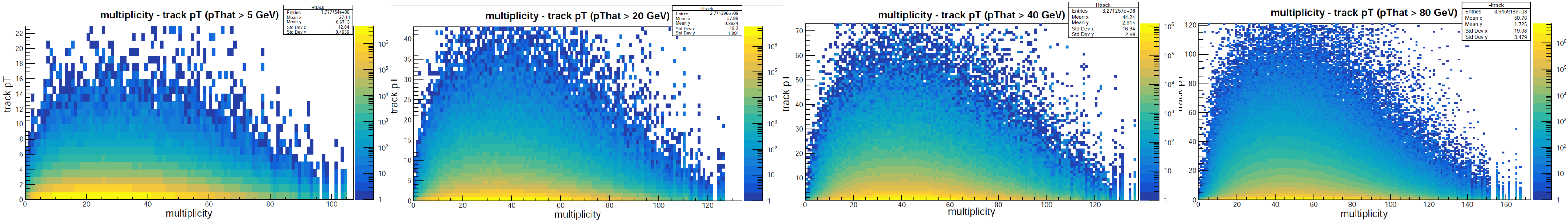

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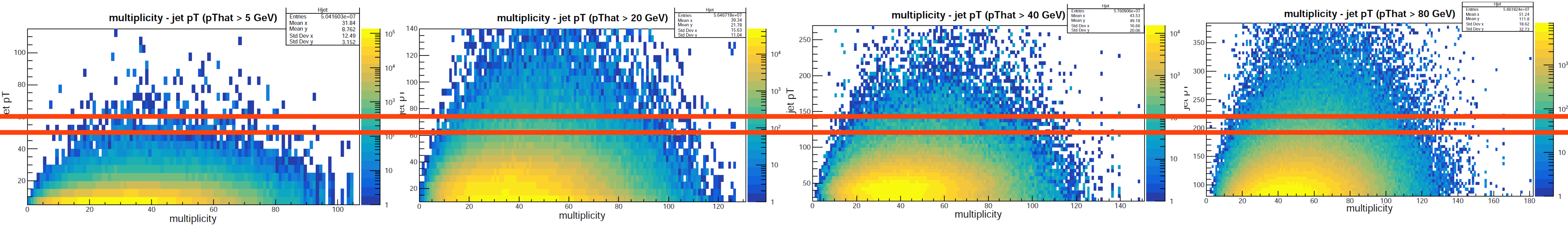
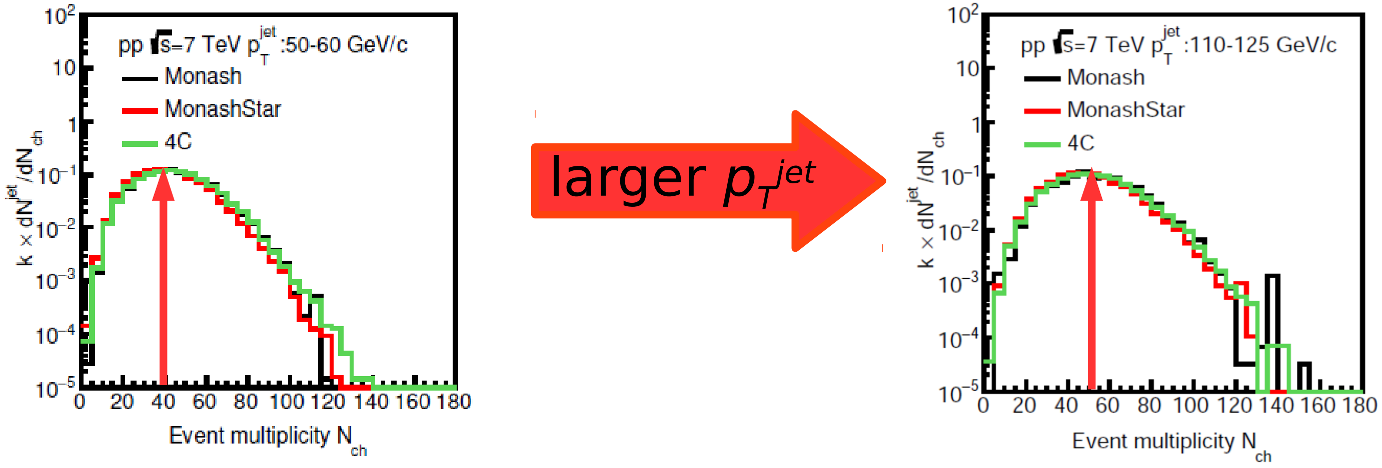


- We can make slices in the multiplicity distribution, by p_T^{jet}

Event multiplicity, N_{ch} distribution as settings & tunes

- Tunes show similar event N_{ch} distributions. The mean multiplicity increases with the p_T^{jet}



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  - CR:on (MPI:on) → high mean N_{ch}
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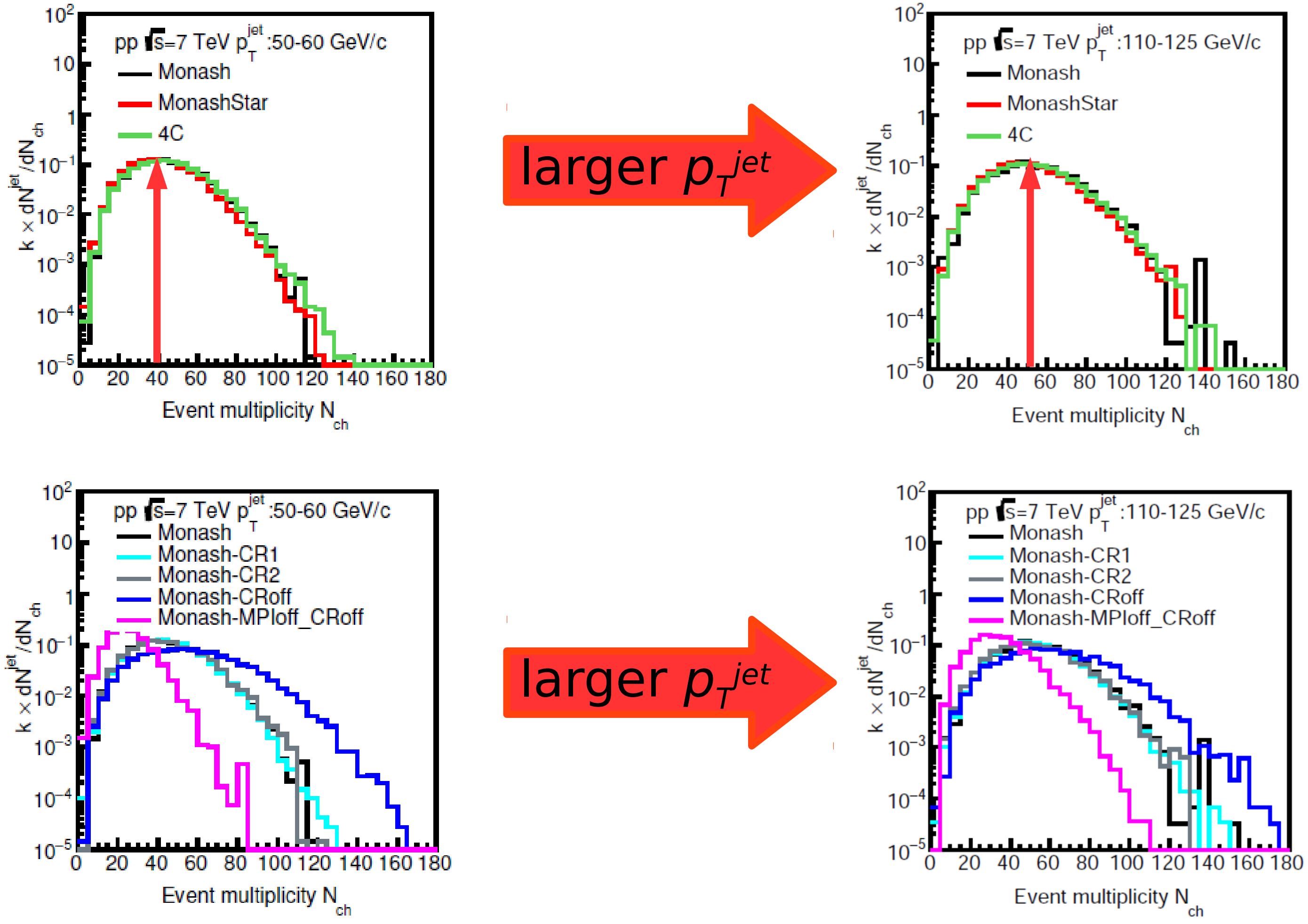

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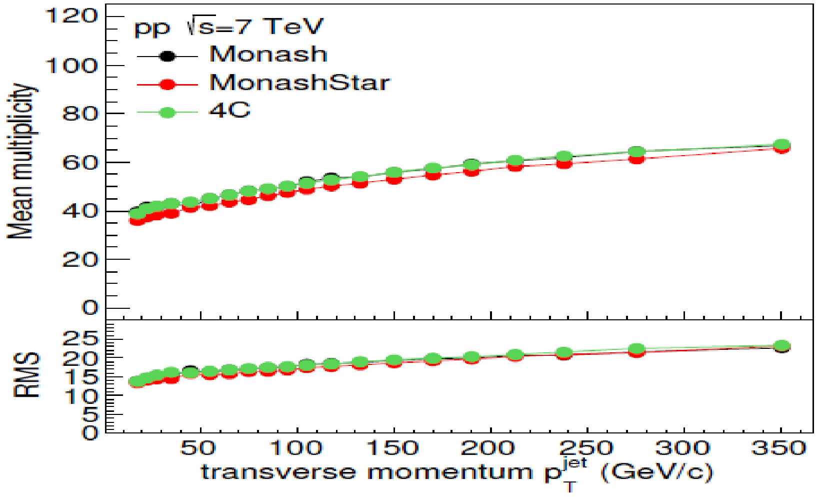
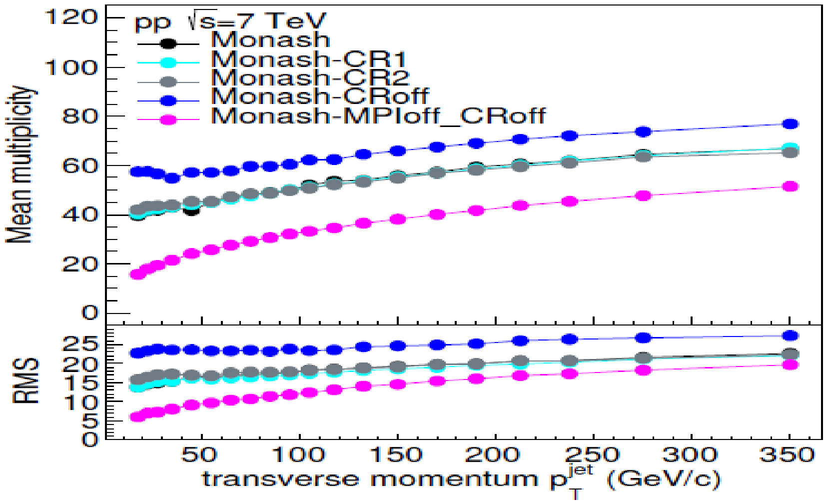
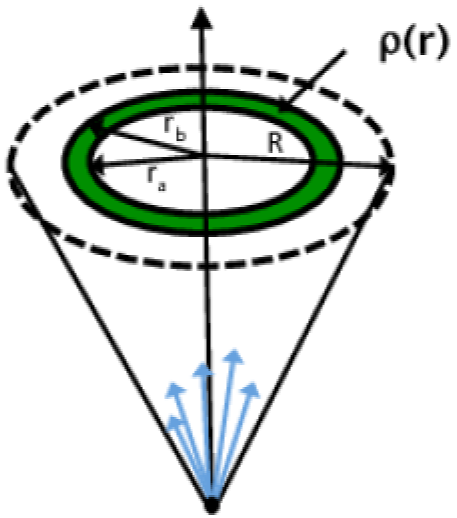




Jet structure variables in pp

Differential & integral jet-shapes

Differential jet shape:



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

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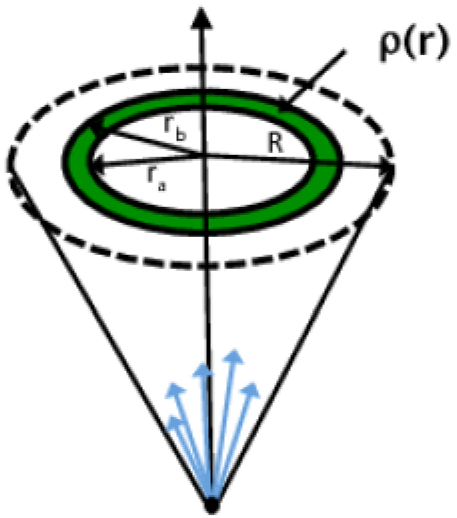

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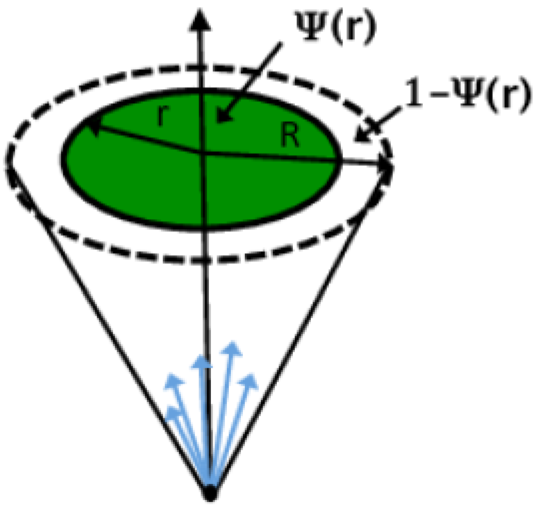

$$\psi(r) = \frac{\sum_{r_i<r} p_t^{(i)}}{p_t^{jet}}.$$

Differential & integral jet-shapes

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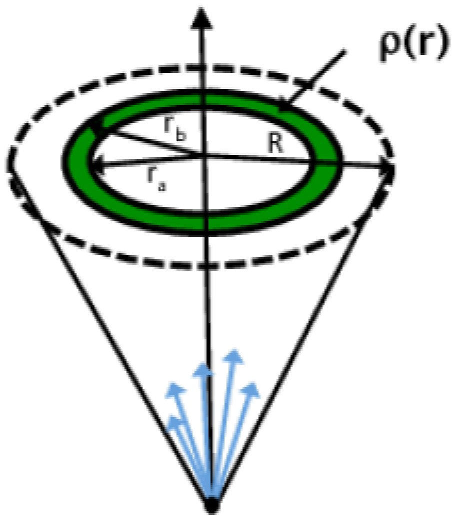

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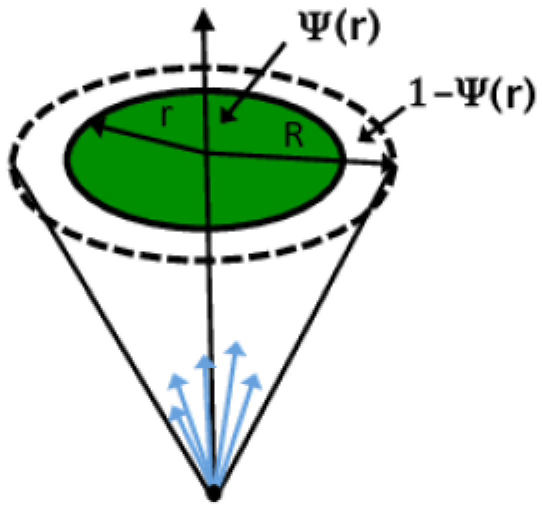
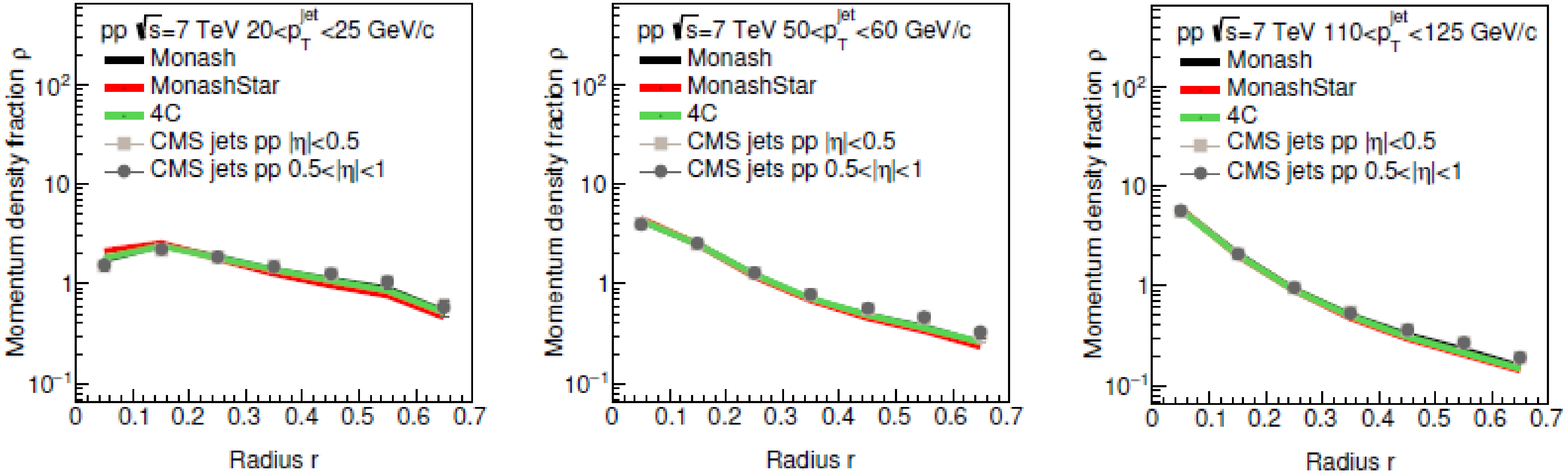


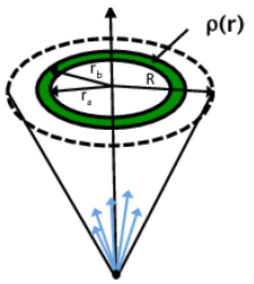
$$\psi(r) = \frac{\sum_{r_i < r} p_t^{(i)}}{p_t^{jet}}.$$

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

Test of the model: validity with *ρ(r)* CMS data

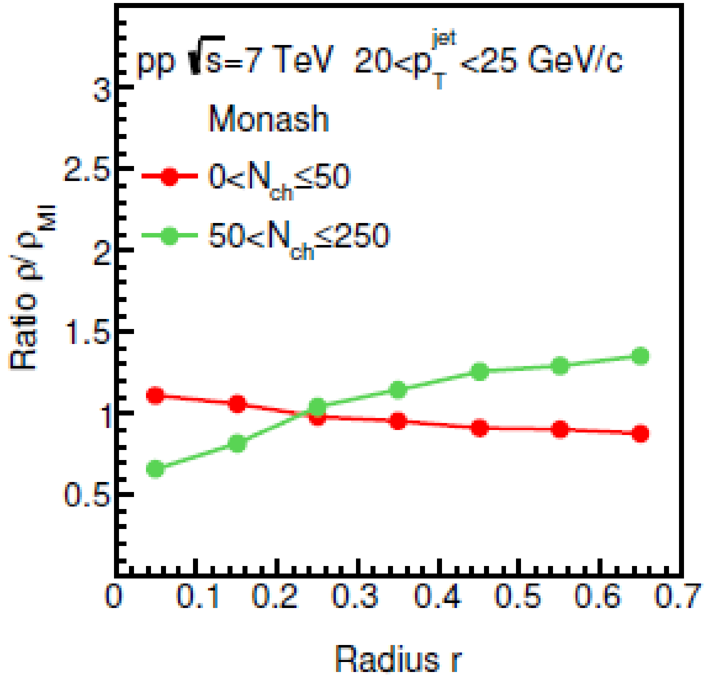


- The three different tunes reproduce the 7 TeV $|\eta|<1$, p-p CMS data within uncertainty.
- We investigated different p_T^{jet} windows between 15 GeV /c < p_T^{jet}< 400 GeV /c.

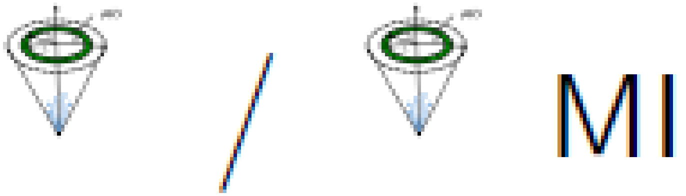


$$\rho(r) = \frac{1}{\delta r}\frac{\sum_{ra<r_i<r_b} p_t^{(i)}}{p_t^{jet}}.$$

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



- 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).



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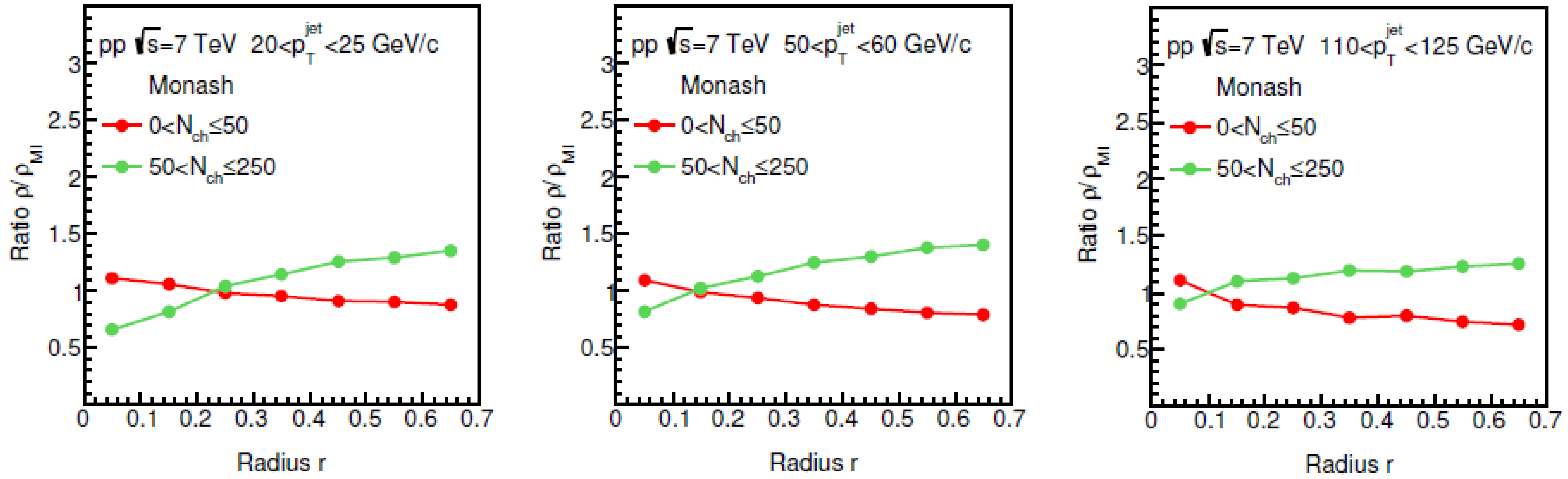

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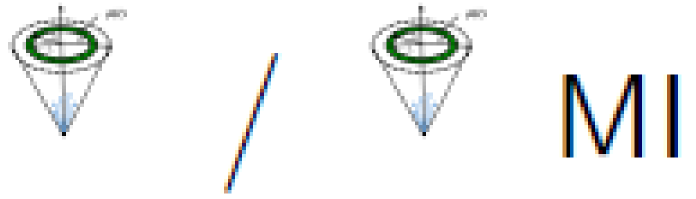
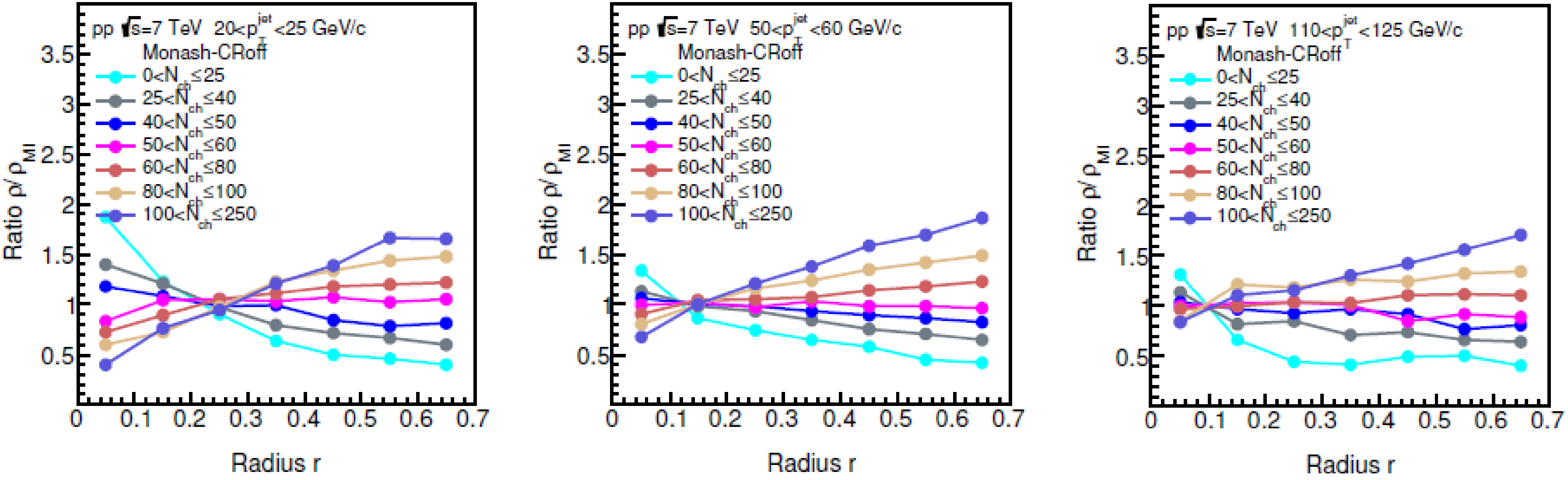
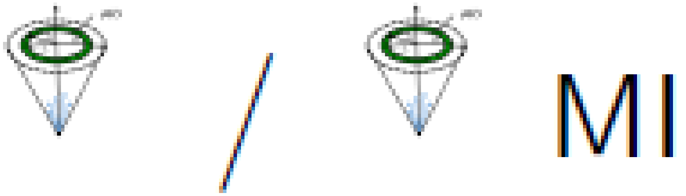


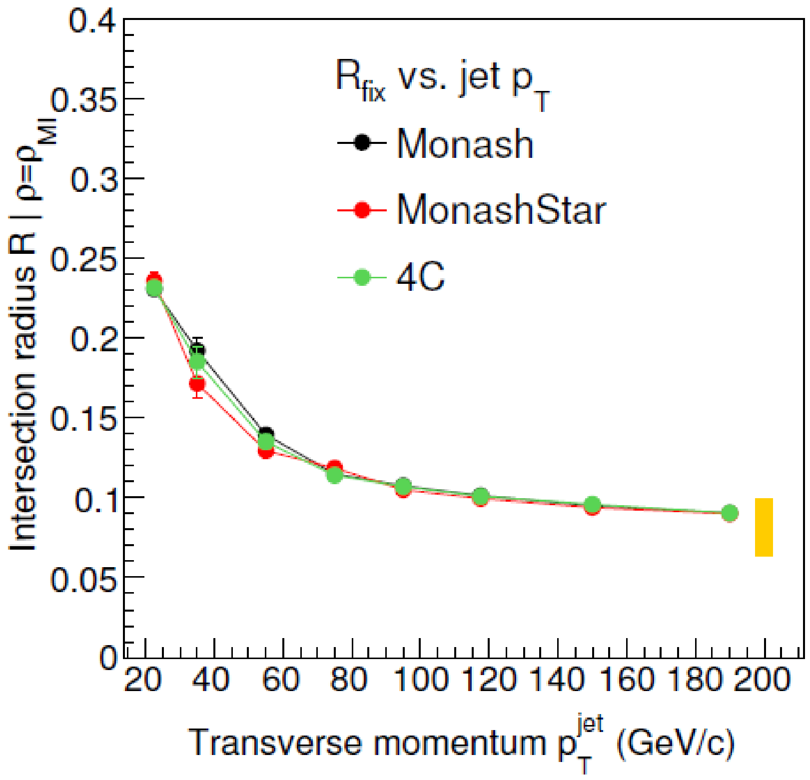
Is this a characteristic jet-size measure?



- 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.

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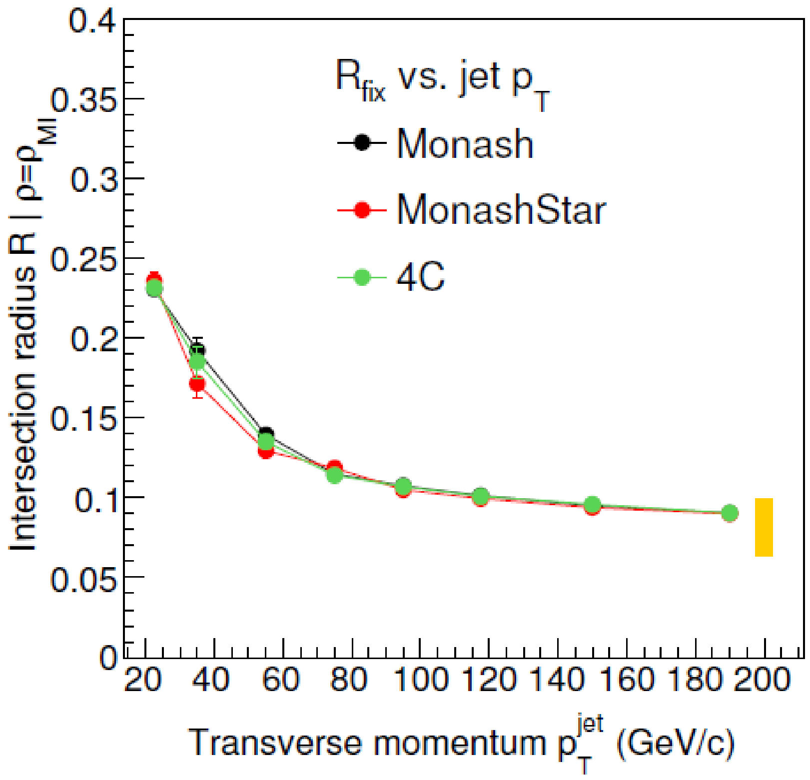
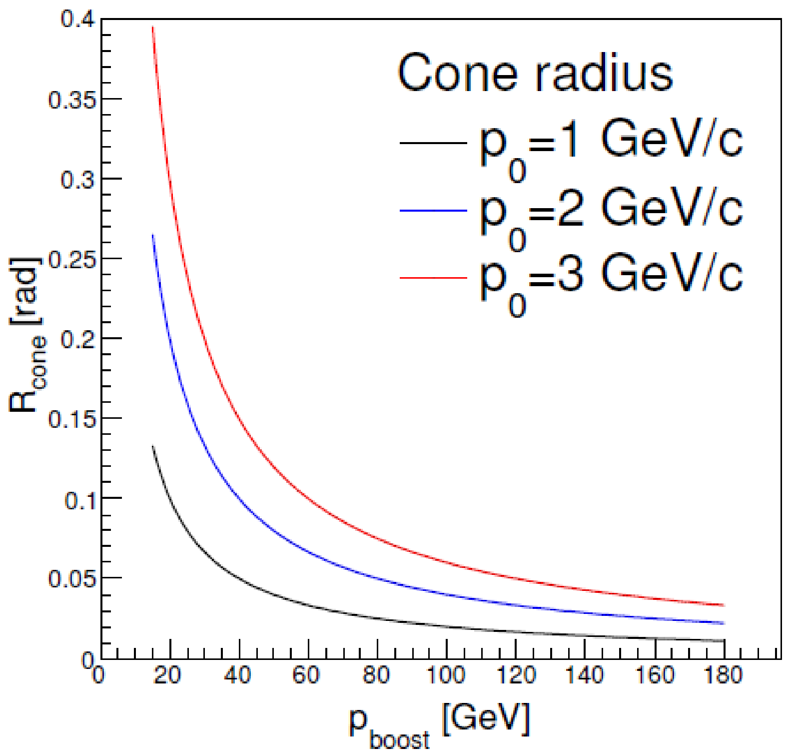
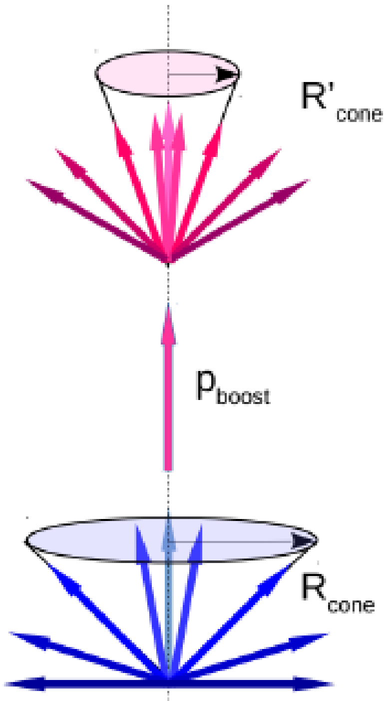
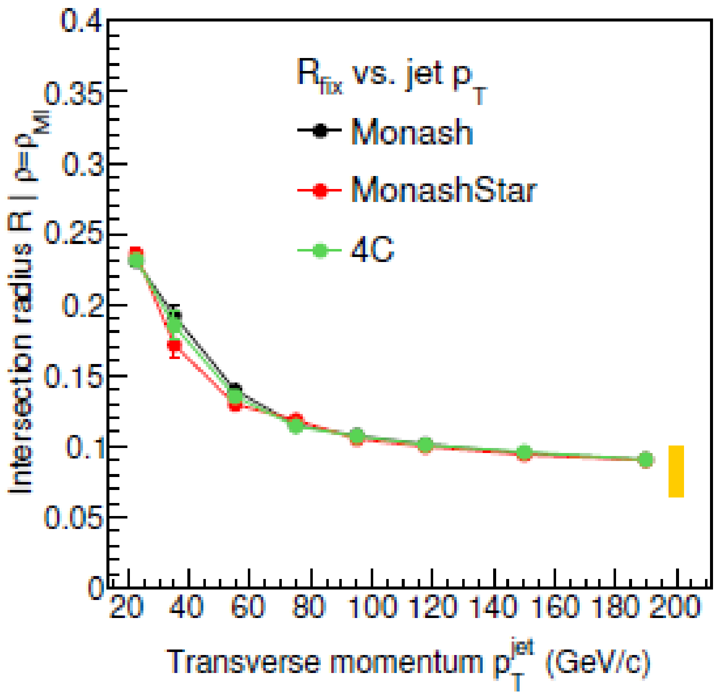




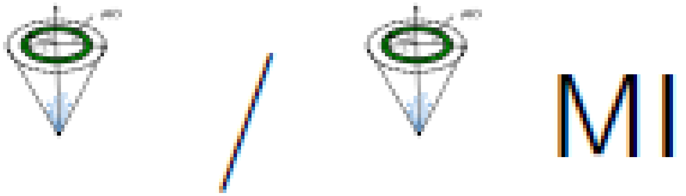


- The R_{fix} depends on the p_T^{jet}.
- The shape of the curve can be qualitatively explained by a Lorentz boost → narrowing/re-distribute, while boosted.

Validity of the p_T^{jet} dependence of R_{fix}



- Good agreement between tunes



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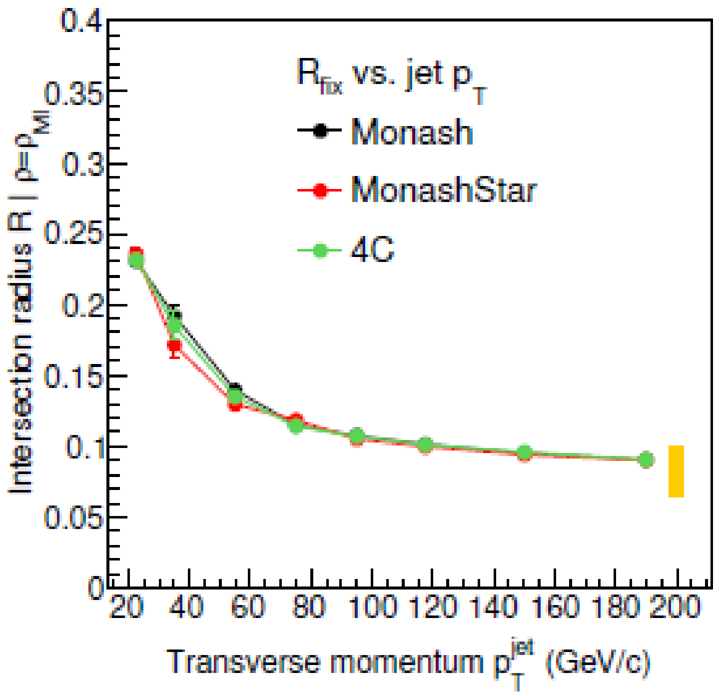
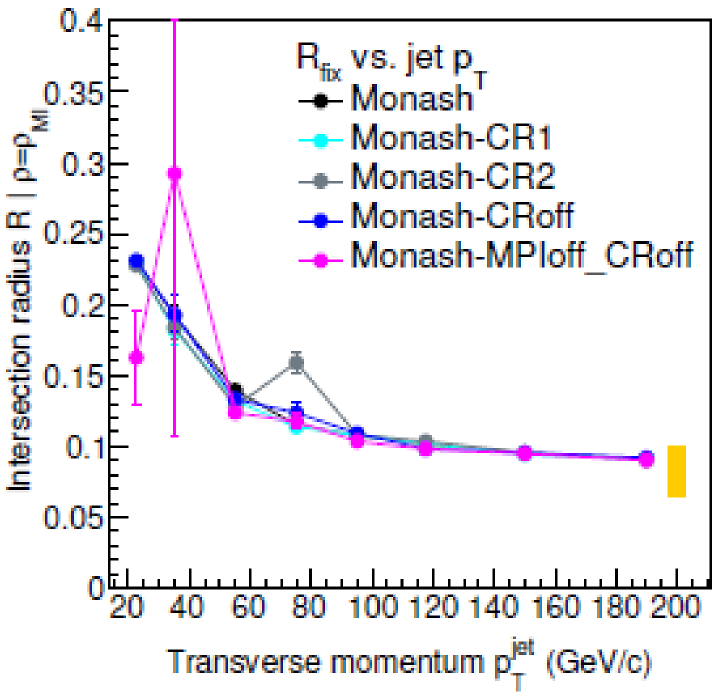
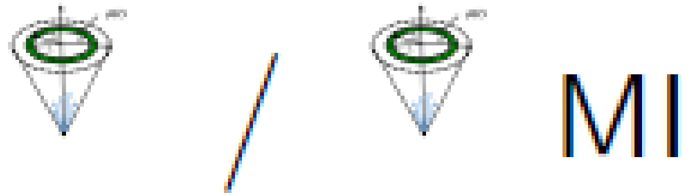




- Good agreement between tunes & settings.



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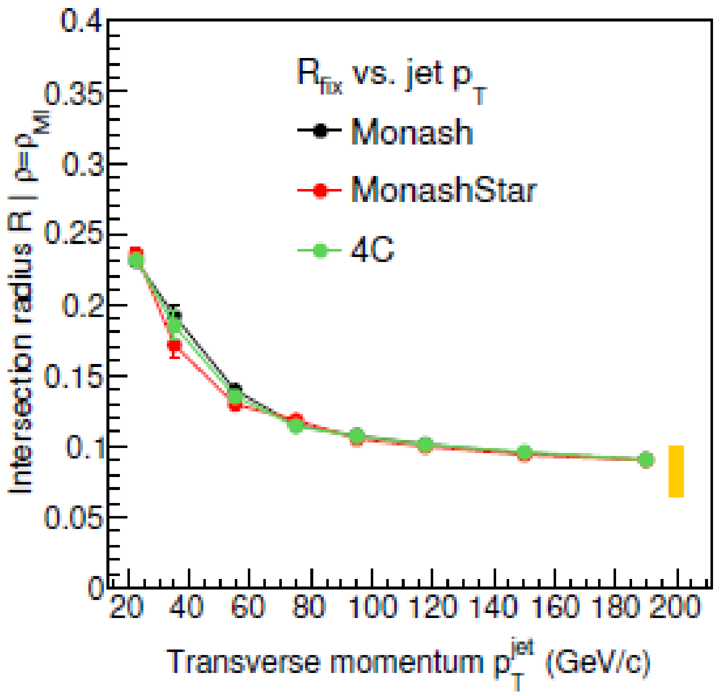
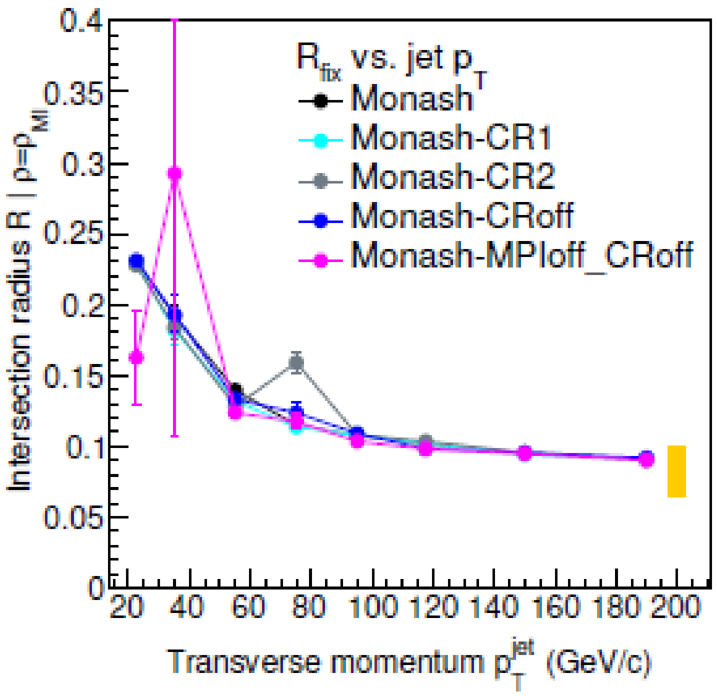
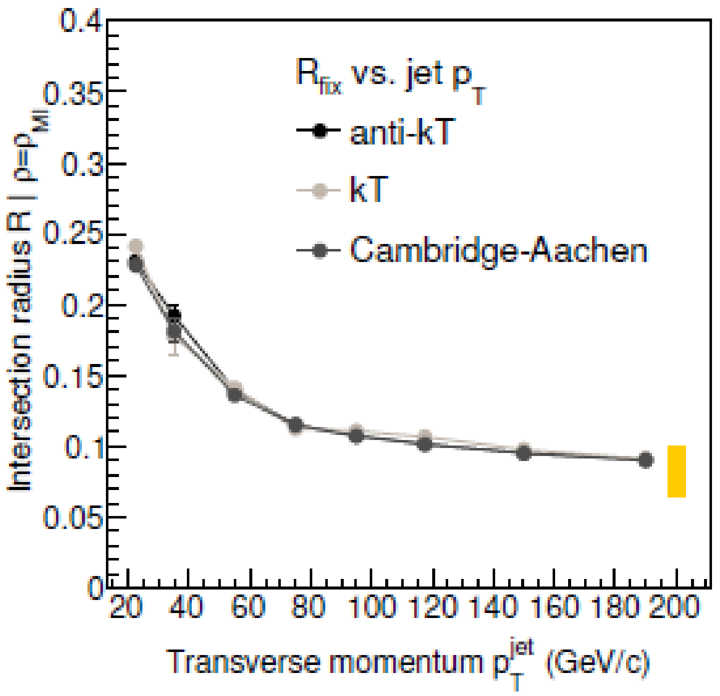
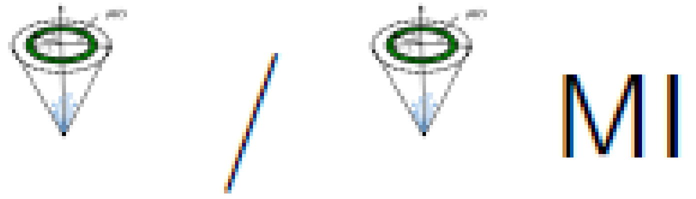


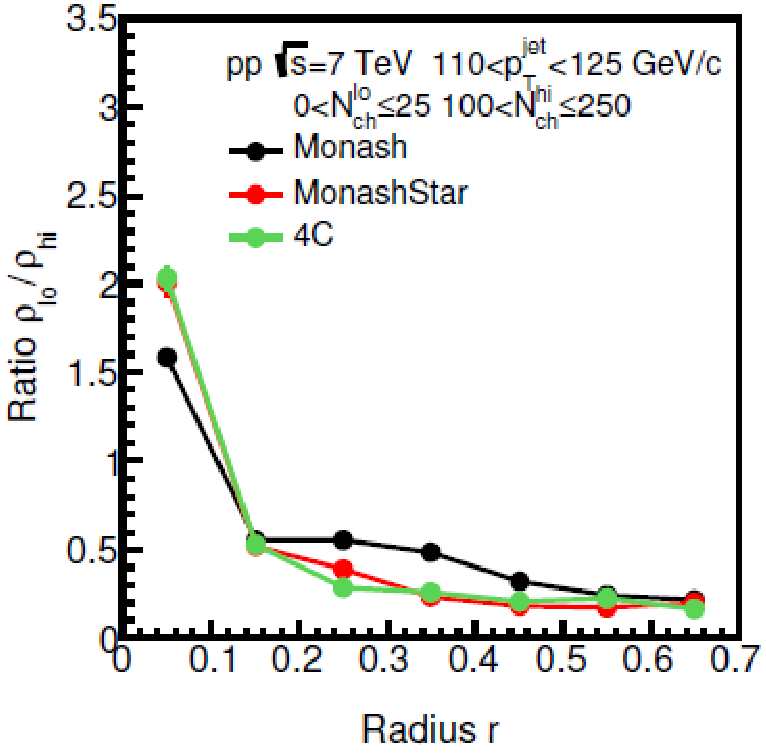


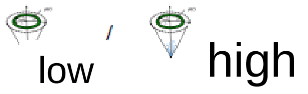


- Good agreement between tunes & settings.
- The R_{fix} does not depend on the three jet reconstruction algorithms.
- R_{fix} is a characteristic jet size at a given p_T^{jet}.



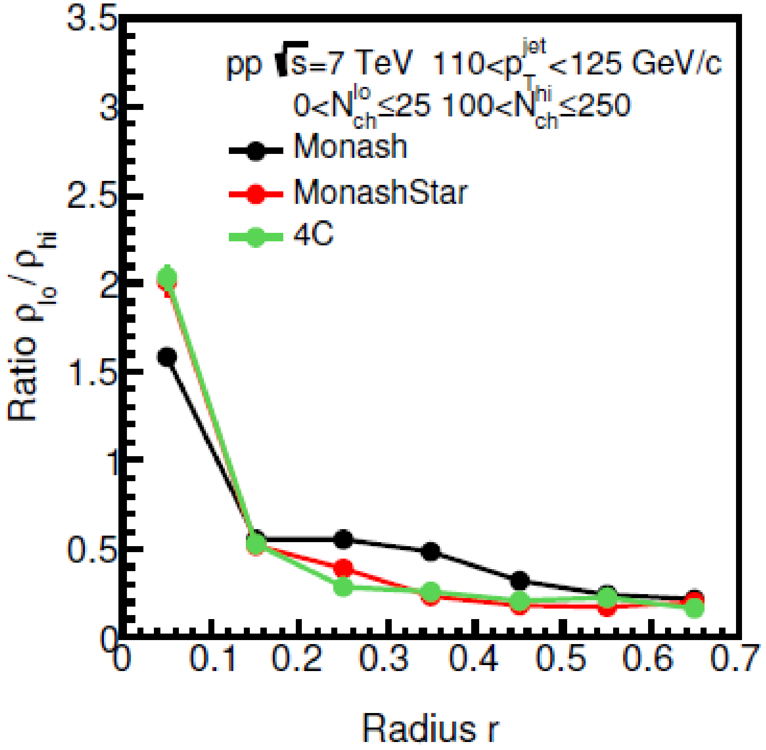
Applying a double ratio for *ρ(r)*

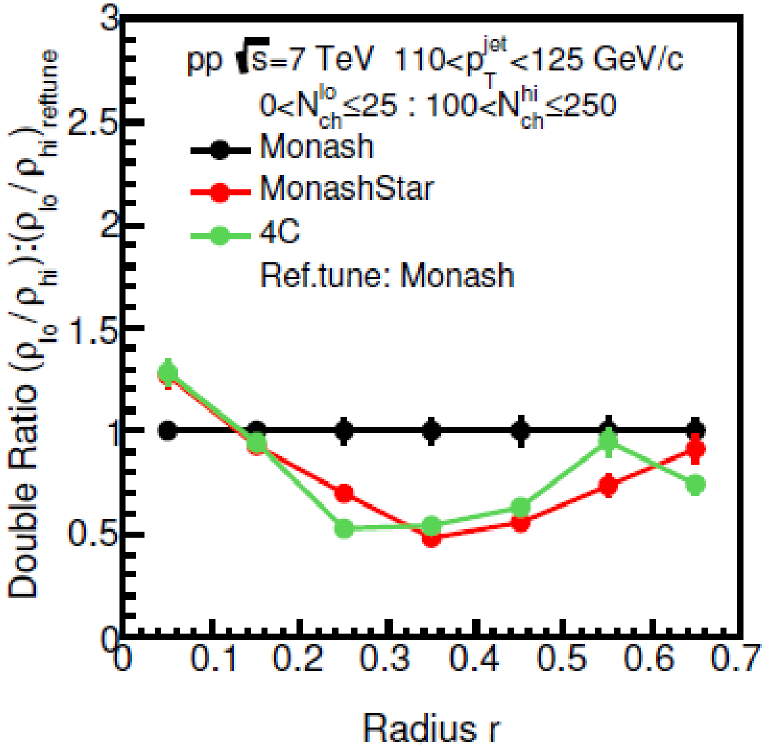


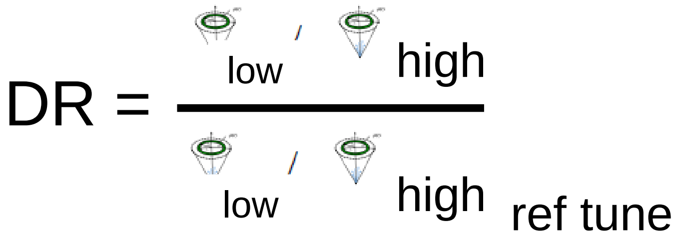


- Canceling out trivial multiplicity bias:

Applying a double ratio for *ρ(r)*

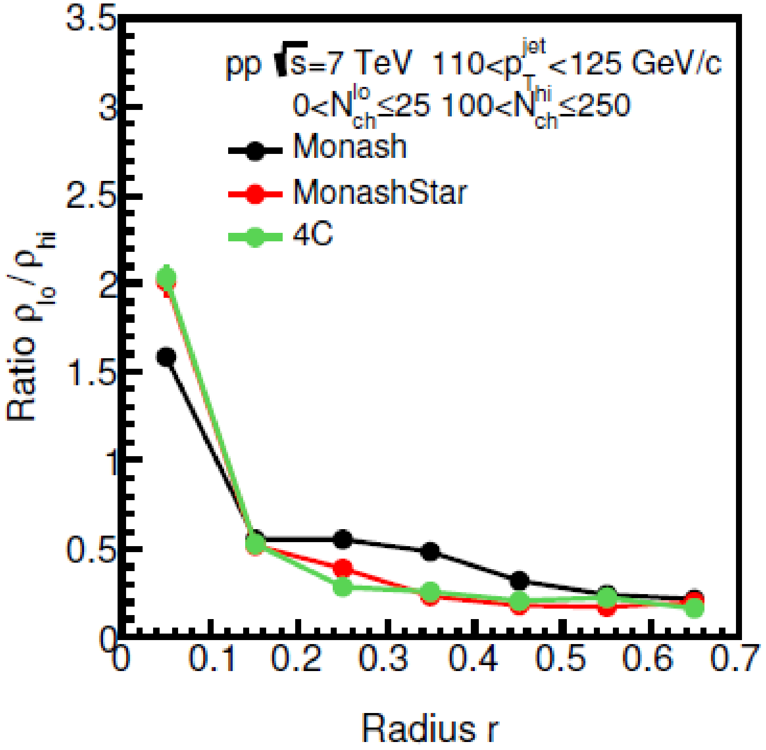


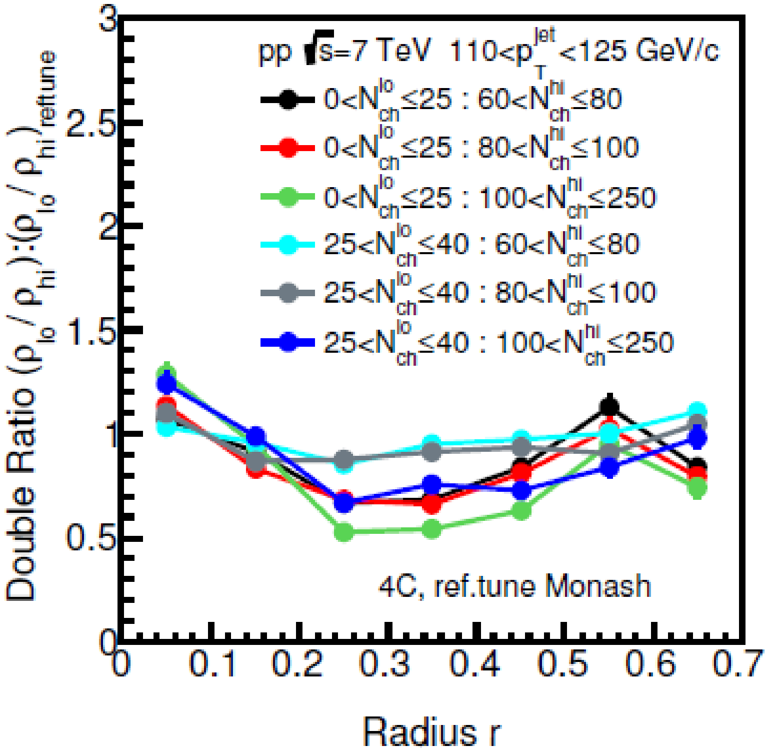


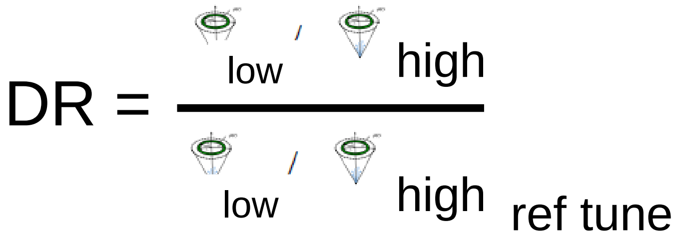


- Canceling out trivial multiplicity bias:
  - We find a significant effect at given double-ratio: $DR(r) = \frac{\rho_{low}/\rho_{high}}{(\rho_{low}/\rho_{high})_{ref.tune}}$
  - Non-trivial dependence on p_T^{jet},
    → the origin of the effect needs further investigation.

Double ratio for different multiplicity bins

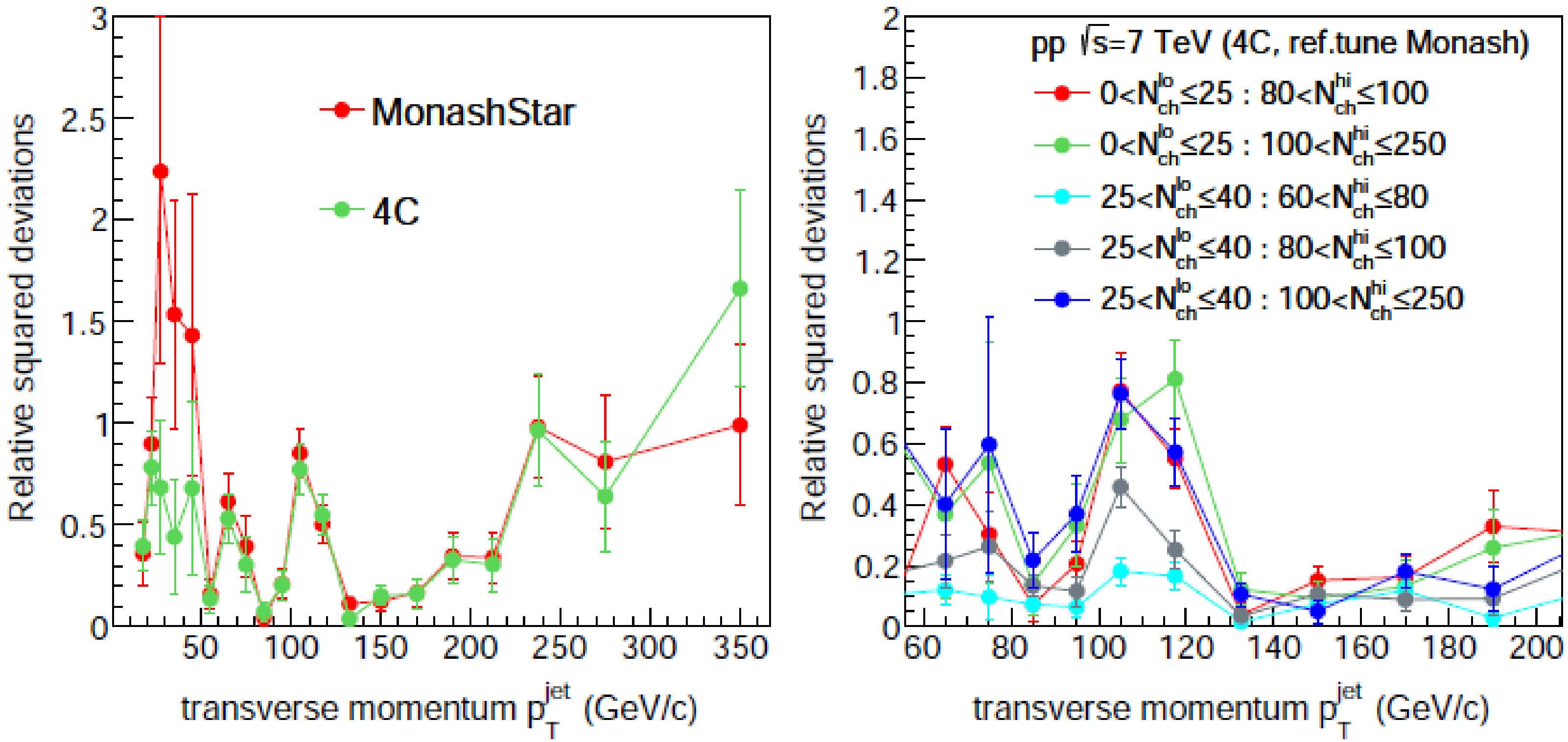






- Same calculations for several different multiplicity bins.
  - The effect is larger as the separation in multiplicity is larger → up to 50%.

Double ratio for different multiplicity bins, uncertainty

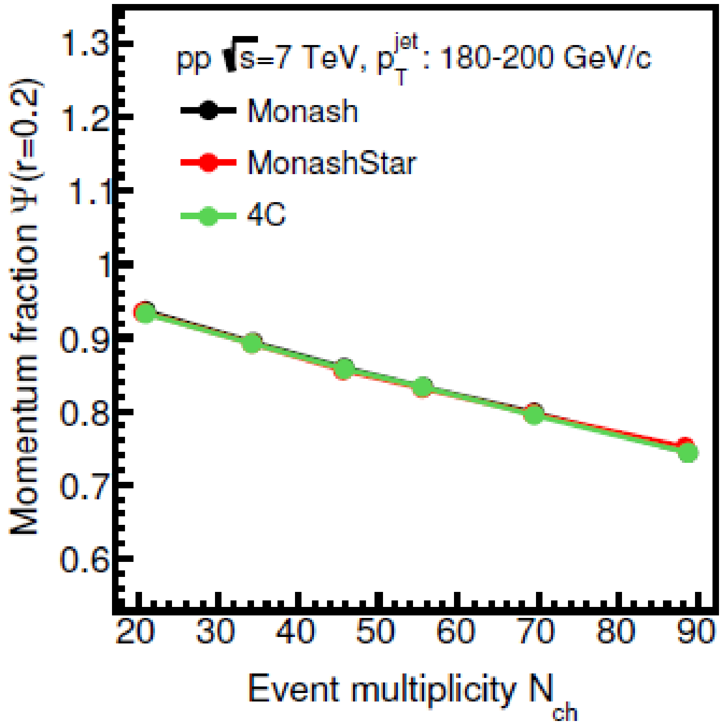


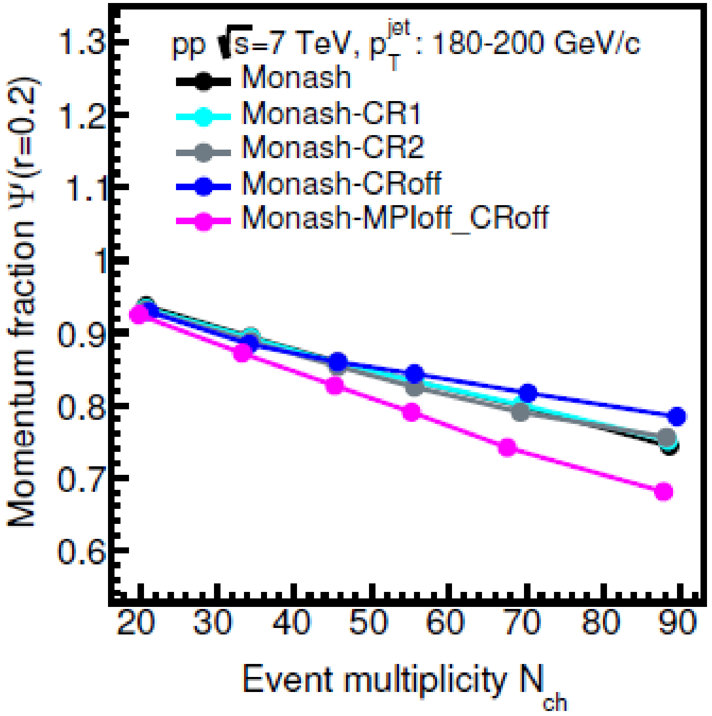
DR = (low / high) / (low / high)$_{\text{ref tune}}$

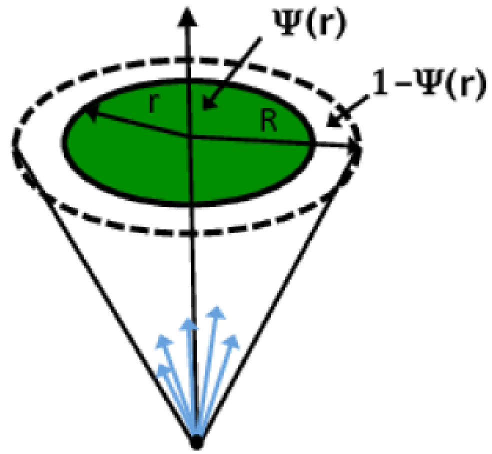
- Same calculations for several different multiplicity bins.
  - The effect is larger as the separation in multiplicity is larger → up to 50%.
  - Statistically independent samples → not fluctuations.

$$RSD = \sqrt{\sum_{0<r_i<R} (DR(r_i) - 1)^2}$$

Cross-check: *ψ(r = 0.2)* dependence on multiplicity







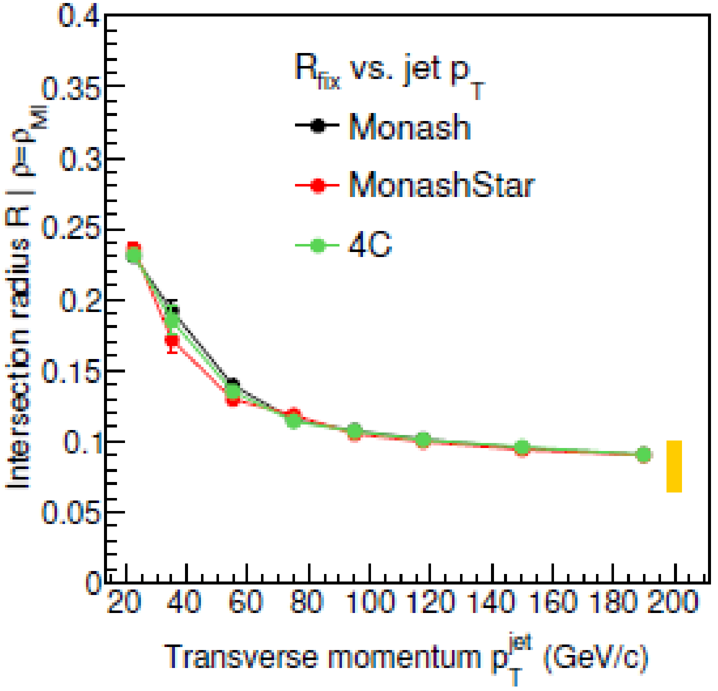
$$\psi(r) = \frac{\sum_{r_i<r} p_t^{(i)}}{p_t^{jet}}.$$

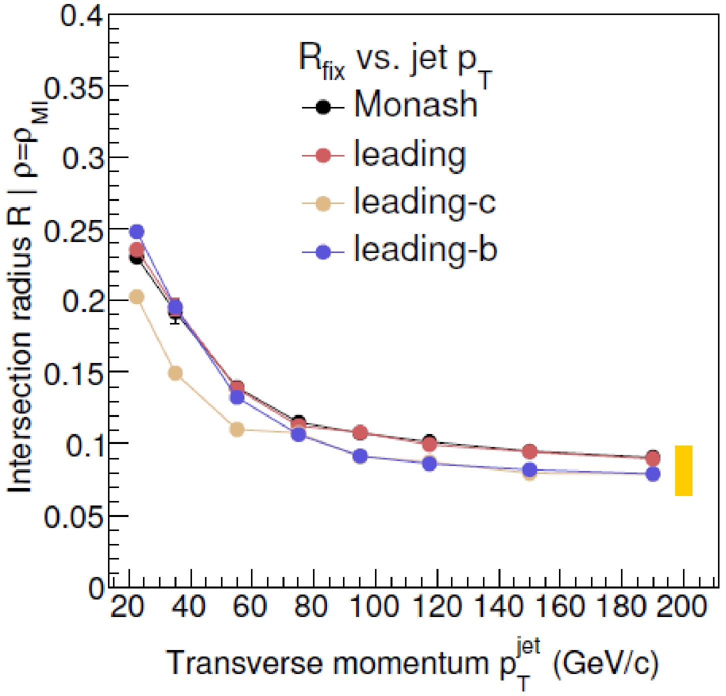
- No significant difference in integral jet structure between the three tunes and between different CR schemes.
- Turning off MPI causes significant differences for higher multiplicities, which can not be explained by bin effects.
→ Observation implies MPI influence on jet structure.

Further tests of the effect

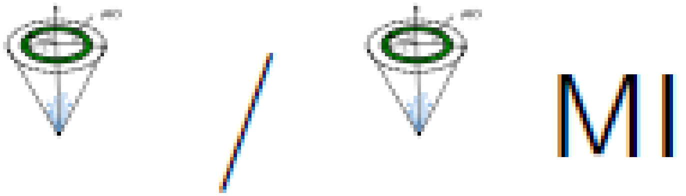
with heavy flavours, MC generator

Heavy quark jets: the p_T^{jet} dependence of R_{fix}

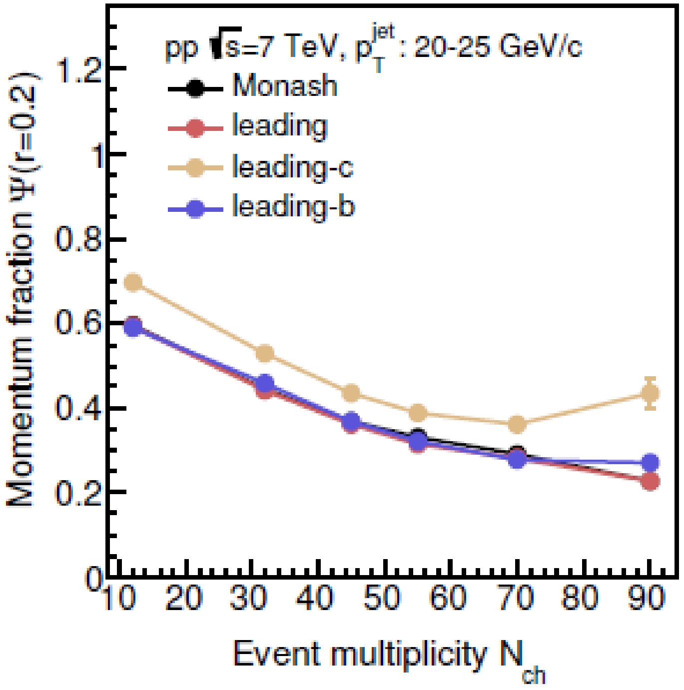


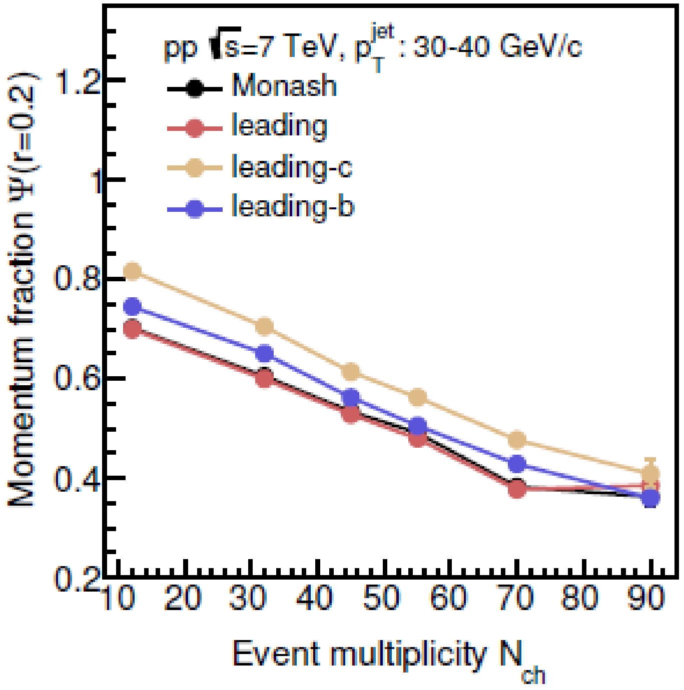


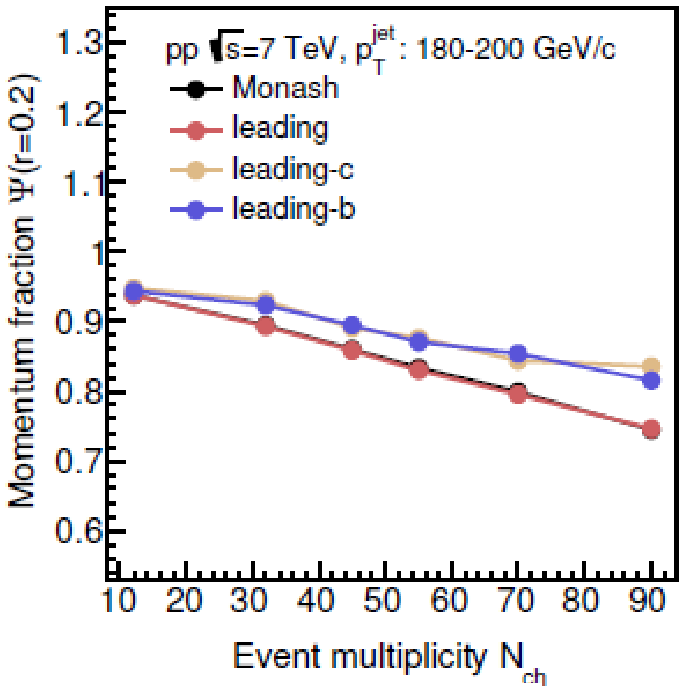
- Leading jet flavour does not make a difference on R_{fix} .
  - Low p_T^{jet} the charm leading jets appear narrower.
  - High p_T^{jet} both charm and bottom jets are narrower.



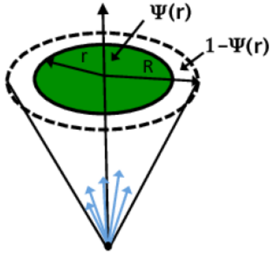
Heavy quark jets: integral jet shape, $\psi(r = 0.2)$







- Charm leading jets always differ (except for very low N_{ch}).
- Bottom leading jets differ for high N_{ch} at high enough p_T^{jet}.
- For certain p_T^{jet} (depends on r) all curves differ → HF fragmentation is different → model differentiation.

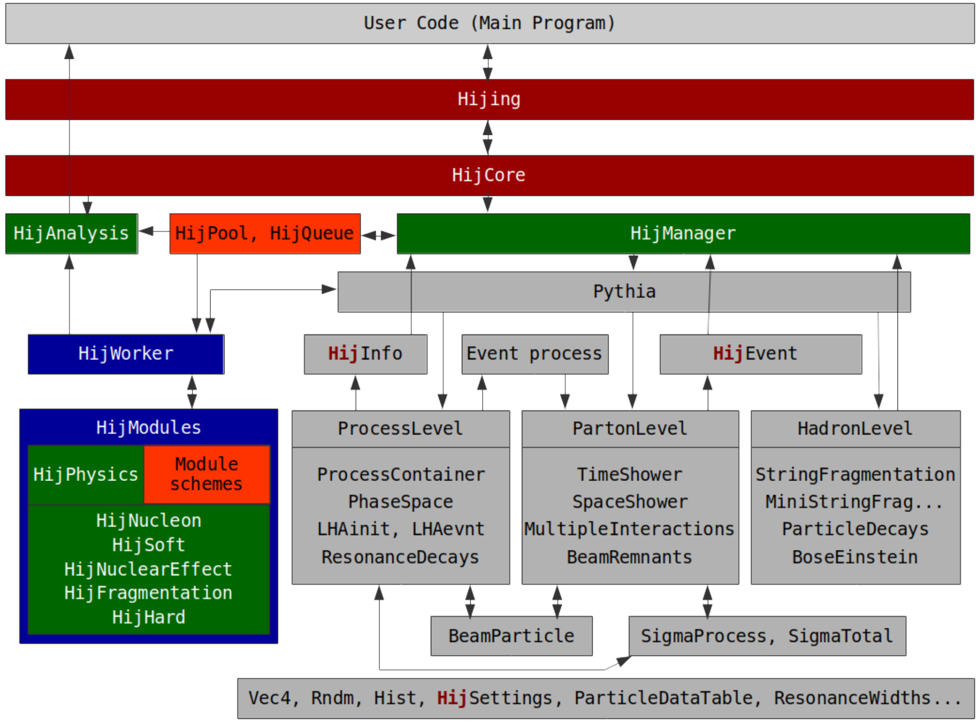


$$\psi(r) = \frac{\sum_{r_i<r} p_t^{(i)}}{p_t^{jet}}.$$

MC test: jet structure with the new Hijing++ code

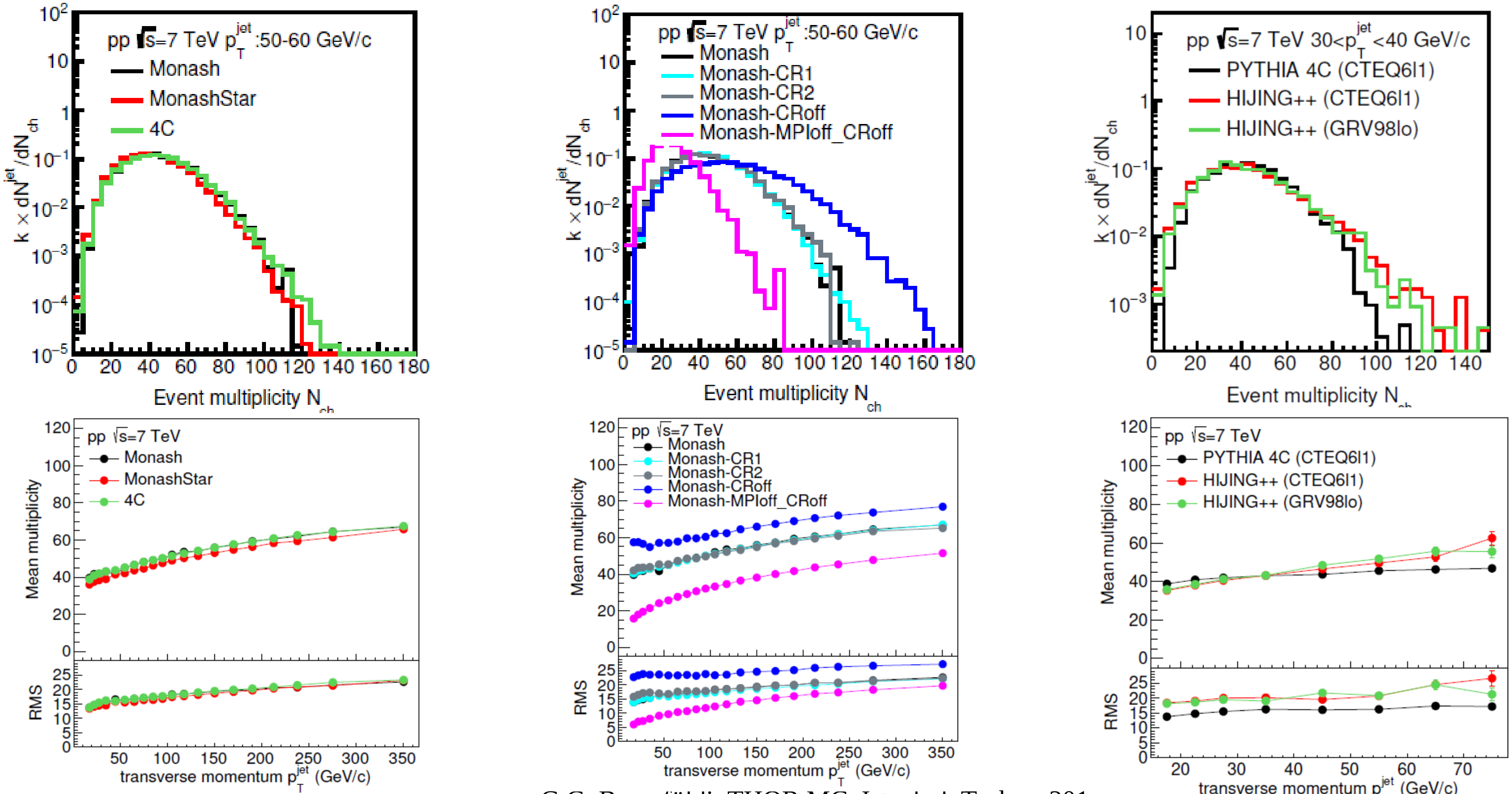
- HIJING++/HIJING/PYTHIA differences

	FORTRAN HIJING	HIJING++:
Precision	single	double
Pythia version	5.3*	8.2+**
PDF	GRV98lo	LHAPDF6.2+
Colour reconnection	✗	✓
Jet quenching	(✓)	(✓)
Multithreading	✗	✓
Analysis interface	✗	✓***
Module management****	✗	✓

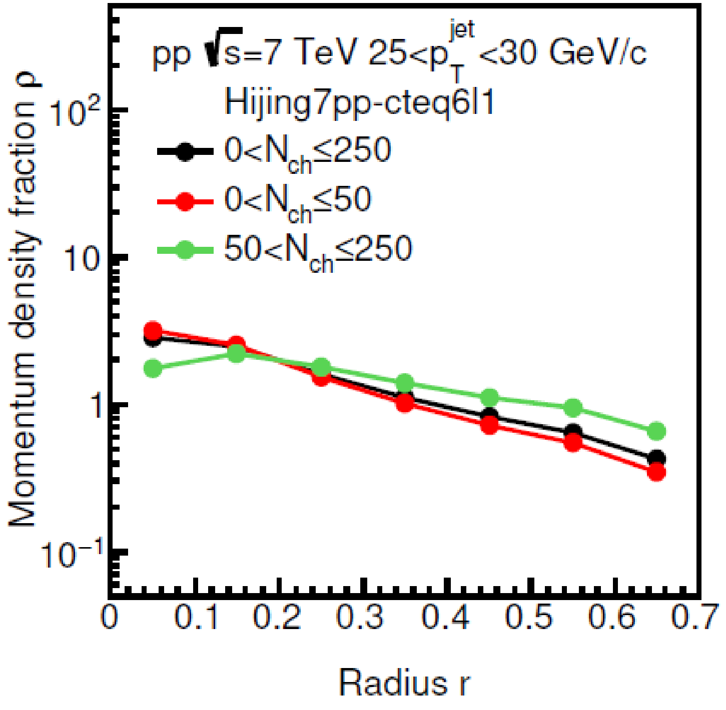


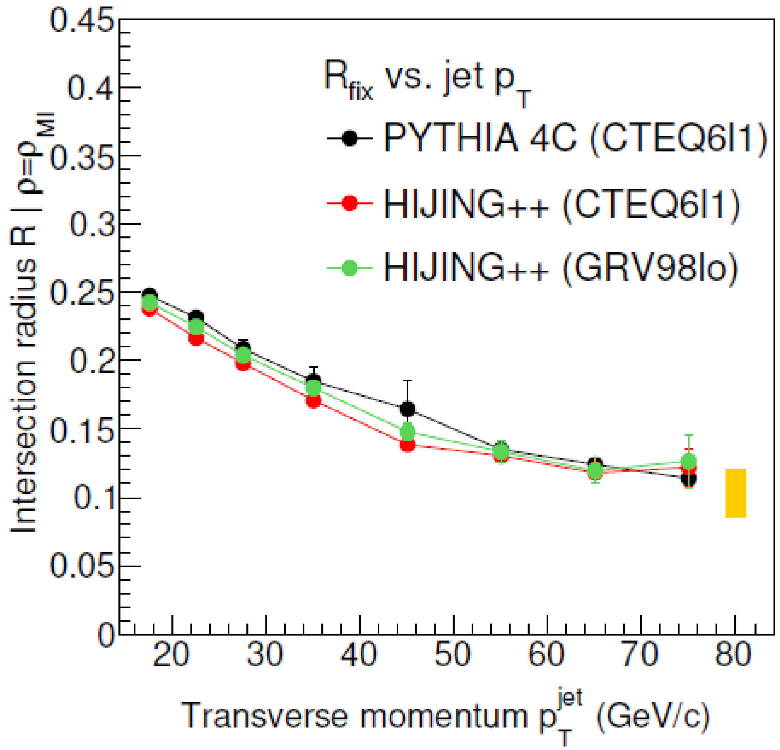
- Preliminary results: R. Vogt NPA 972 (2018) 18
- PHYSICS → Differences at low N_{ch} and low p_T^{jet}
- Small deviation → tuneable

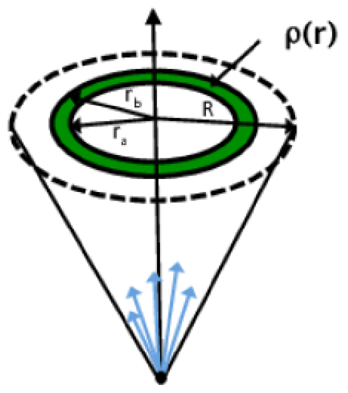
Multiplicity distribution for Pythia8 & Hijing++



Jet structure with Hijing++







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

- Comparison between Pytia8 and Hijing++ code
  - The R_{fix} phenomenon is visible.

Summary

- We gave predictions for several jet structure observables in $\sqrt{s}$ = 7 TeV p+p collisions using PYTHIA8.
- 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 structures of heavy flavor jets are sensitive probes of flavor-dependent fragmentation.

Summary

- We gave predictions for several jet structure observables in $\sqrt{s}$ = 7 TeV p+p collisions using PYTHIA8.
- 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 structures of heavy flavor jets are sensitive probes of flavor-dependent fragmentation.
- Further studies:
  - Check the validity with real data (ALICE)
  - Energy dependence
  - Similar study in heavy-ion collisions

Zimányi Winter School 2019

- 2-6 December 2019
- Wigner Research Centre for Physics, Budapest, Hungary.
- Free for PhD students
- Web: zimanyischool.kfki.hu

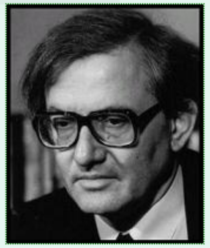
ZIMÁNYI SCHOOL'19

Janos Kass: Cantata Profana

19. ZIMÁNYI SCHOOL

WINTER WORKSHOP ON HEAVY ION PHYSICS

Dec. 2. - Dec. 6., Budapest, Hungary



József Zimányi (1931 - 2006)

Home

Invitation

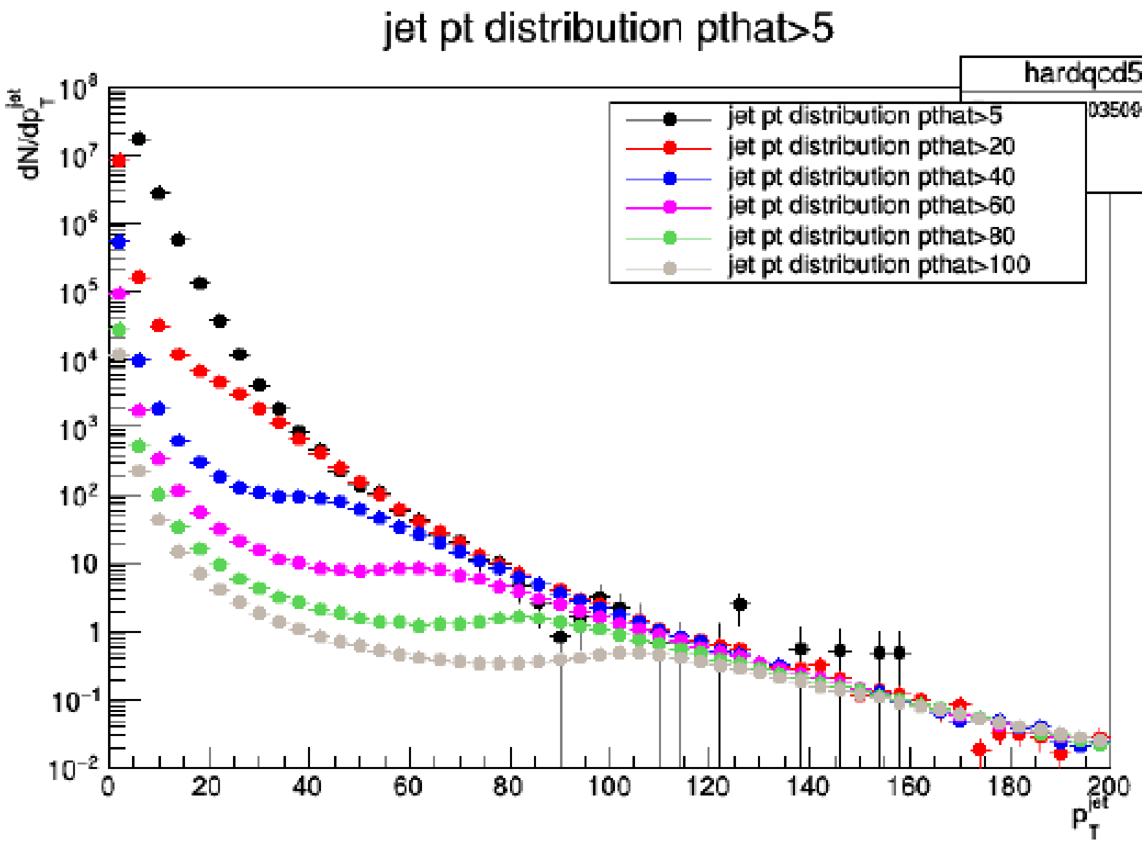
Dear Colleagues,

We would like to invite you to participate in this year's workshop that aims to summarize the developments of 2019 in high energy heavy ion physics, with particular attention to the new data emerging from the **Relativistic Heavy Ion Collider (RHIC)** and the **Large Hadron Collider (LHC)**, **SPS** and **J-PARC**. We will discuss results from other high energy nuclear and particle physics facilities of the world, most importantly lower energy colliders, exploring the nuclear phase diagram (with special attention to **FAIR** and **NICA**). Another important point of the School is to discuss important new results in hydrodynamics, flow and femtoscopy. One of the main aims of the School is to encourage interaction between the theoretical and experimental community. A slightly overlapping list of topics of the School includes (in alphabetical order):

- Effective QCD theory/model approaches
- Elastic scattering and diffraction (experiment+theory)
- Femtoscopy (experiment+theory)
- Flow and hydrodynamics (experiment+theory)
- Gluon saturation and electron-ion collider (experiment+theory)
- Heavy flavor and quarkonia (experiment+theory)
- Intermediate energies (FAIR, J-PARC, nuclear physics)
- Jets and high pT probes (experiment+theory)
- Magnetic field in heavy ion collisions (experiment+theory)
- Photons and dileptons (experiment+theory)
- QCD at non-zero temperature and density
- Search for the QCD critical point (experiment+theory)
- Strongly coupled gauge theories (beyond SM, AdS/CFT)
- Vorticity and polarization in heavy ion physics (experiment+theory)

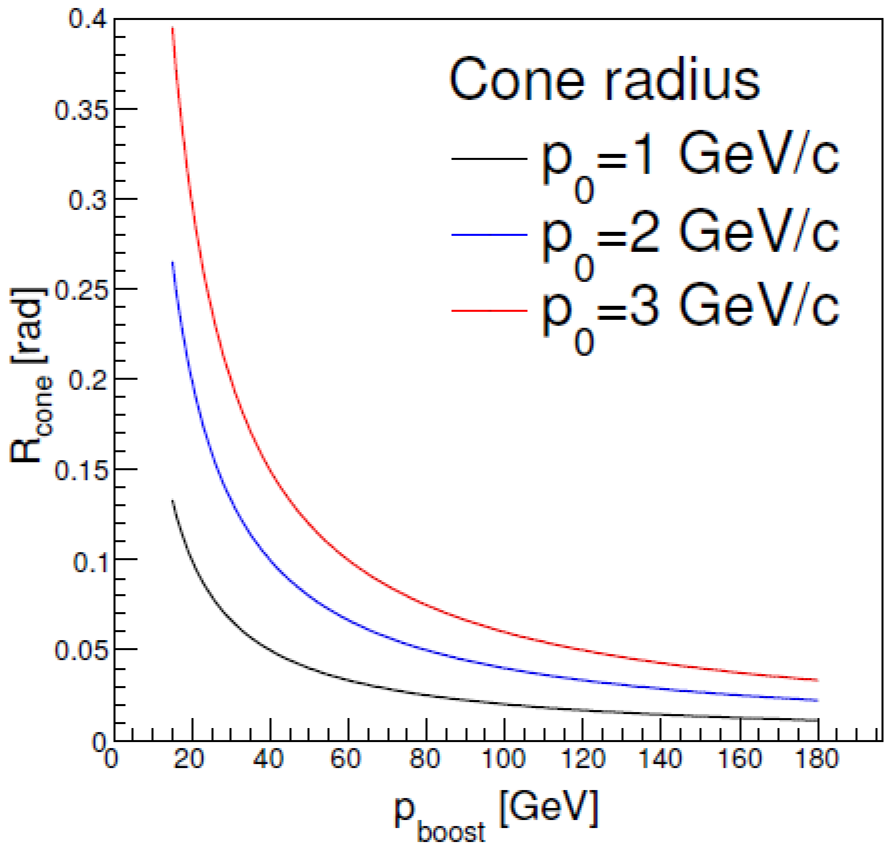
Backup

pT jet distributions for different pThat



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 $\leq$

The jet-shape ‘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.