Flavor-dependent fragmentation via jet structures and correlations in high-multiplicity pp collisions

arXiv:1805.03101, 1809.10102, 1904.06389

Róbert Vértesi
vertesi.robert@wigner.mta.hu
with
Zoltán Varga
Gergely G. Barnaföldi

Supported by: **NKFIH/OTKA** K 120660 grant; János **Bolyai scholarship** of the Hungarian Academy of Sciences; **MOST-MTA** Chinese-Hungarian Research Collaboration

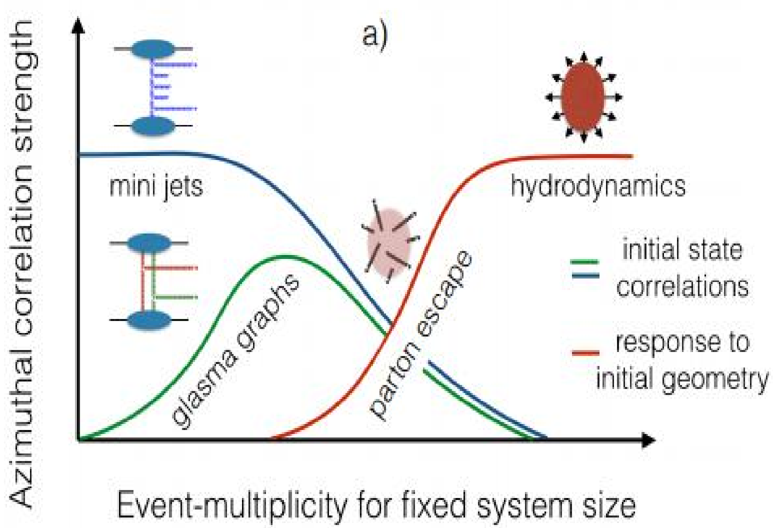
Motivation

- High-multiplicity p+p at LHC energies: **unexpected findings**
  - Long-range correlations
  - Substantial v_n in high-multiplicity pp events
    eg. **L. Yan, J. Y. Ollitrault, PRL 112, 082301 (2014).**
  - Stronger-than-linear dependence of HF production with event multiplicity
    ALICE Collaboration, JHEP 1608, 078 (2016).

Motivation

- High-multiplicity p+p at LHC energies: **unexpected findings**
  - Long-range correlations
  - Substantial v_n in high-multiplicity pp events
    eg. L. Yan, J. Y. Ollitrault, PRL 112, 082301 (2014).
  - Stronger-than-linear dependence of HF production with event multiplicity
    ALICE Collaboration, JHEP 1608, 078 (2016).

- Current understanding:
  - Collectivity can arise from features other than QGP
  - Pure QCD can generate it at the soft-hard boundary
  - Eg. Multiple Parton Interactions (qualitatively explain HF enhancement)



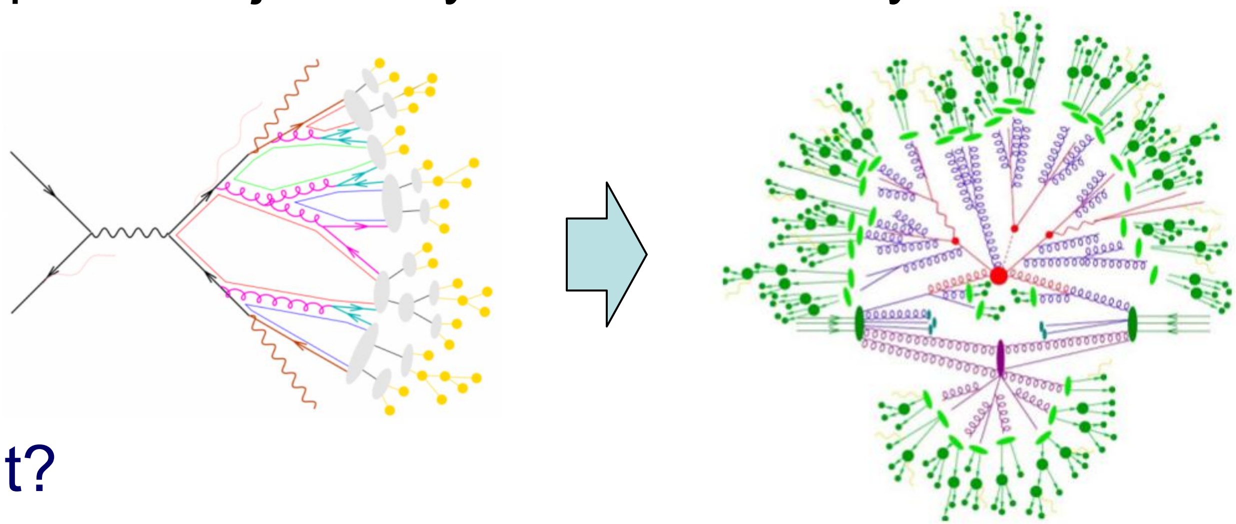
S. Schlichting, arXiv:1601.01177

Effect on jets

- Jet modification as a key QGP signature
  - Features in pp traditionally associated by QGP questions the role of pp as a reference
  - Jet quenching is not excepted without QGP in a larger volume

Effect on jets

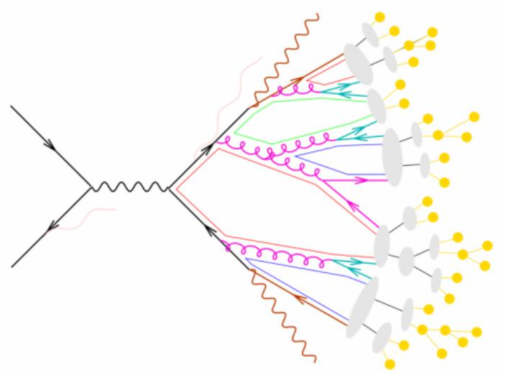
- Jet modification as a key QGP signature
  - Features in pp traditionally associated by QGP questions the role of pp as a reference
  - Jet quenching is not excepted without QGP in a larger volume, but...
  - The development of jets may be influenced by semi-hard processes

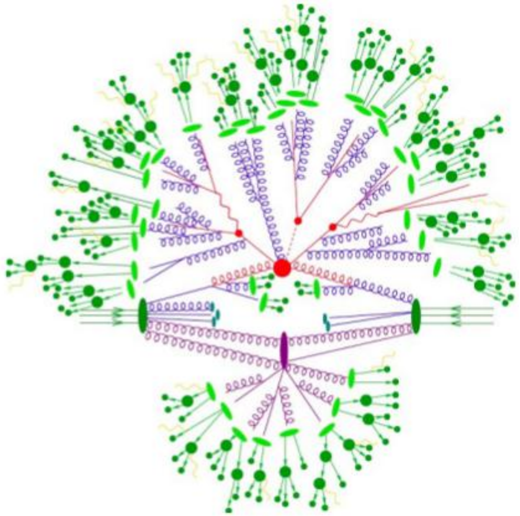


- Can we test it?

Effect on jets

- Jet modification as a key QGP signature
  - Features in pp traditionally associated by QGP questions the role of pp as a reference
  - Jet quenching is not excepted without QGP in a larger volume, but...
  - The development of jets may be influenced by semi-hard processes





- Can we test it?

Look for nontrivial modification of jet structures

Simulation and jet reconstruction

- pp collisions at $\sqrt{s}$ = 7 TeV
- Simulations with **PYTHIA 8.2**
  - **Tunes**: **-** Monash (with NNPDF2.3LO) - tuned for a large set of LHC data
    - Monash* (CUETP8M1-NNPDF2.3LO), based on underlying events)
    - 4C (with CTEQ6L1): based on key LHC observables and UE
  - **Multiple Parton Interactions**: *on* and *off*
  - **Color Reconnection schemes**: 0: MPI-based scheme (default in PYTHIA)
    1: QCD-based string length minimisation
    2: gluon-move scheme.
    off: we don't use it.
- Simulations with **HIJING++** (experimental):
  - **nPDF sets:** GRV98LO and CTEQ6L1
- Full jet reconstruction with R=0.7 (using standalone Fastjet)
  - **Algorithms:** - anti-kT (default)
    - Cambridge-Aachen
    - kT

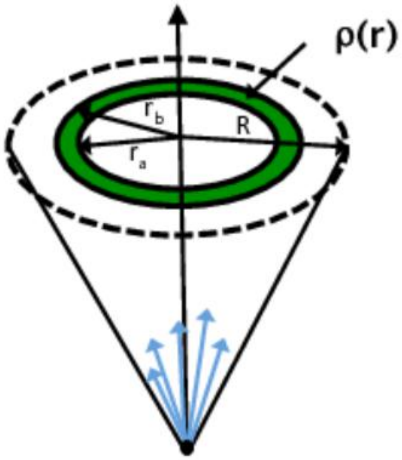
Jet shape measurables

CMS, JHEP 06, 160 (2012).

- Differential jet shape

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

$$r_i = \sqrt{(\phi_i - \phi_{\mathrm{jet}})^2 + (\eta_i - \eta_{\mathrm{jet}})^2}$$



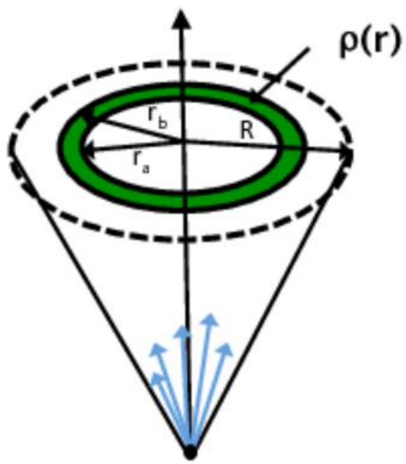
Jet shape measurables

CMS, JHEP 06, 160 (2012).

- Differential jet shape

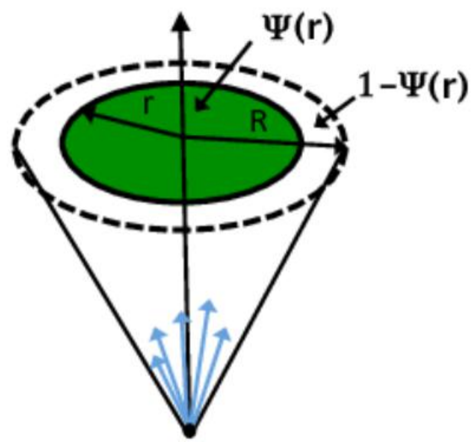
$$\rho(r) = \frac{1}{\delta r}\frac{1}{p_T^{\text{jet}}} \sum_{r_a<r_i<r_b} p_T^i$$

$$r_i = \sqrt{(\phi_i - \phi_{\text{jet}})^2 + (\eta_i - \eta_{\text{jet}})^2}$$



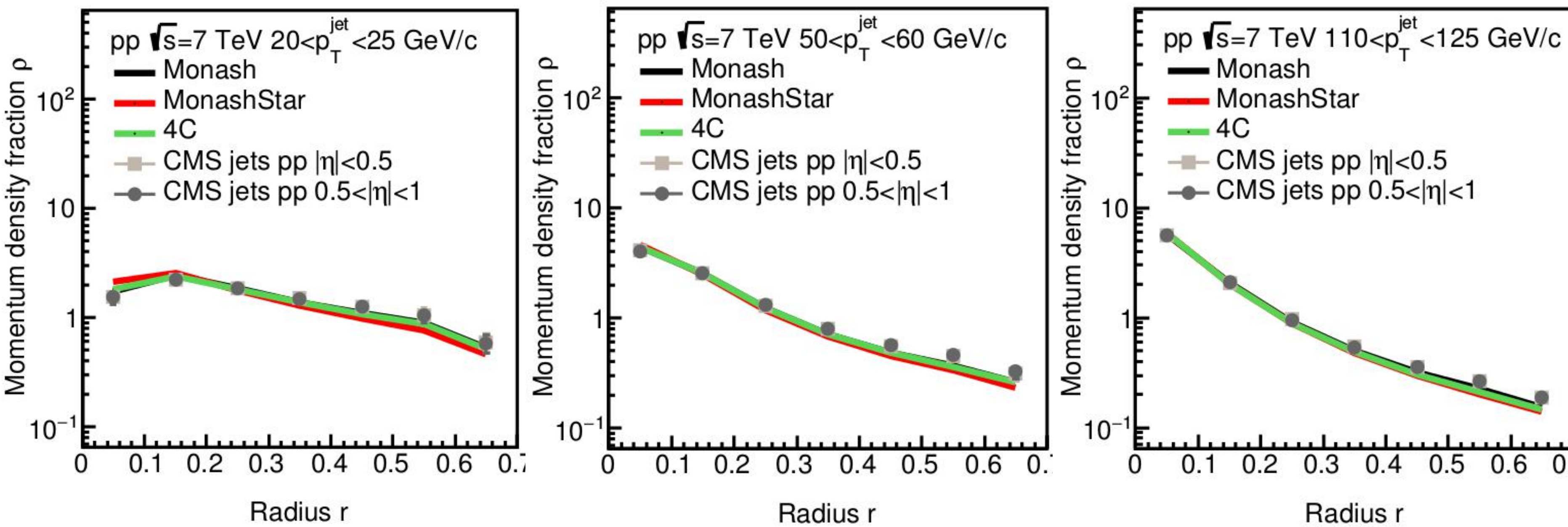
- Integral jet shape

$$\psi(r) = \frac{1}{p_T^{\text{jet}}} \sum_{r_i<r} p_T^i$$



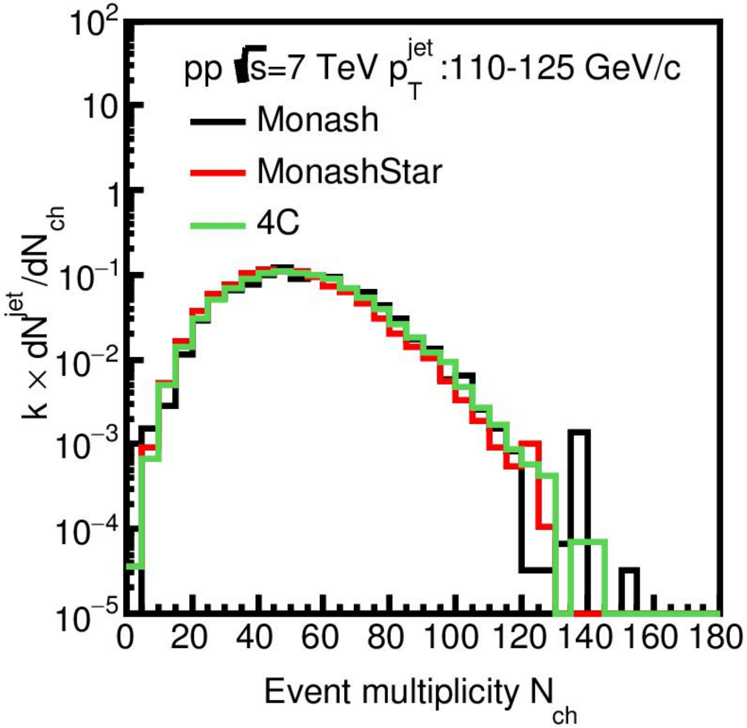
$$\psi(R) = \int_0^R \rho(r')dr' = 1$$

Validation: compare to CMS data



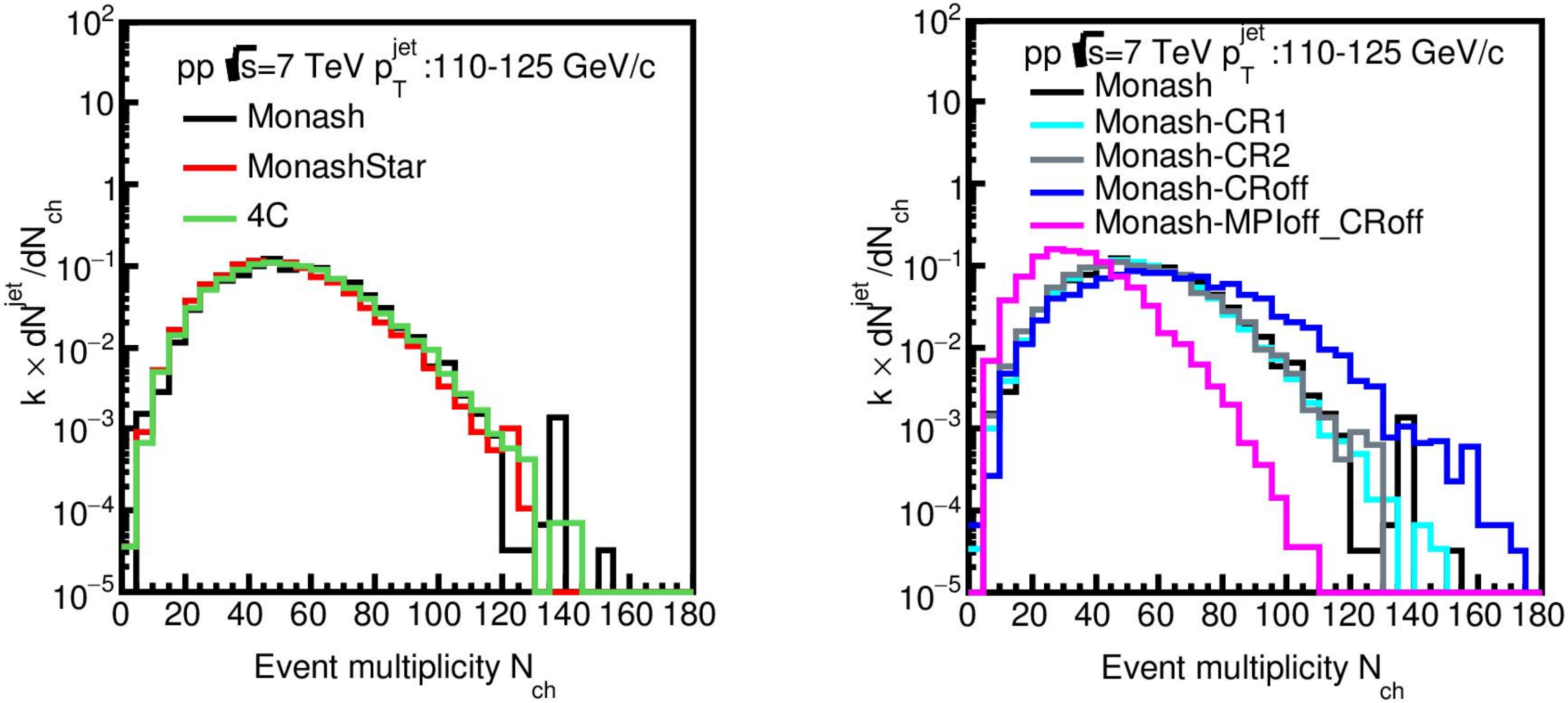
- The three different "stock" tunes reproduce CMS $|y|<1$ pp data at 7 TeV within uncertainty
- Between $15 < p_T < 400$ GeV/c (3 examples shown)

Event charged multiplicity (at mid-η)



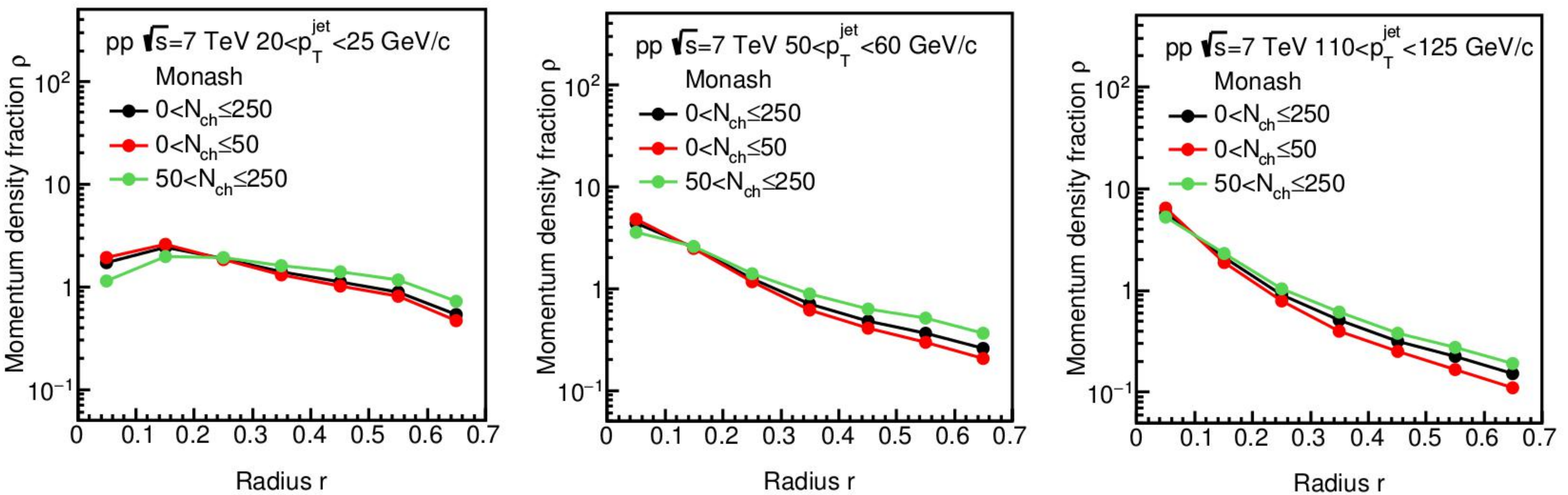
- The three different "stock" tunes show similar multiplicity dependences (all tuned to describe data)

Event charged multiplicity (at mid-η)



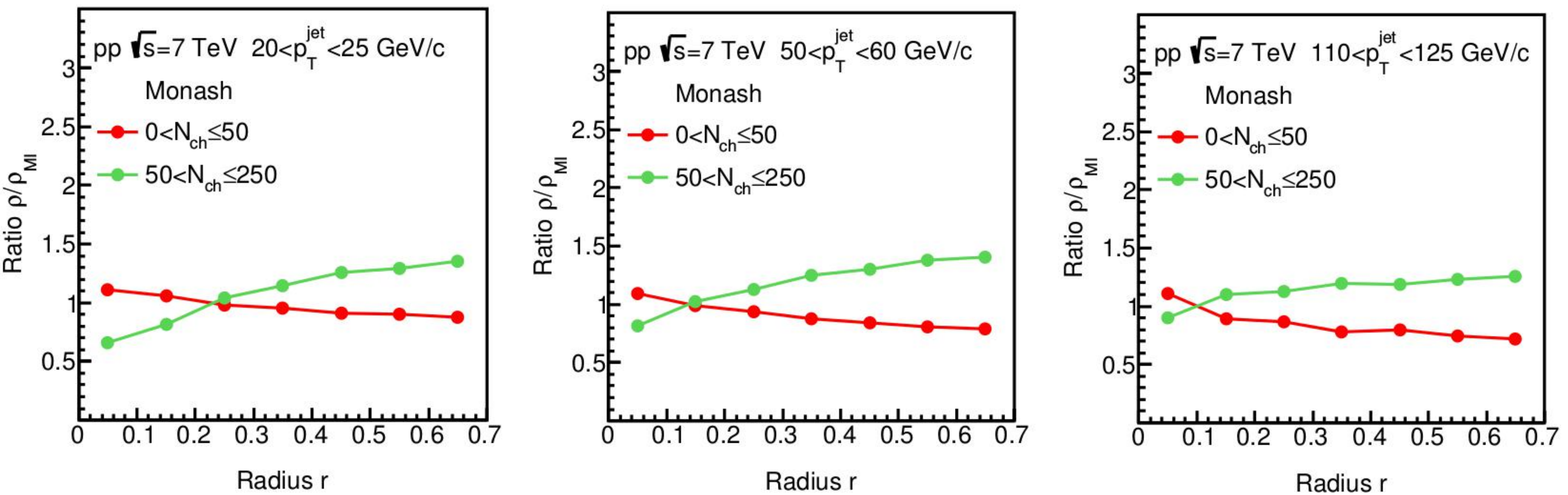
- The three different "stock" tunes show similar multiplicity dependences (all tuned to describe data)
- Different CR-schemes also yield similar N_{ch} distributions
- MPI:off - yields less multiplicity on the average
- MPI:on, CR:off - more multiplicity on the average

Jet structure for different multiplicities



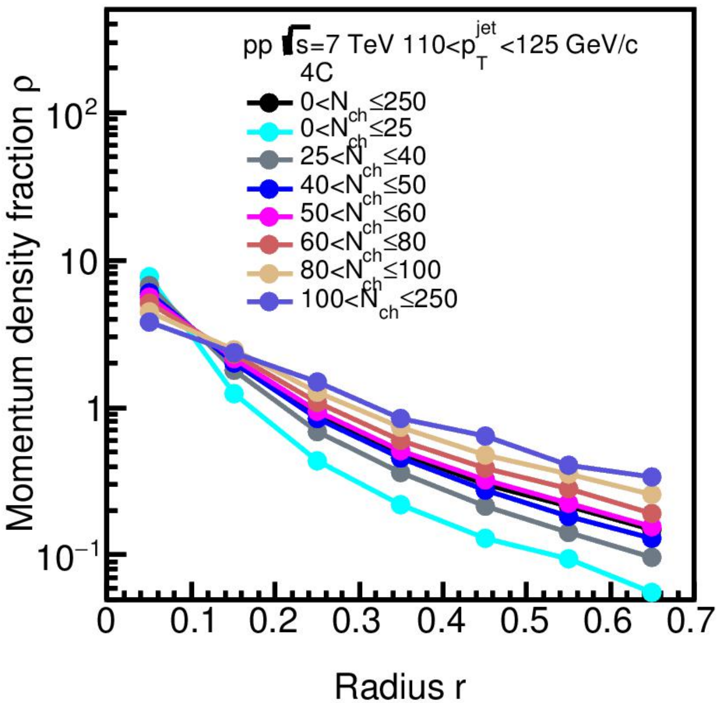
- Multiplicity dependence of differential jet shape ρ(r)
  - **$\rho_{\text{any-Nch}} \equiv \rho_{\text{MI}}$; $\rho_{\text{low-Nch}}$; $\rho_{\text{high-Nch}}$**
    Note: "multiplicity-integrated" (MI) just means no selection on multiplicity; contains certain biases introduced by the p_T selection,
- This is the expected, trivial behavior:
  - Event N_{ch} correlates with jet multiplicity, that correlates with ρ(r)
  - Lower-multiplicity jets are more concentrated than higher-mult jets

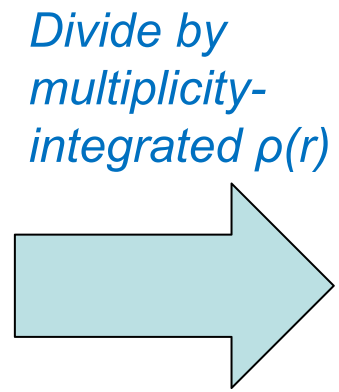
Evolution of structure: ratio to MB

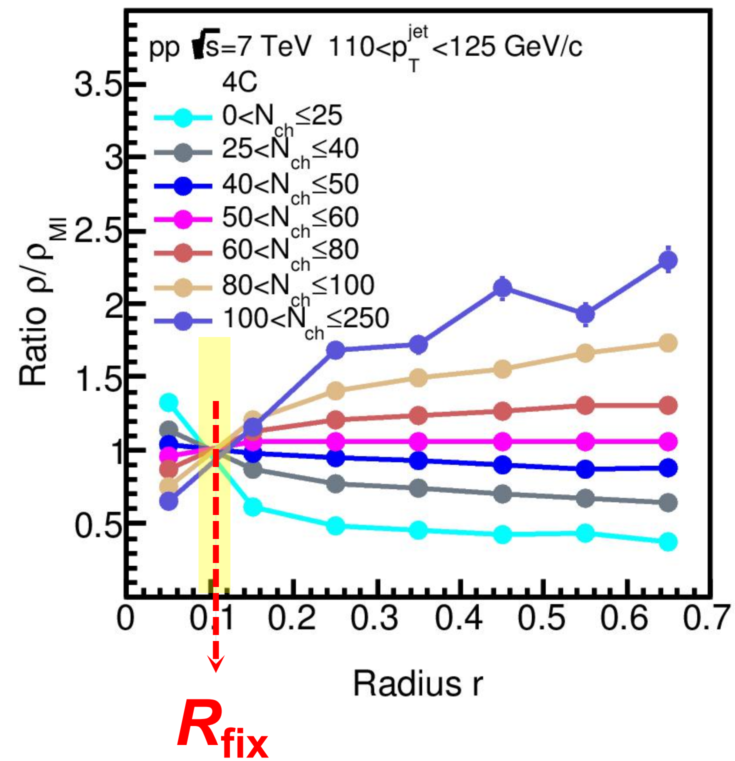


- Multiplicity dependence of jet shape ratios to MB:
  - Curves are $\rho_{low\text{-}Nch}/\rho_{MB}$; $\rho_{high\text{-}Nch}/\rho_{MB}$
- Intersection of the two curves at unity (trivial for two curves)
- Evolution with p_T: higher-momentum jets are narrower

More multiplicity classes



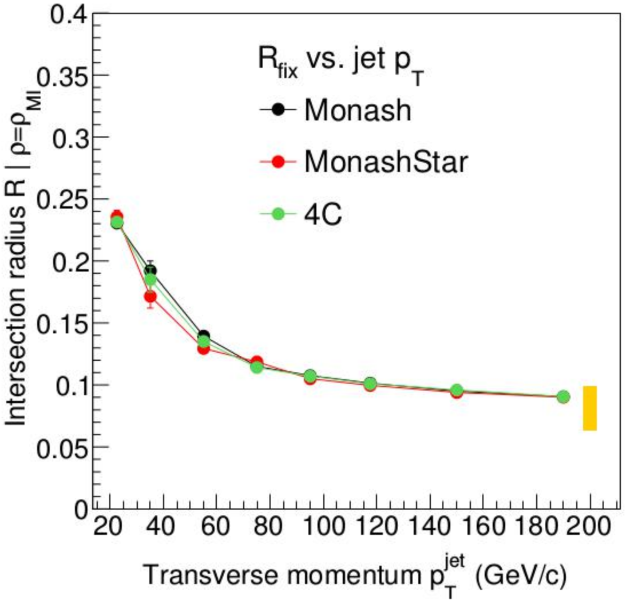


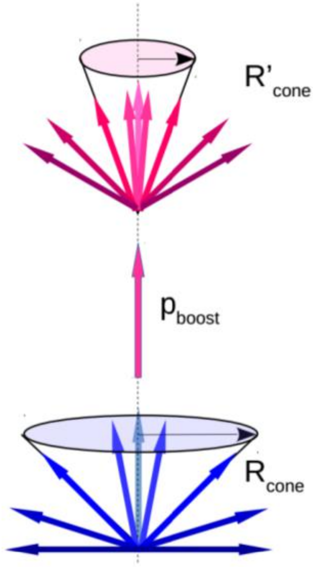


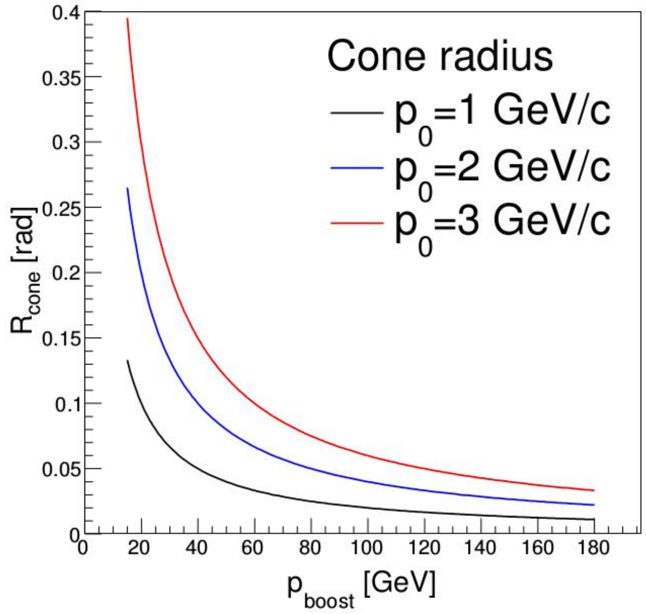
- All curves intersect at a given point
- This is non-trivial -> a given ratio R_{fix}

- Evolution with p_T?
- How strongly does it depend on simulation settings?

R_{fix} versus jet momentum

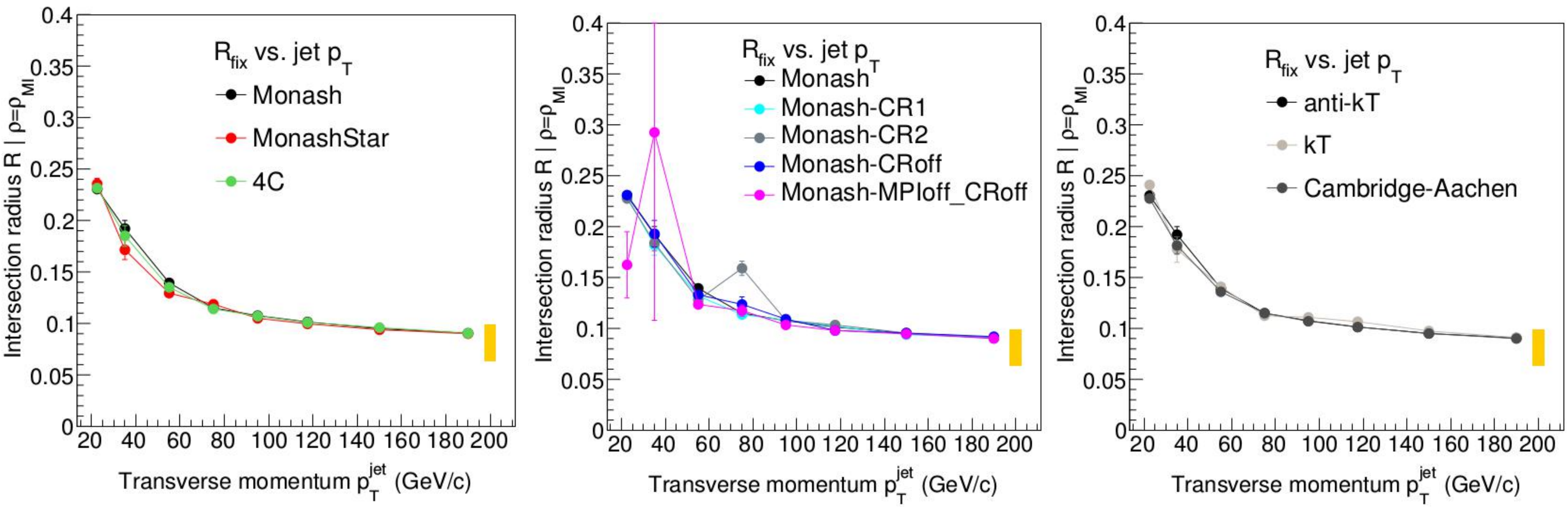






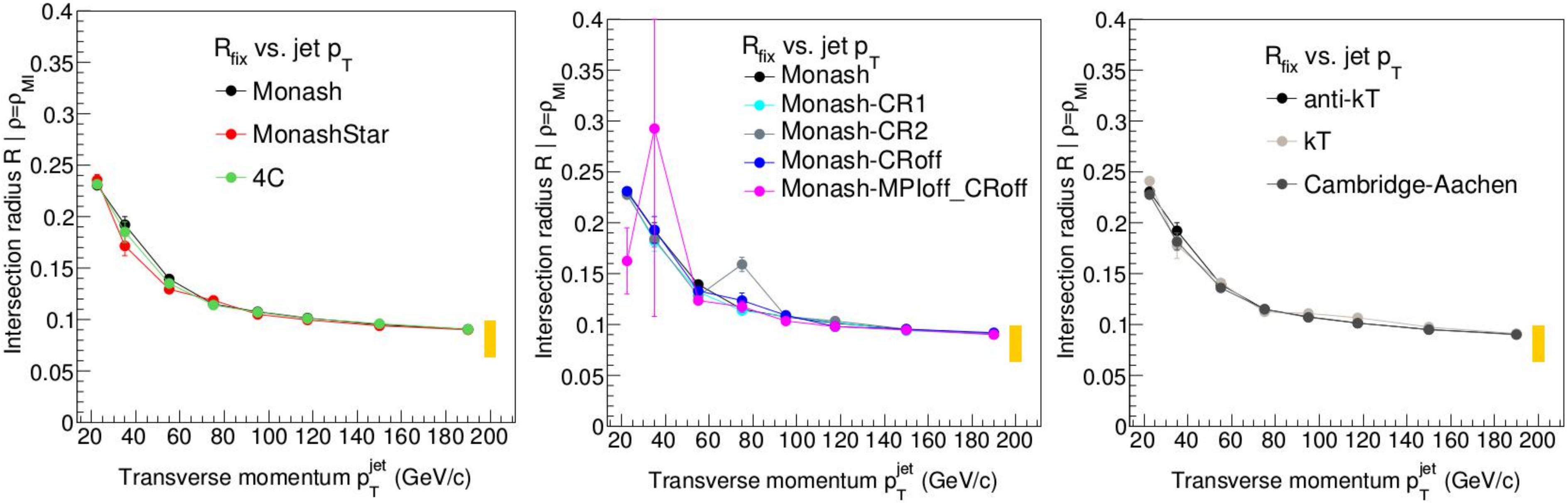
- Toy model to understand $R_{fix}(p_T)$ evolution
  - Jet consisting of particles with equal momenta p_0,
  - Boosted toward the jet axis with p_{boost}
- High-p_T : qualitatively similar behaviour to the MC
- Low-p_T : blow-up - not expected in data because jet reconstruction is limited by R and also angular cut-off in splitting

R_{fix} - is it universal?



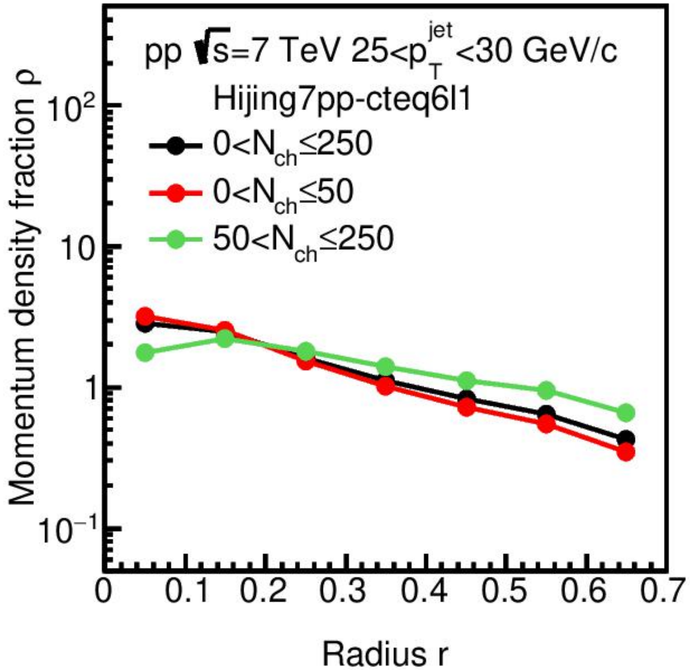
- *R_{fix}* does not depend on... (within uncertainties)
  - The choice of PYTHIA tune (Monash, Monash*, 4C)
  - CR schemes or even whether CR or MPI are on/off.
    Note: MPI:off is very different physics, different UE
  - Clustering algorithm (k_T, anti-k_T, Cambridge-Aachen)
    These algorithms create very different jets

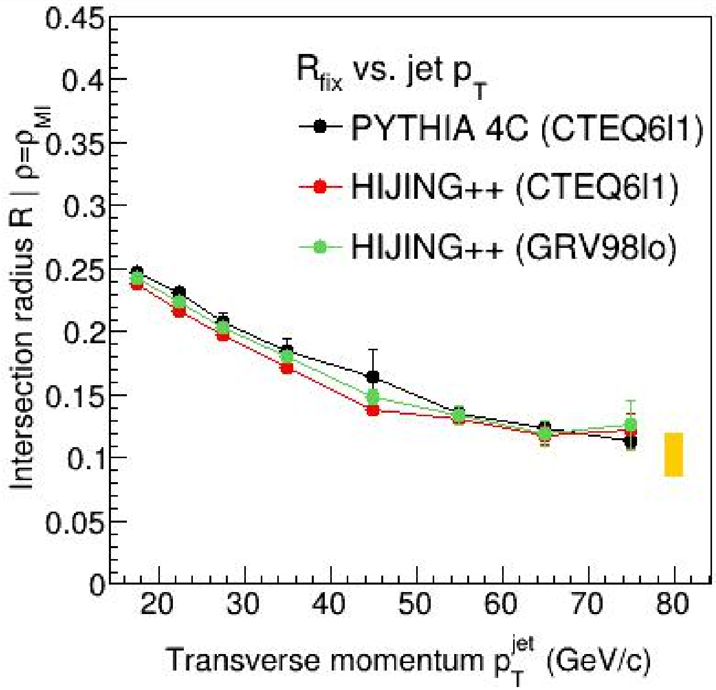
R_{fix} - is it universal?



- *R_{fix}* does not depend on... (within uncertainties)
  - The choice of PYTHIA tune (Monash, Monash*, 4C)
  - CR schemes or even whether CR or MPI are on/off.
    Note: MPI:off is very different physics, different UE
  - Clustering algorithm (k_T, anti-k_T, Cambridge-Aachen)
    These algorithms create very different jets
  - Is it only a PYTHIA 8 feature?

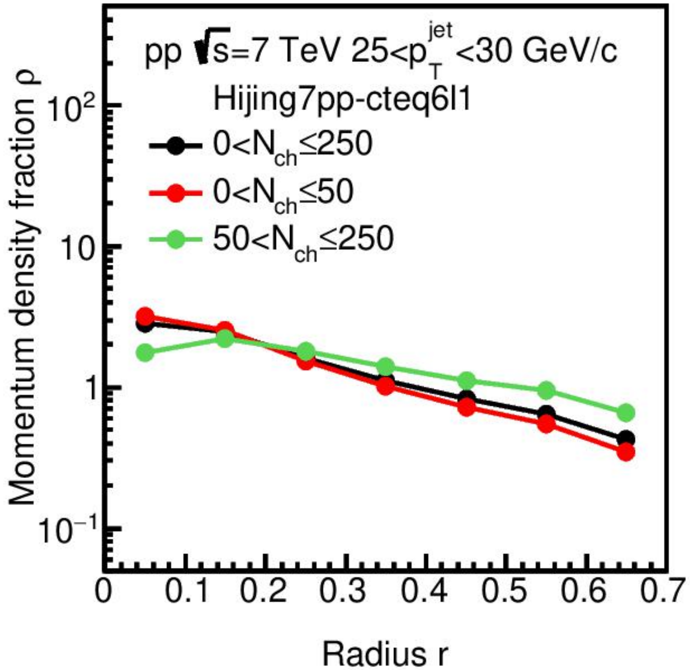
Cross-check with HIJING++

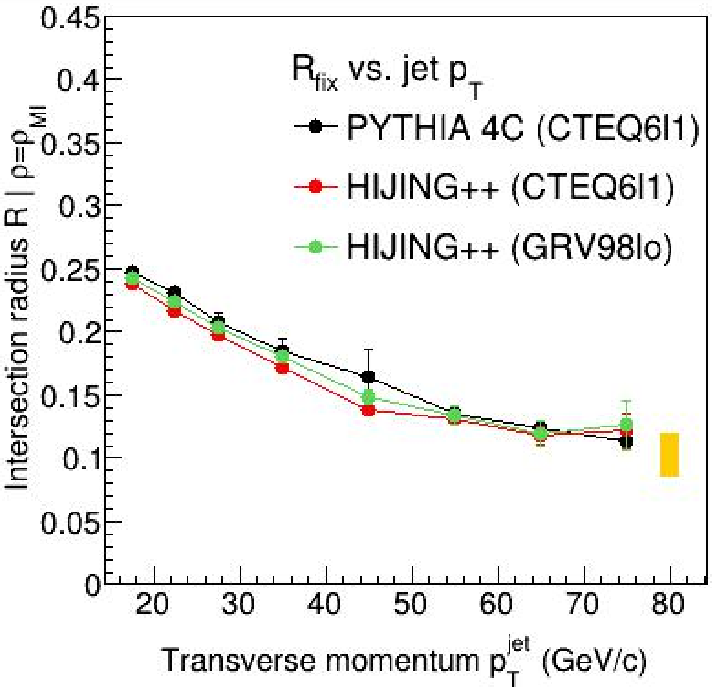




- HIJING++ : Soft-hard interactions, minijets
  - No PYTHIA8 MPI, but CR is applied

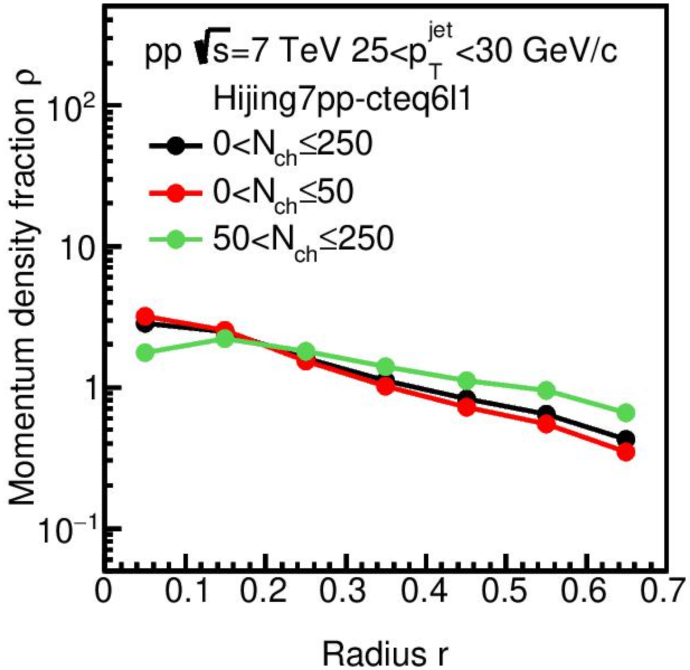
Cross-check with HIJING++

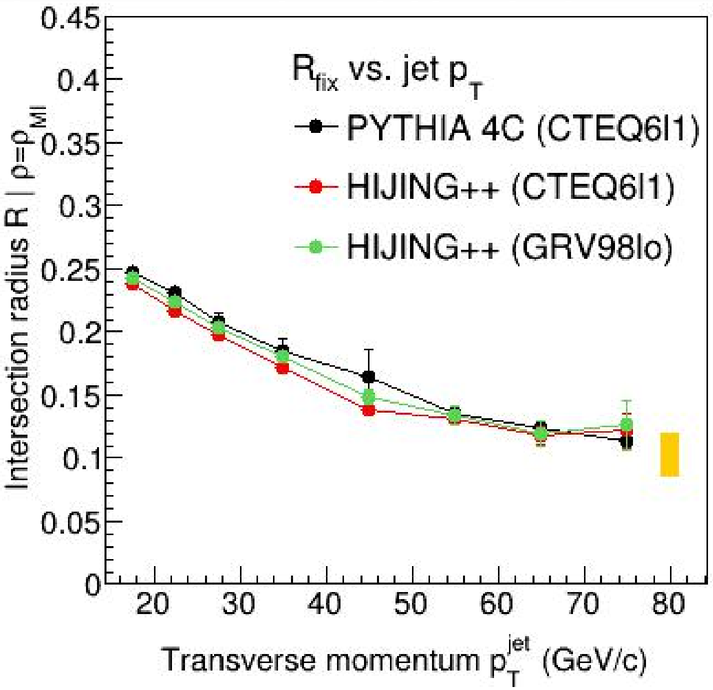




- HIJING++ : Soft-hard interactions, minijets
  - No PYTHIA8 MPI, but CR is applied
  - Still, R_{fix} phenomenon is present and consistent to PYTHIA
  - Very different nPDF sets - no change

Cross-check with HIJING++

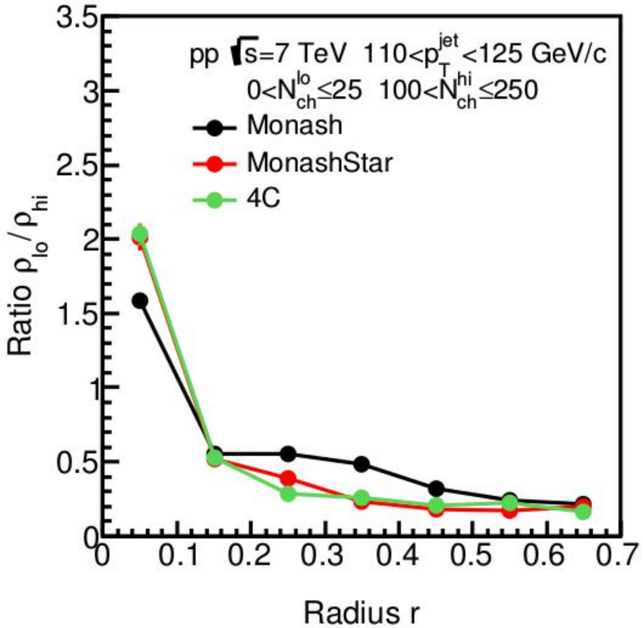




- HIJING++ : Soft-hard interactions, minijets
  - No PYTHIA8 MPI, but CR is applied
  - Still, R_{fix} phenomenon is present and consistent to PYTHIA
  - Very different nPDF sets - no change

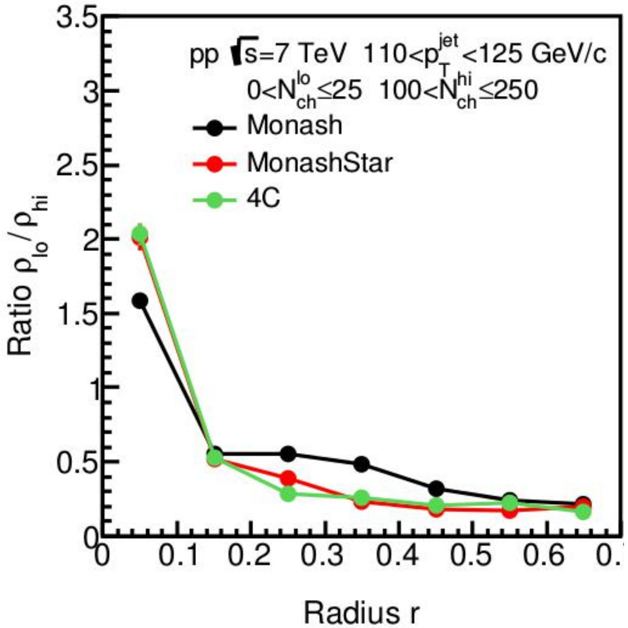
R_{fix} - A jet size measure? Is it sensitive to something?

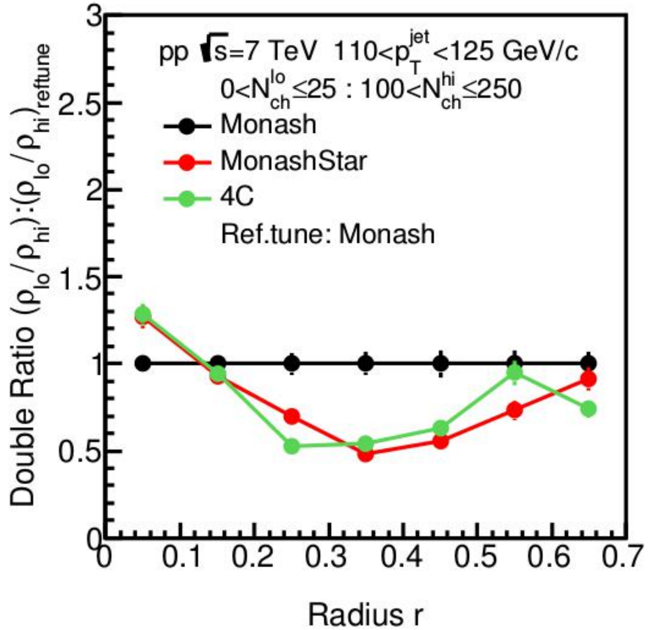
Tune comparison: low and high N_{ch}



- Comparing $\boldsymbol{\rho}_{\textbf{low-Nch}}/\boldsymbol{\rho}_{\textbf{high-Nch}}$ ratios for different tunes

Tune comparison: the double ratio

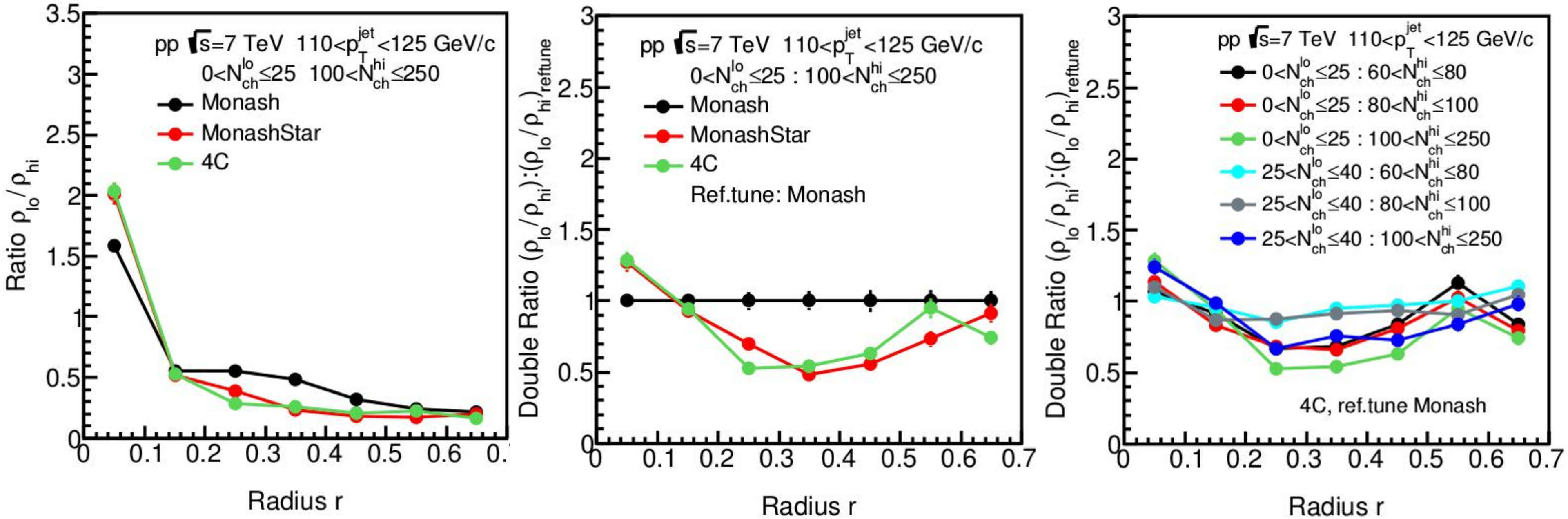




- Comparing $\boldsymbol{\rho_{\text{low-Nch}}/\rho_{\text{high-Nch}}}$ ratios for different tunes
- **Double ratio** (given p_T) - cancels trivial multiplicity bias
  - Significant effect (can be factor **x2**)

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

Tune comparison: the double ratio

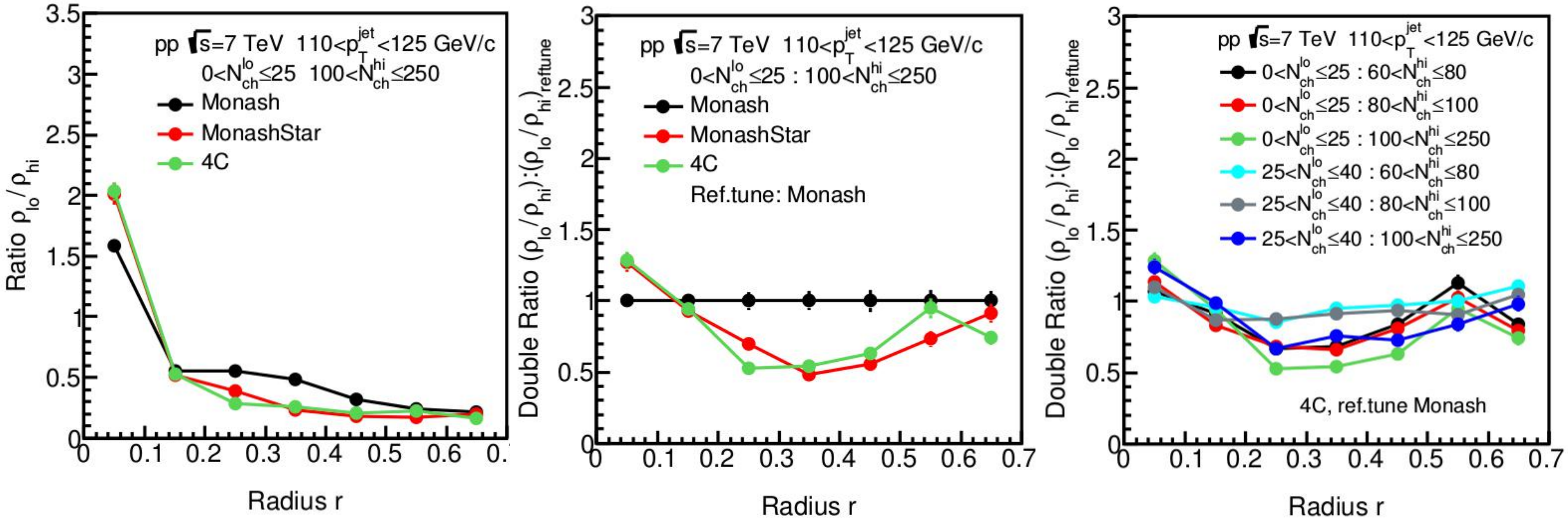


- Comparing $\boldsymbol{\rho_{\text{low-Nch}}/\rho_{\text{high-Nch}}}$ ratios for different tunes
- **Double ratio** (given p_T) - cancels trivial multiplicity bias
  - Significant effect (can be factor **x2**)

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

- Larger effect for more distant $\{N_{ch}^{low}, N_{ch}^{high}\}$ pairs
  - Statistically independent samples --> not fluctuations

Tune comparison: the double ratio



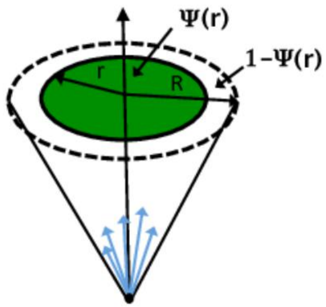
- Comparing $\boldsymbol{\rho}_{\textbf{low-Nch}}/\boldsymbol{\rho}_{\textbf{high-Nch}}$ ratios for different tunes
- **Double ratio** (given p_T) - cancels trivial multiplicity bias
  - Significant effect (can be factor **x2**)

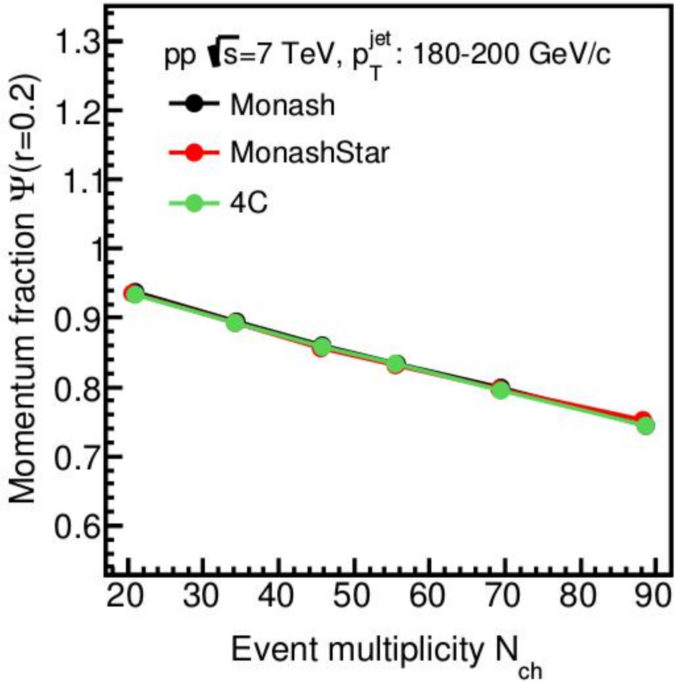
$$DR(r) = \frac{(\rho_{low}/\rho_{high})}{(\rho_{low}/\rho_{high})_{ref.tune}}$$

- Larger effect for more distant $\{N_{ch}^{low}, N_{ch}^{high}\}$ pairs
  - Statistically independent samples --> not fluctuations

Predictions can serve as sensitive model tests

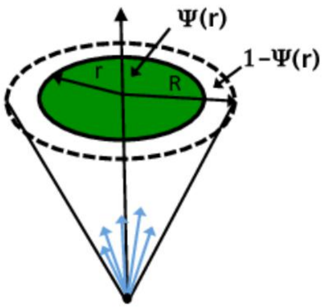
Integrated jet shapes vs. N_{ch} (r=0.2)

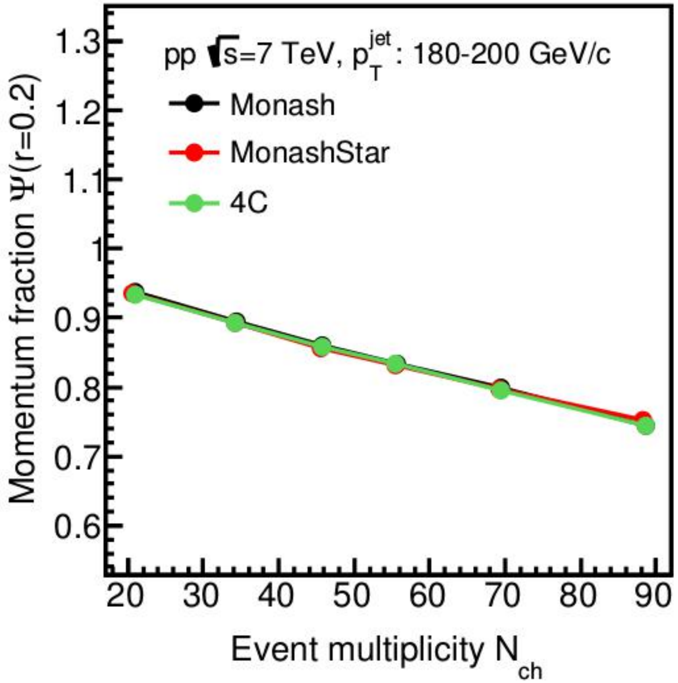


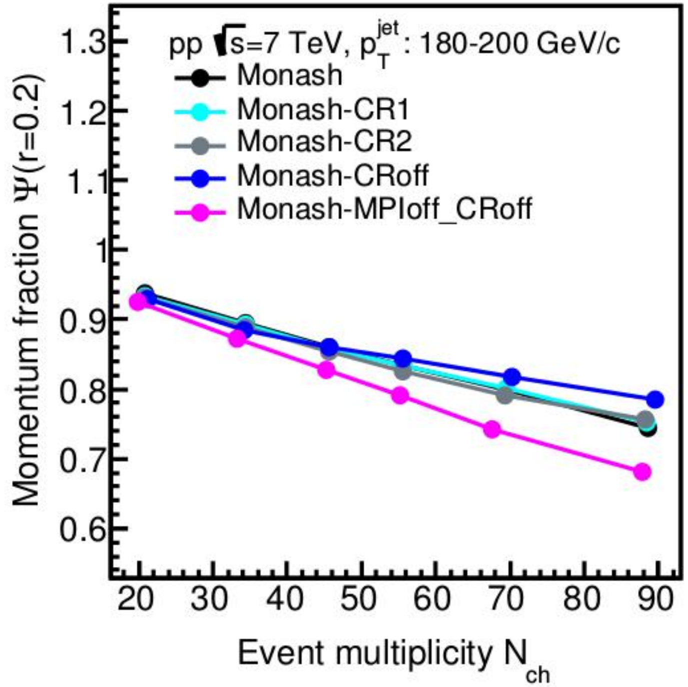


- No significant difference for 3 "stock" tunes or CR schemes

Integrated jet shapes vs. N_{ch} (r=0.2)

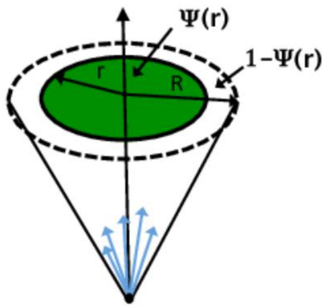


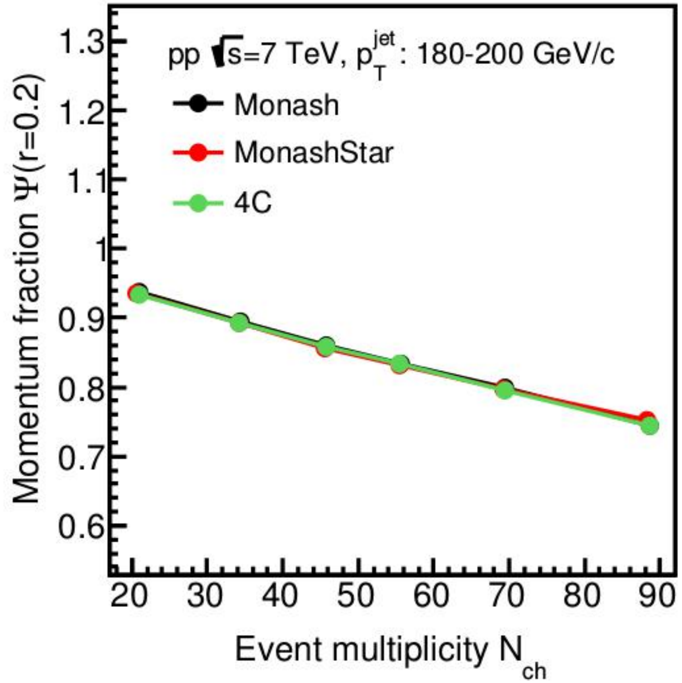


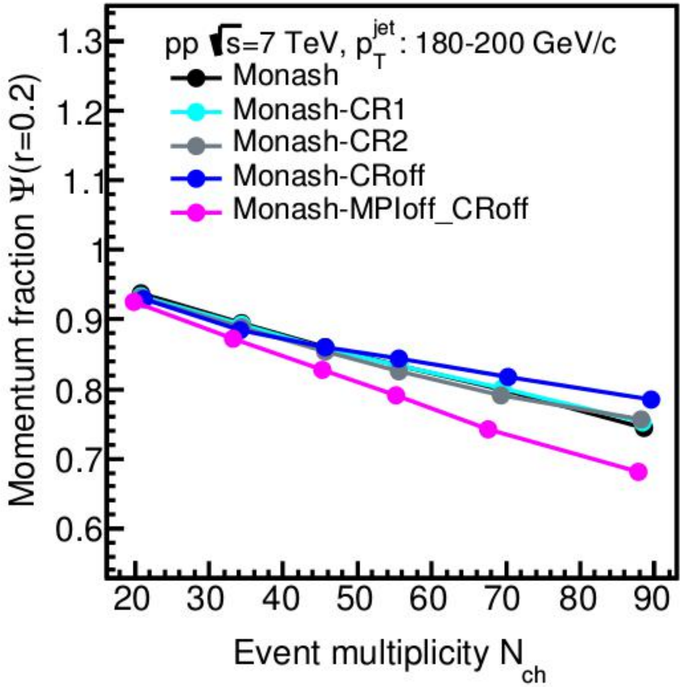


- No significant difference for 3 "stock" tunes or CR schemes
- **MPI:off case is significantly different at high N_{ch}**
  - not explained by the sizeable bin shift effect

Integrated jet shapes vs. N_{ch} (r=0.2)







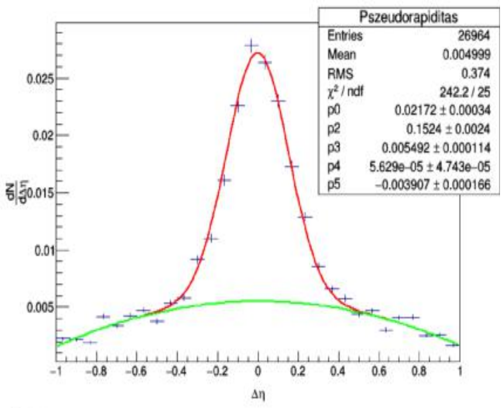
- No significant difference for 3 "stock" tunes or CR schemes
- **MPI:off case is significantly different at high N_{ch}**
  - not explained by the sizeable bin shift effect

Modification of jet structures by MPI

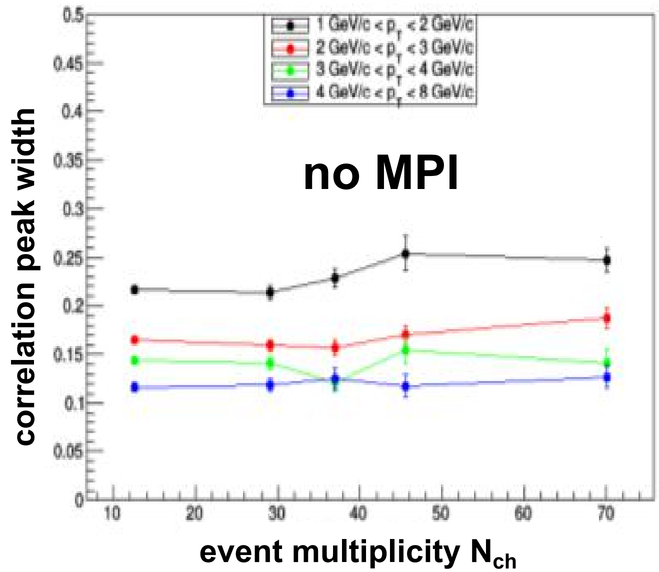
- Word of caution: we do not separate UE in this observable!

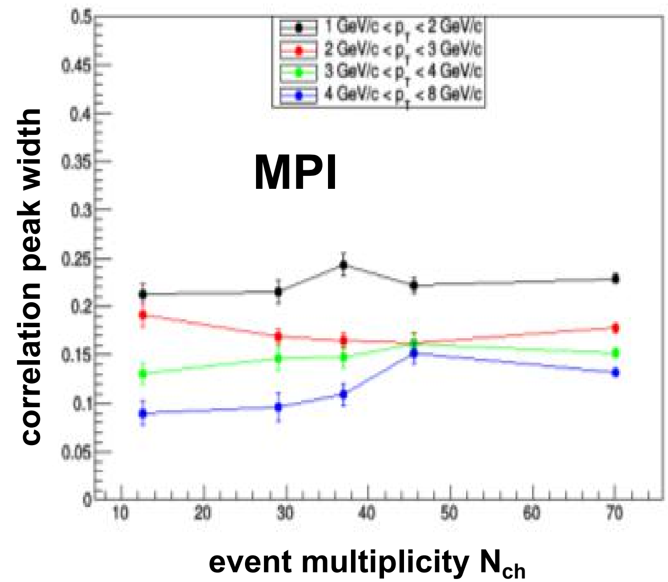
Detour: Angular correlations (Gauss)

Miklós Kovács - BSc. thesis, BME (2018)



(d) $\Delta\eta$-irány
$4\ \mathrm{GeV}/c < p_T < 8\ \mathrm{GeV}/c$; $50 < N_{ch}$





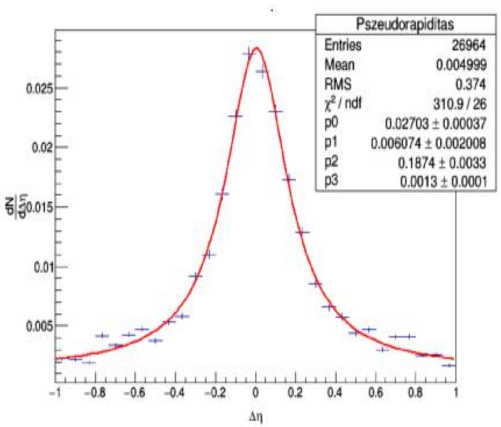
- **Gaussian** fit: Peak mostly includes **fragmentation** components
- Long-range initial stage is in the parabolic backgound

- **Broadening by MPI is moderate towards higher multiplicity**

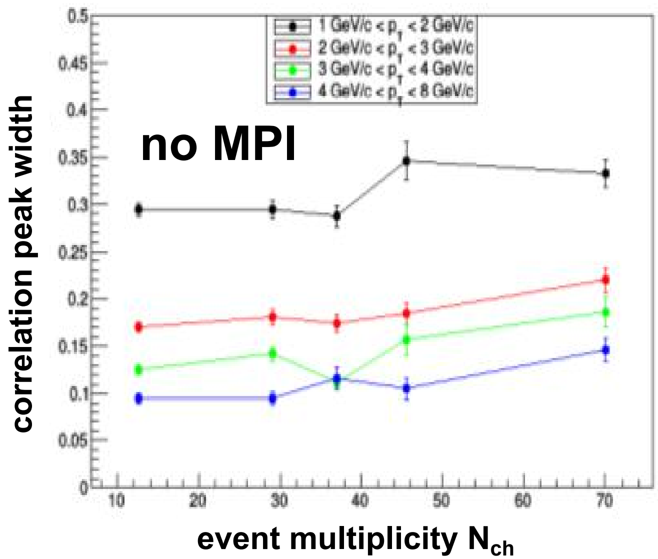
=> HF correlations: Eszter Frajna, Tue 9:30

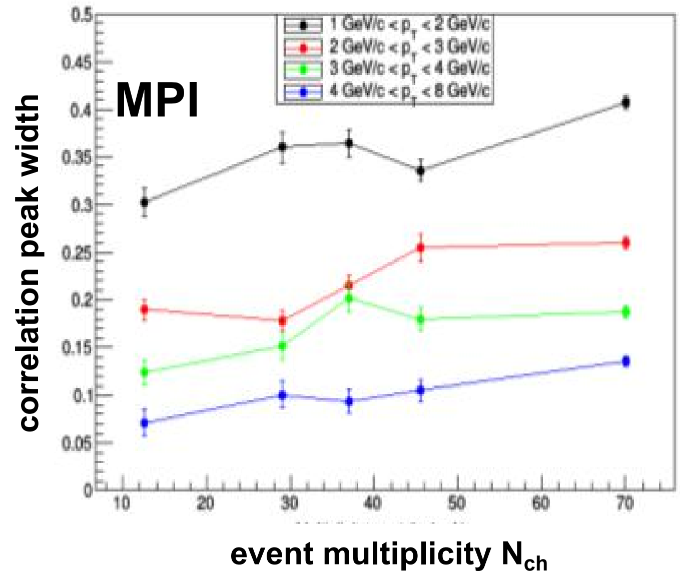
Detour: Angular correlations (Cauchy)

Miklós Kovács - BSc. thesis, BME (2018)



(d) $\Delta\eta$-irány
$4\ \mathrm{GeV}/c < p_T < 8\ \mathrm{GeV}/c\ ;\ 50 < N_{ch}$

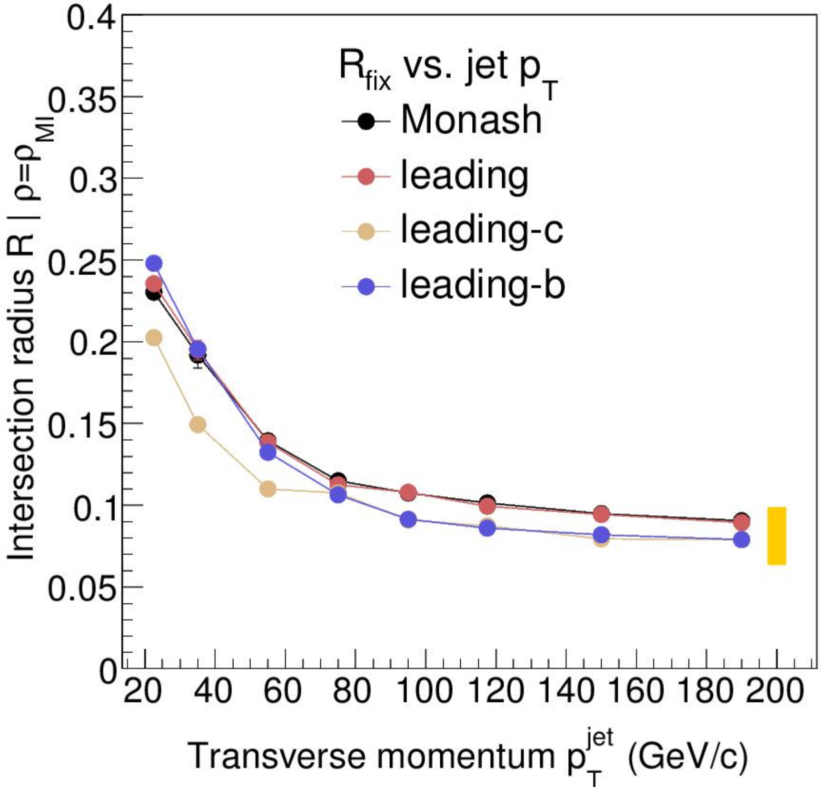




- **Cauchy**-fit (special case of Lévy):
  Peak includes **early-stage and fragmentation** components
- **Significant broadening by MPI towards higher multiplicities**

Modification of correlation by MPI

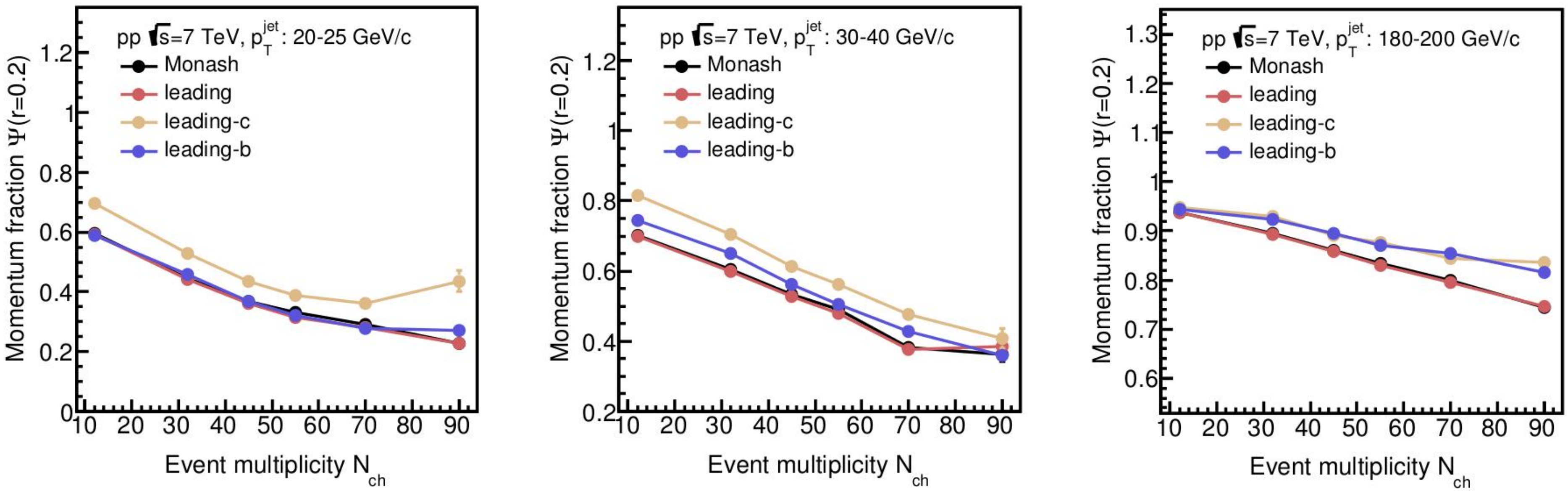
Heavy Flavor - R_{fix}



- PYTHIA: leading order HF production (qq/gg->bb/cc)
- we select leading+subleading jets
- we compare to leading+subleading inclusive jets

- Selection of leading jets does not make a difference for R_{fix}
- Heavy flavor R_{fix} is different! (Trends are similar however)
  - For smaller p_T^{jet} the charm leading jets appear narrower.
  - For higher p_T^{jet} jet both charm and bottom jets are narrower.

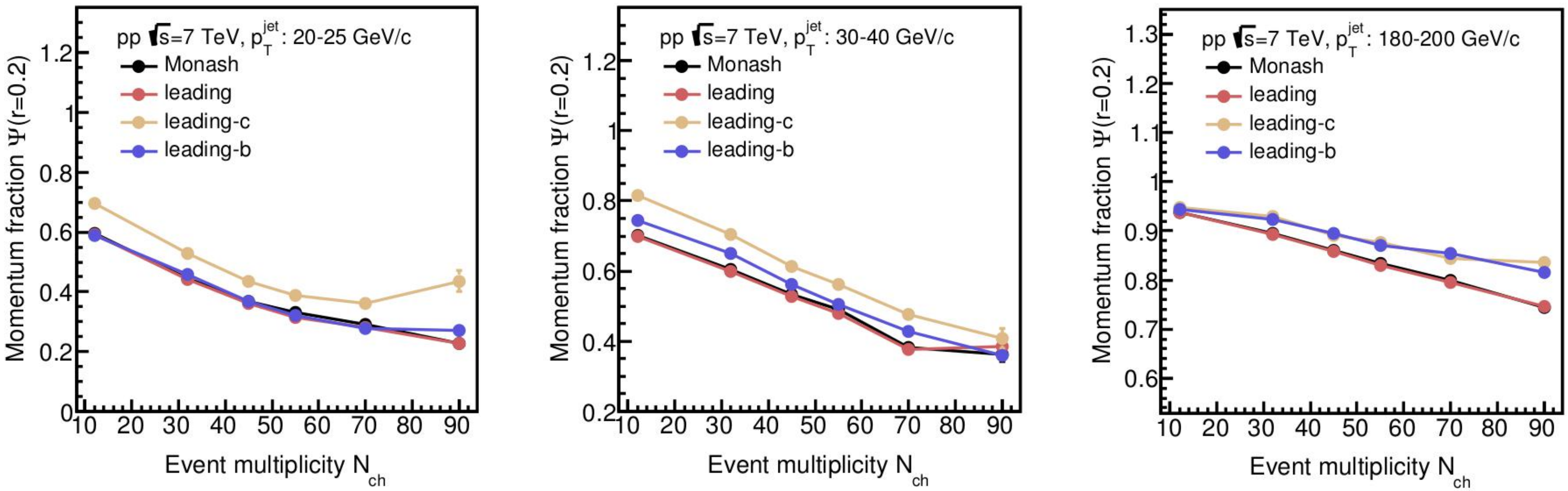
Heavy Flavor - Integrated jet structure



- Charm leading jets are more concentrated than inclusive*
- At high-enough p_T, bottom jets are also more concentrated*
- In a certain p_T range (depends on *r*) all curves differ

*except for very low N_{ch} at high p_T

Heavy Flavor - Integrated jet structure



- Charm leading jets are more concentrated than inclusive*
- At high-enough p_T, bottom jets are also more concentrated*
- In a certain p_T range (depends on *r*) all curves differ

*except for very low N_{ch} at high p_T

HF jet structures sensitive to PS / fragmentation

Conclusions

- Multiplicity-differential jet structure measurements in pp collisions at LHC energies are **sensitive tests of MC models**
  - A way to differentiate between otherwise well-performing models

- We see a **non-trivial modification of the jet shapes** by multiple parton interactions

- We suggest a **multiplicity-independent jet size** measure
  - Independent of choice and settings of examined models
  - Modification of R_{fix} in heavy-ion collisions may be tell-tale

- Heavy-flavor jets have different structure, unexpected way
  - R_{fix} is sensitive to flavor, similarly to the integral jet structure
  - Ordering is unexpected!

Conclusions and outlook

- Multiplicity-differential jet structure measurements in pp collisions at LHC energies are **sensitive tests of MC models**
  - A way to differentiate between otherwise well-performing models
  - **Data up to high p_T would be essential**
- We see a **non-trivial modification of the jet shapes** by multiple parton interactions
  - We are extending our study to **less UE-sensitive observables**
- We suggest a **multiplicity-independent jet size** measure
  - Independent of choice and settings of examined models
  - Modification of R_{fix} in heavy-ion collisions may be tell-tale
  - Moving to **event generators with medium effects** (HIJING++)
- Heavy-flavor jets have different structure, unexpected way
  - R_{fix} is sensitive to flavor, similarly to the integral jet structure
  - Ordering is unexpected! **We need HF measurements**

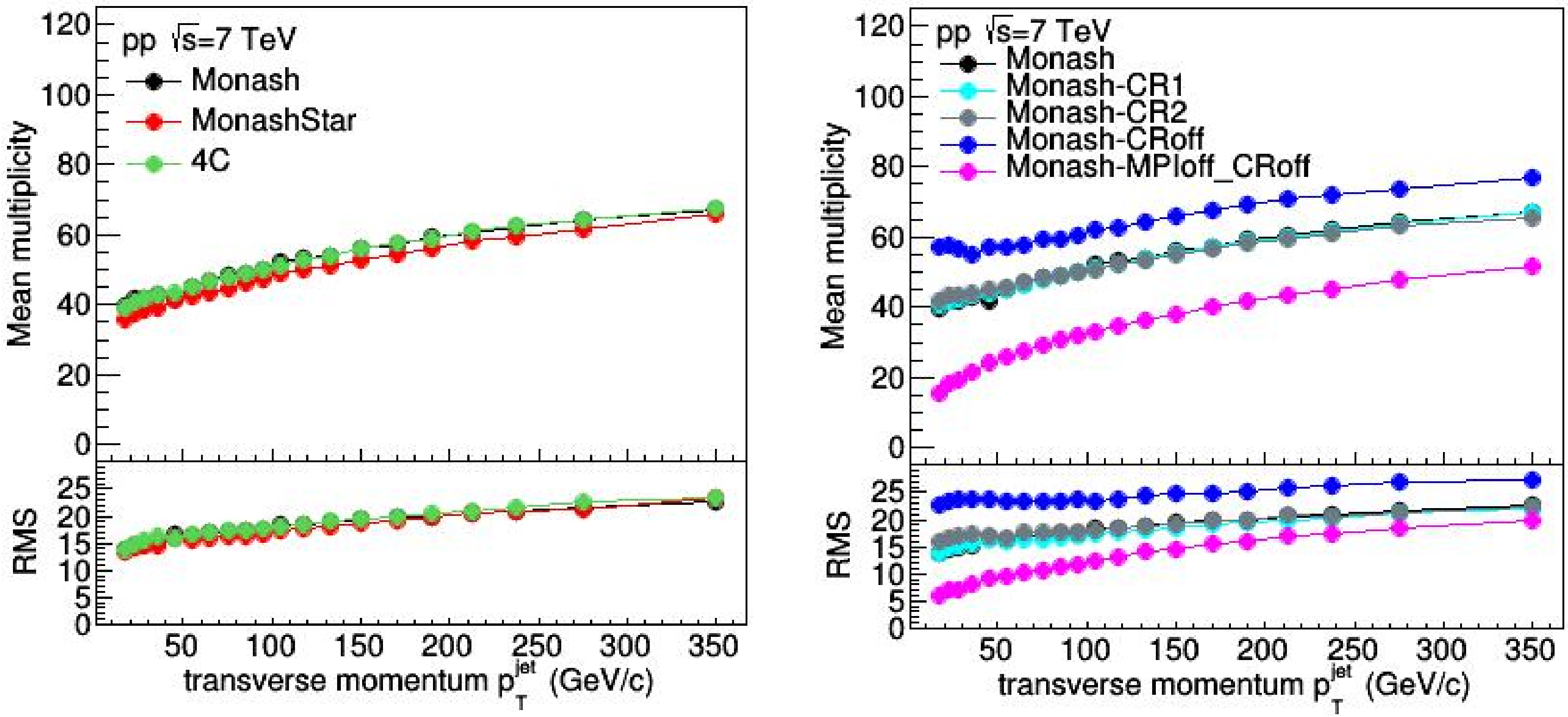
Thank you!

...and please stay tuned

Acknowledgements:
Jana Bielčíkova
Miklós Kovács
Filip Krízek
Yaxian Mao
Antonio Ortiz

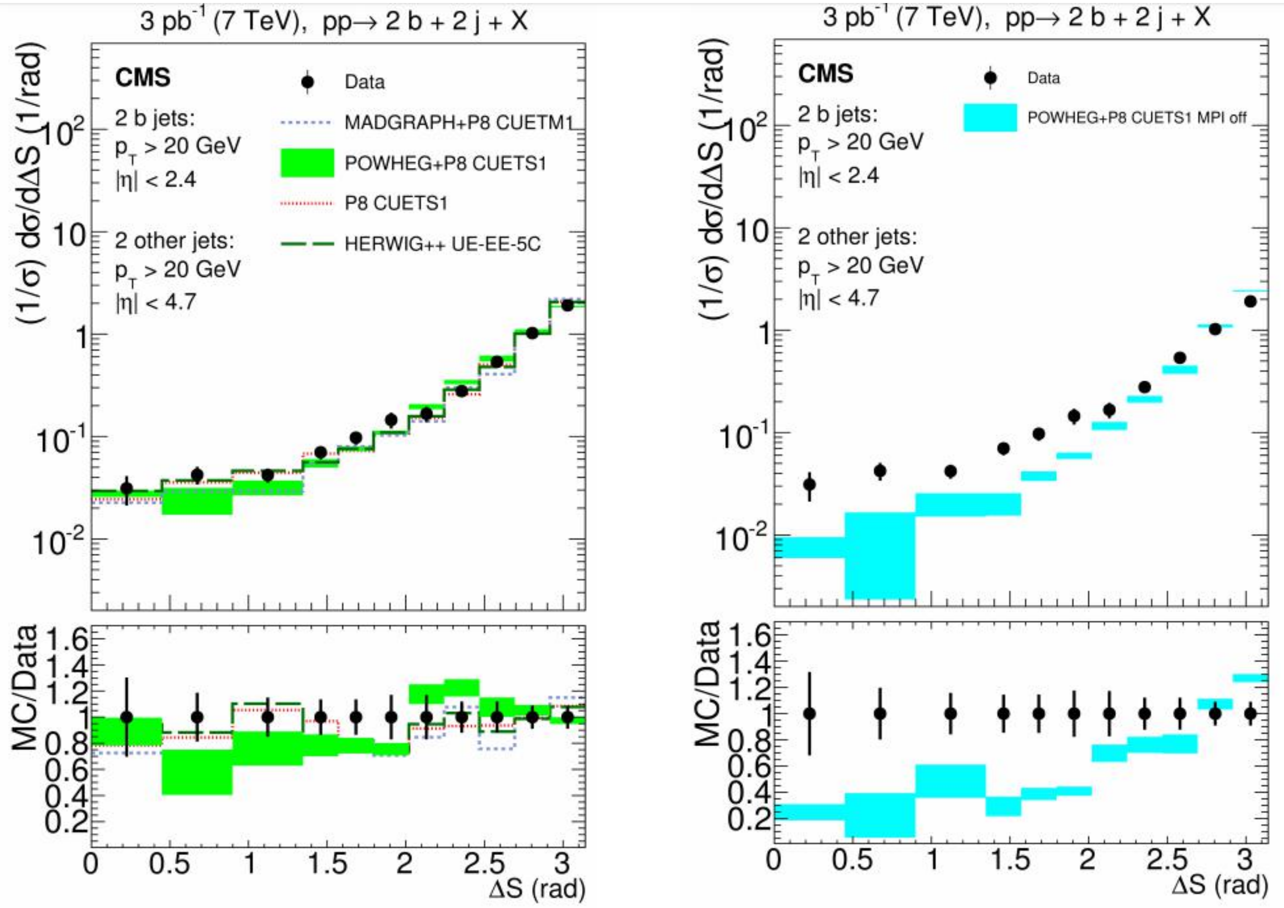
Supported by: **NKFIH/OTKA** K 120660 grant; János **Bolyai scholarship** of the Hungarian Academy of Sciences; **MOST-MTA** Chinese-Hungarian Research Collaboration

Event charged multiplicity vs. pT



- A rising trend with p_T (excepted)

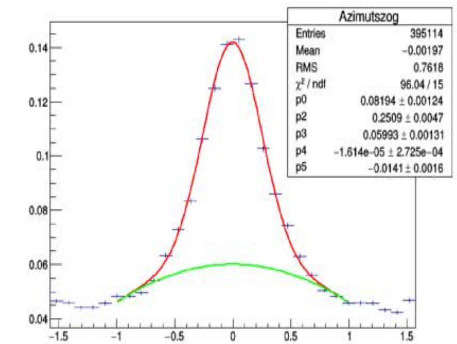
CMS 2j+2b dijet azimuthal angle ΔS



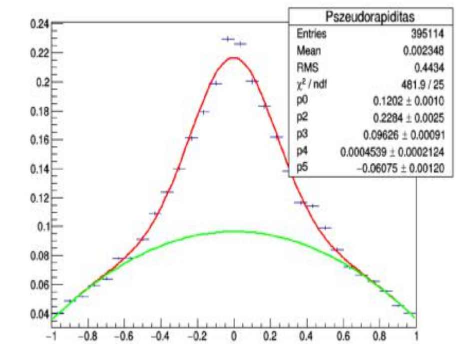
CMS, PRD94, 112005 (2016)

- Sensitive to MPI
- Robust regarding UE, choice of simulations

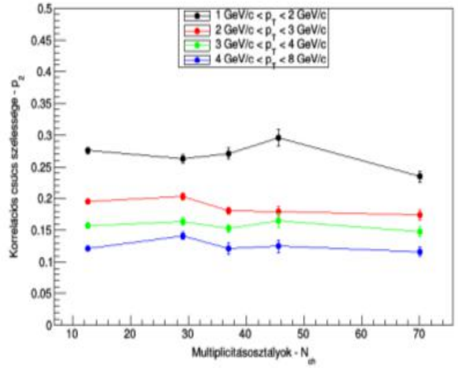
h-h correlations, near-side Gaus+p2 fit



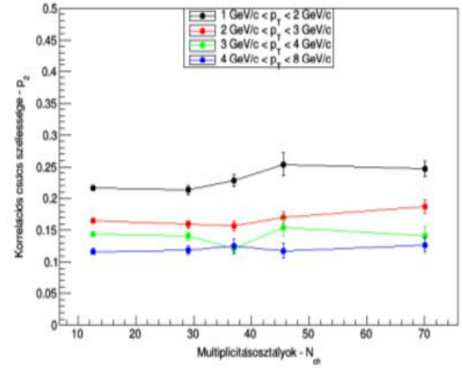
(a) $\Delta\phi$-irány
$1\ \mathrm{GeV}/c < p_T < 2\ \mathrm{GeV}/c\ ;\ 50 < N_{ch}$



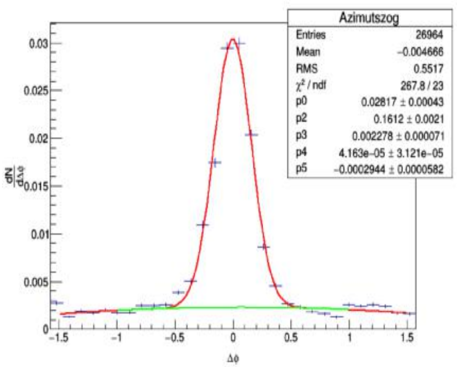
(b) $\Delta\eta$-irány
$1\ \mathrm{GeV}/c < p_T < 2\ \mathrm{GeV}/c\ ;\ 50 < N_{ch}$



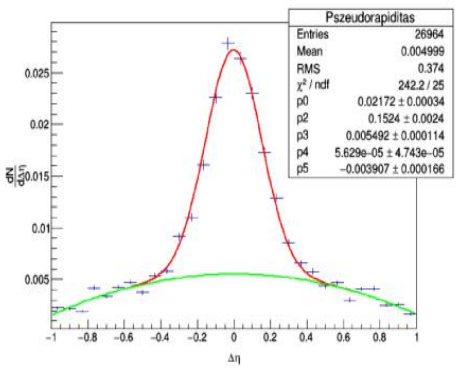
(a) $\Delta\phi$-irány , MPI: off , CR: off



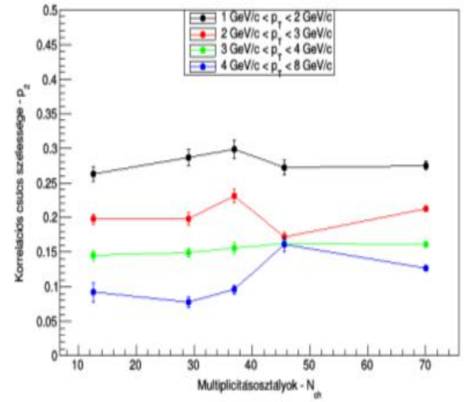
(b) $\Delta\eta$-irány , MPI: off , CR: off



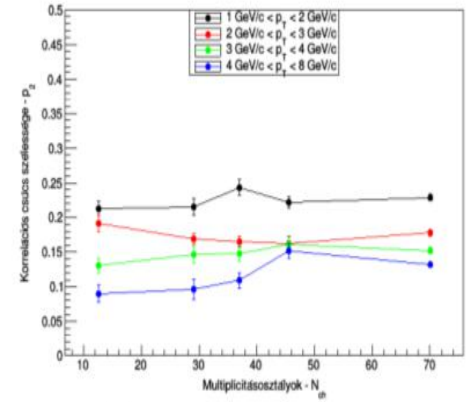
(c) $\Delta\phi$-irány
$4\ \mathrm{GeV}/c < p_T < 8\ \mathrm{GeV}/c\ ;\ 50 < N_{ch}$



(d) $\Delta\eta$-irány
$4\ \mathrm{GeV}/c < p_T < 8\ \mathrm{GeV}/c\ ;\ 50 < N_{ch}$



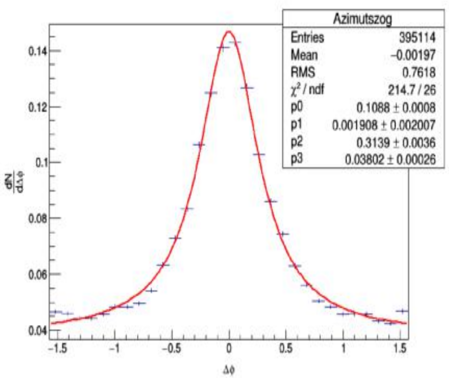
(e) $\Delta\phi$-irány , MPI: on , CR: on



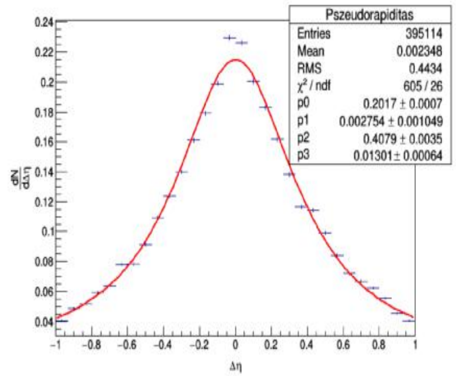
(f) $\Delta\eta$-irány , MPI: on , CR: on

- Peak mostly includes fragmentation components,
- Long-range initial stage is in the parabolic backgound
- Broadening by MPI moderate

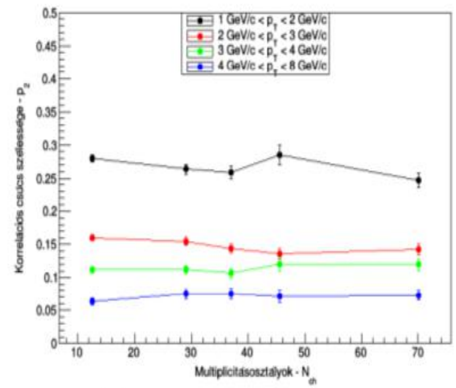
h-h correlations, near-side Cauchy fit



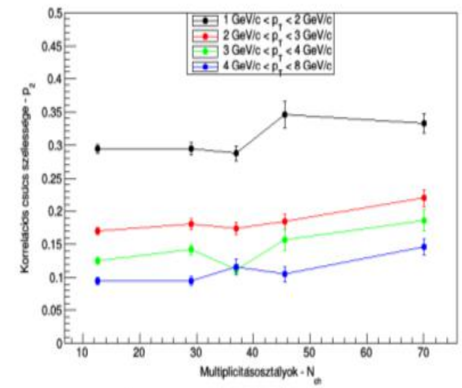
(a) $\Delta\phi$-irány
1 GeV/$c < p_T <$ 2 GeV/c ; $50 < N_{ch}$



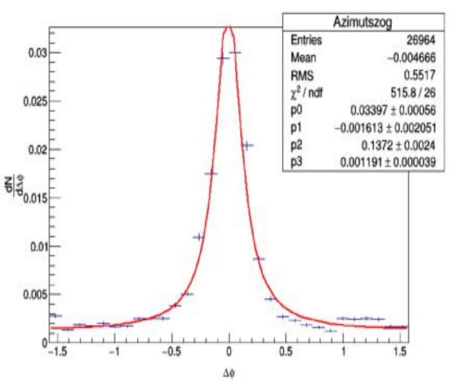
(b) $\Delta\eta$-irány
1 GeV/$c < p_T <$ 2 GeV/c ; $50 < N_{ch}$



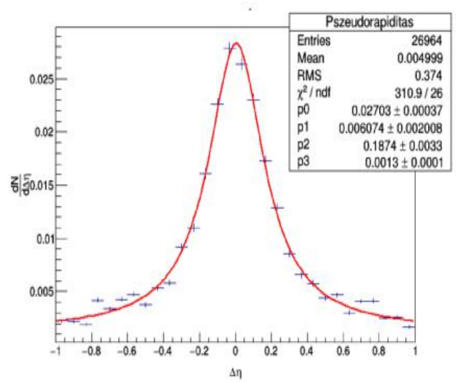
(a) $\Delta\phi$-irány , MPI: off , CR: off



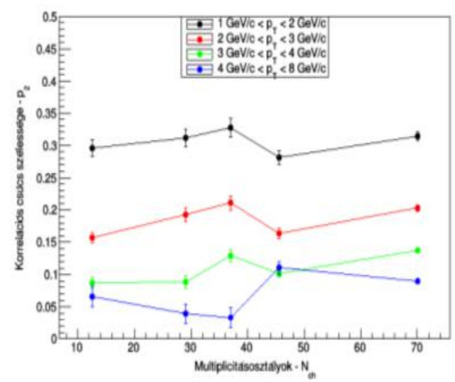
(b) $\Delta\eta$-irány , MPI: off , CR: off



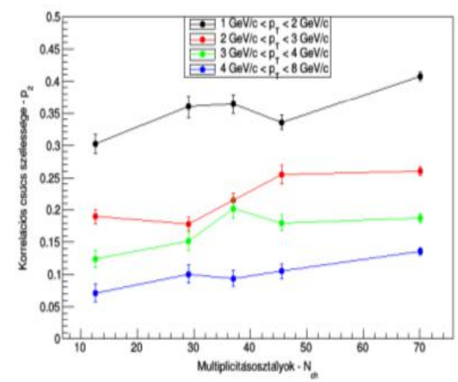
(c) $\Delta\phi$-irány
4 GeV/$c < p_T <$ 8 GeV/c ; $50 < N_{ch}$



(d) $\Delta\eta$-irány
4 GeV/$c < p_T <$ 8 GeV/c ; $50 < N_{ch}$



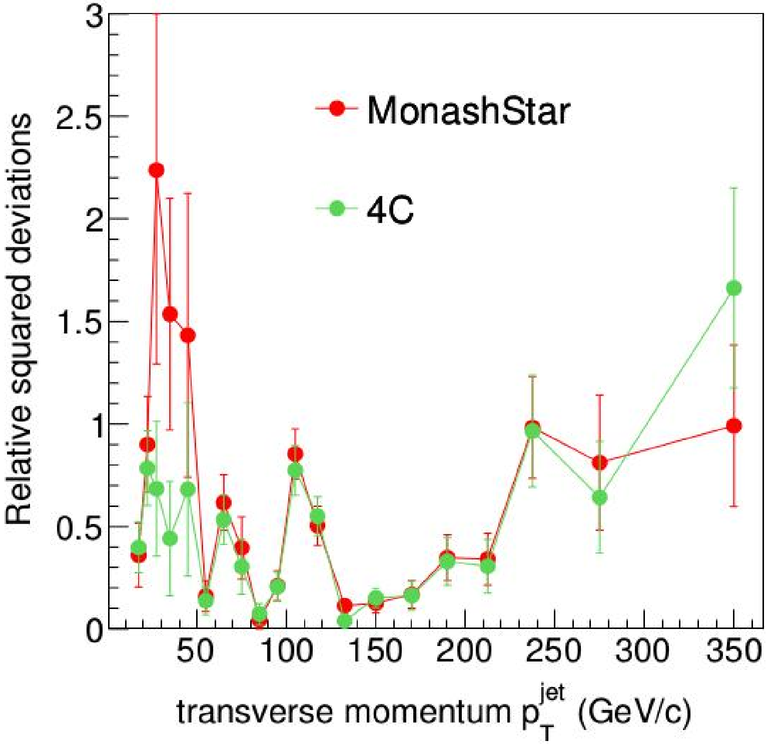
(e) $\Delta\phi$-irány , MPI: on , CR: on

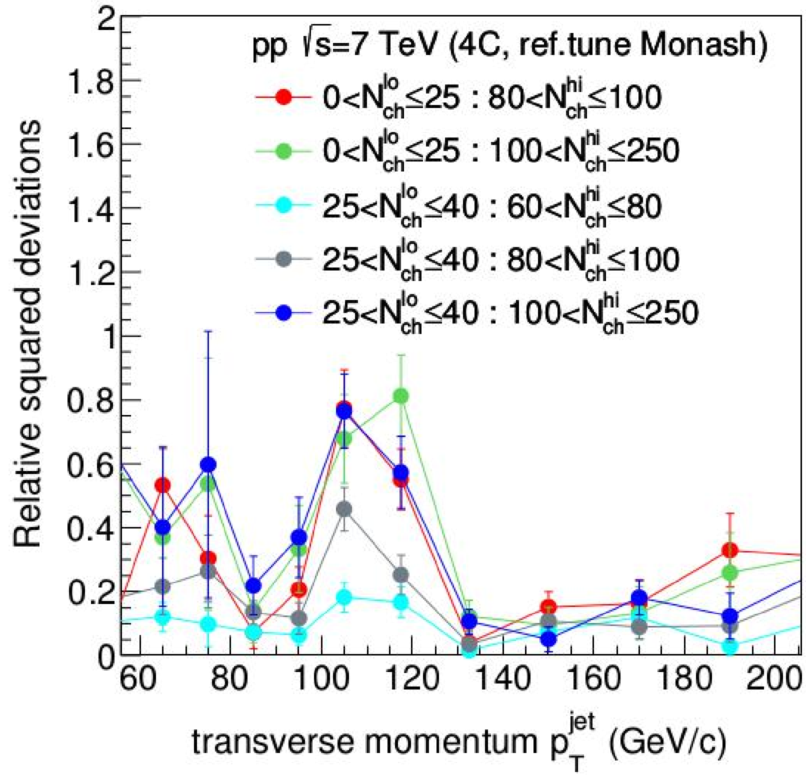


(f) $\Delta\eta$-irány , MPI: on , CR: on

- Peak includes early-stage and fragmentation components
- Sizeable broadening by MPI

Tune comparison: deviations vs. p_T





- Reminder: double ratio

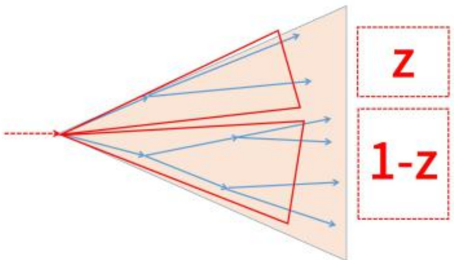
$$DR(r) = \frac{(\rho_{low}/\rho_{high})}{(\rho_{low}/\rho_{high})_{ref.tune}}$$

- Dependence on p_T complicated

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

Jet Substructures in ALICE

- Find the first intra-jet splitting



$$z = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

- At small angles (ΔR < 0.1): consistent Pb-Pb and vacuum z_g distributions
- At large angles (ΔR > 0.1): z_g distributions are steeper in medium than in vacuum
- **Early jet development influenced by medium**