

Scaling properties of jets in high-energy pp collisions

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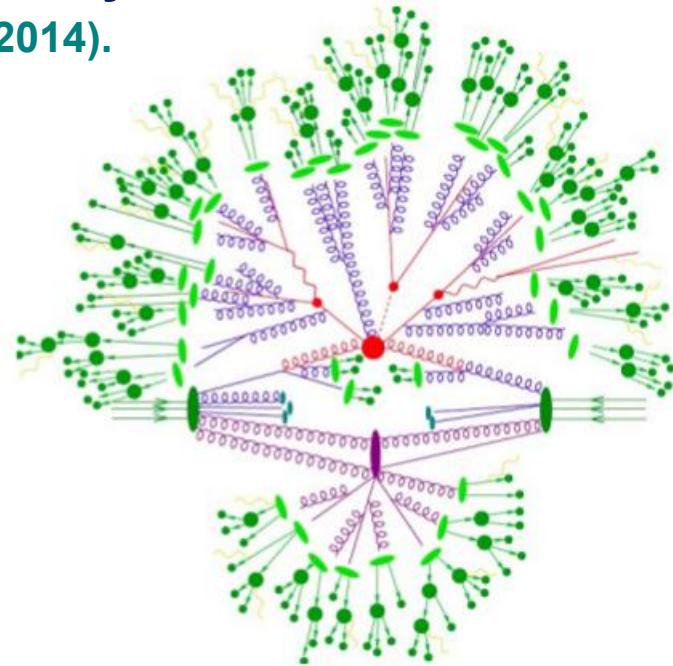


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University

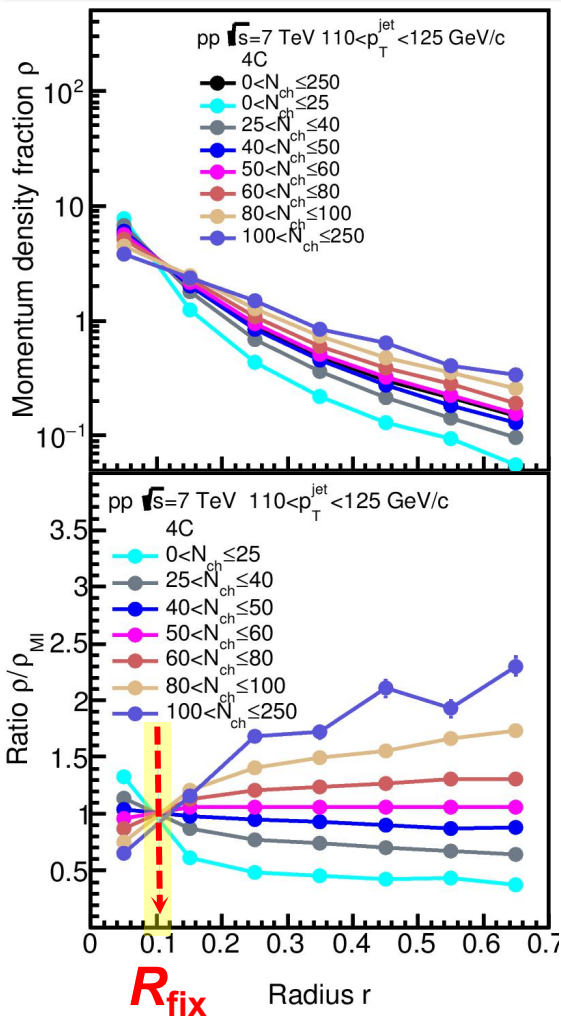
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Motivation

- **Collectivity in small systems with high-multiplicity at LHC**
 - Substantial v_n , eg. [Yan-Ollitrault, PRL 112, 082301 \(2014\)](#).
- **Current understanding:**
 - QGP is not necessary for collectivity
 - Vacuum-QCD effects at the soft-hard boundary:
for instance **multiple-parton interactions (MPI)**
eg. [Schlichting, arXiv:1601.01177](#)
 - and **color reconnection (CR)** [model element]
eg. [Ortiz-Bencédi-Bello, J.Phys.G 44 \(2017\)](#)
- **Jets:**
 - **A-A**: sensitive probe of nuclear modification.
 - **pp**: No suppression expected.
However: soft and hard processes are related by MPI
=> jets can serve to study this connection



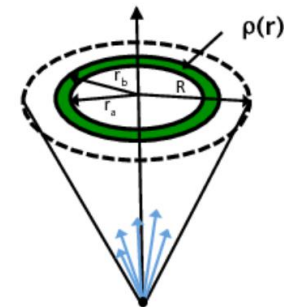
1) Radial jet profiles



Radial jet profiles

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

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



PYTHIA 8.2 simulations

pp collisions at $\sqrt{s} = 7$ TeV, $R=0.7$, $50 < p_T^{\text{jet}} < 60$ GeV/c, $|y| < 1$

7 multiplicity classes: jet profile curves intersect at a given point R_{fix} in any p_T^{jet} window

- R_{fix} independent of**
 - generator:** Pythia, Hijing++
 - tune:** 4C, Monash, Monash*
 - nPDF sets**
 - CR scheme or MPI**
 - jet algorithm:** anti- k_T , C/A, k_T

=> Is it a scaling behavior?

Z. Varga, R.V, G.G.B,
Adv.HEP 2019, 6731362 (2019)

Parametrizing the jet profiles

- Detailed PYTHIA 8 simulations (4C)

- Jet radius: 12 bins up to $r=0.6$
- Multiplicity 6 bins up to $N=100$
- Momentum: 20 bins up to $p_T^{\text{jet}}=400$

- Statistically motivated distributions:

- Gamma distribution

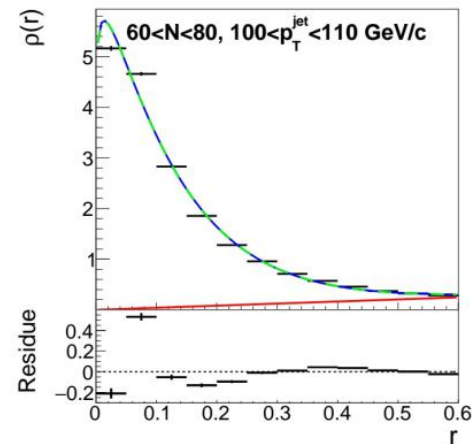
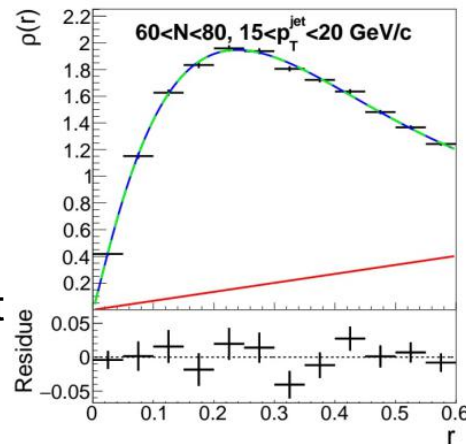
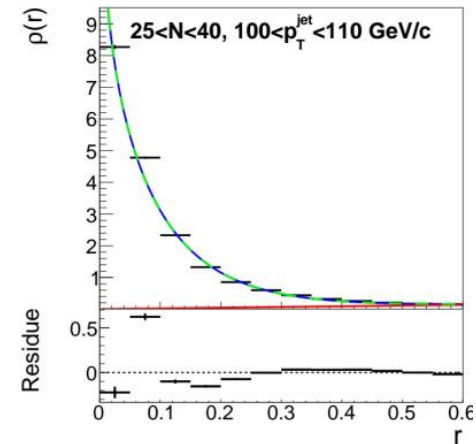
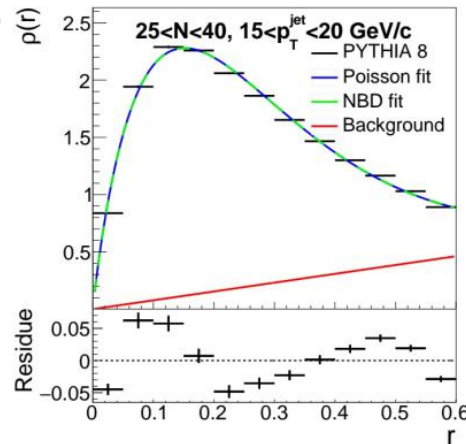
$$\rho(r) = Cr^\gamma e^{-\alpha r}$$

- NBD (Negative binomial distribution)

$$\rho(r) = C \frac{\Gamma(rk+a)}{\Gamma(a)\Gamma(rk+1)} p^{rk} (1-p)^a$$

Note: both in the wide-jet ($p \rightarrow 1$) and narrow-jet limit ($\gamma \rightarrow -1$), NBD reduces to a Gamma

- Simultaneous fit with a $\sim br$ background



Gribov-90 Memorial Volume, 81 (2021) [arXiv:2008.08500]

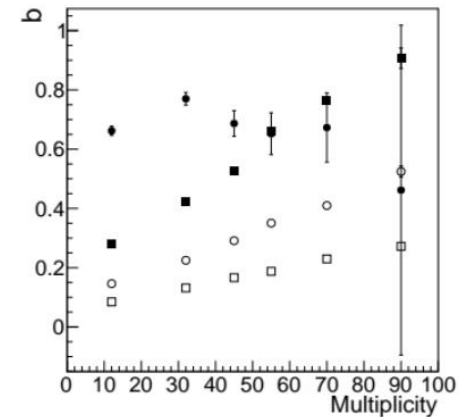
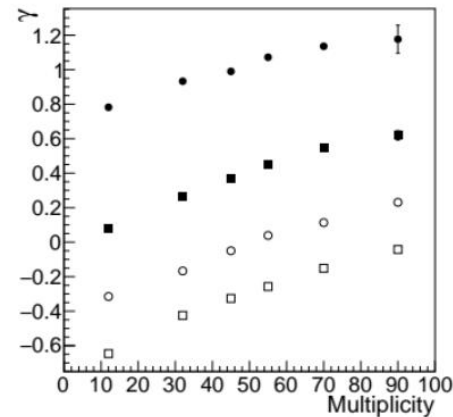
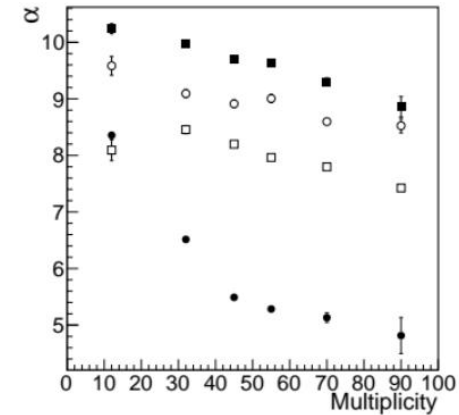
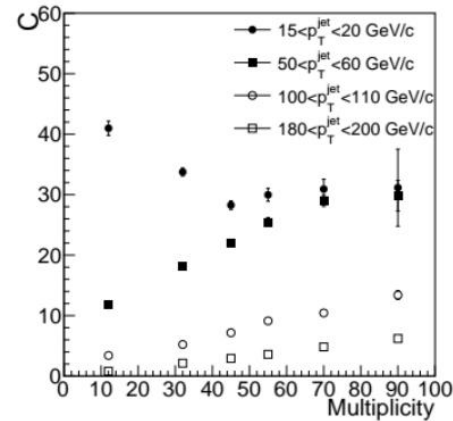
Parameters of the fits

- Gamma distribution with background

$$\rho(r) = Cr^\gamma e^{-\alpha r} + br$$

- Monotonic trends observable

- Exception: lowest p_T
 - Underdetermined background fit (mostly affects b and C)
 - Leakage of jet outside $R=0.7$ (affects C)



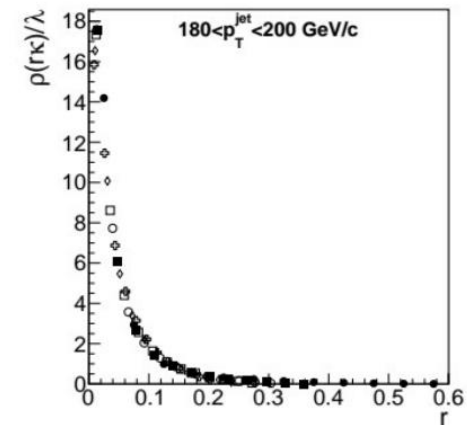
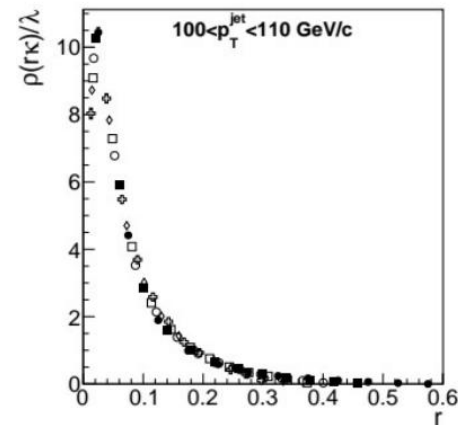
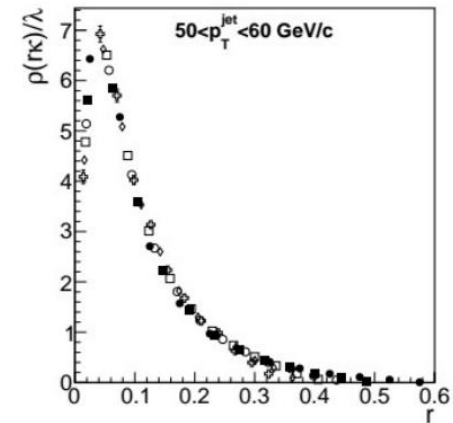
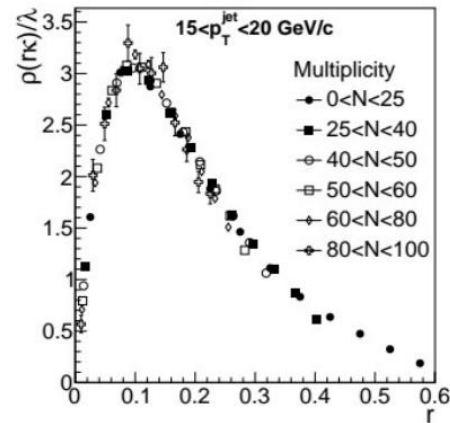
Gribov-90 Memorial Volume, 81 (2021) [arXiv:2008.08500]

Scaling of the jet profiles

- Scaling assumption: profiles at all multiplicities collapse into a single distribution,

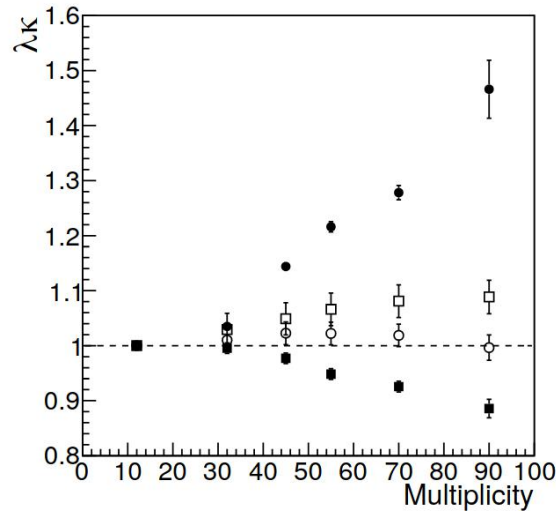
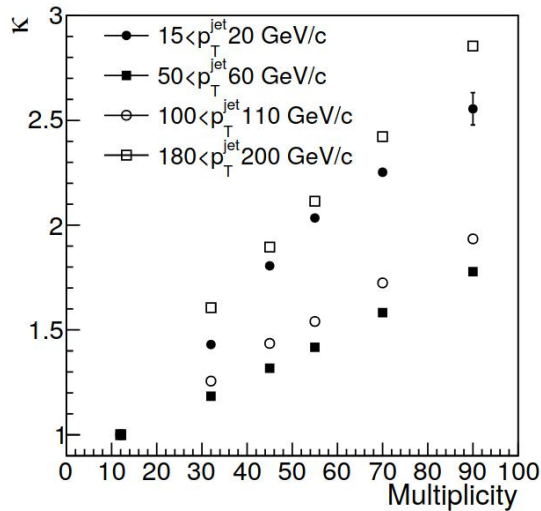
$$\rho_N(r) = \lambda(N) f\left(\frac{r}{\kappa(N)}\right)$$

- Scaling is determined based on the Gamma distribution fits
 - Chosen “good” mid-multiplicity fits, then others scaled to it minimizing χ^2
- The scaling works within 5-10% in the peak region**



Gribov-90 Memorial Volume, 81 (2021) [arXiv:2008.08500]

Scaling factors



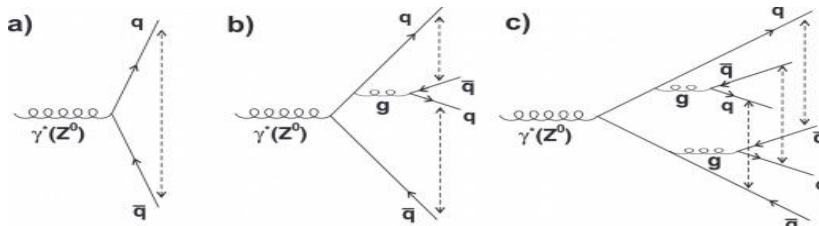
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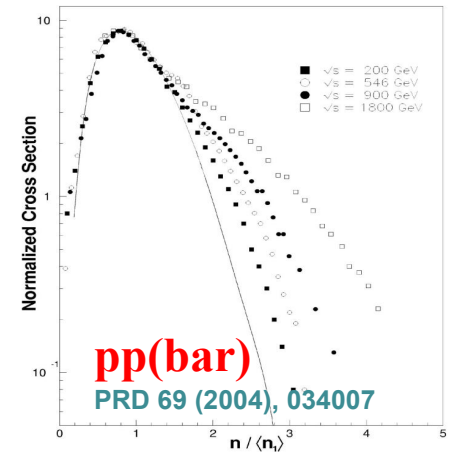
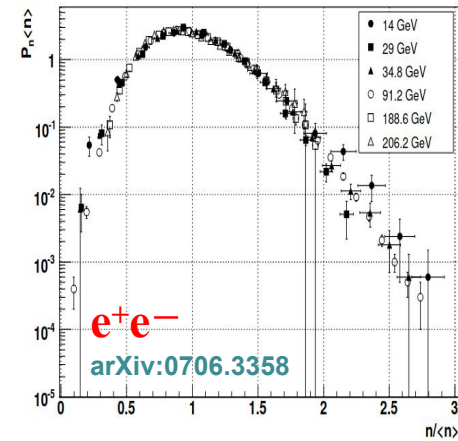
- The scaling parameter κ is approximately linear with multiplicity
- Ideally, $\lambda\kappa \sim 1$. This is fulfilled on the 10% level except for the lowest- p_T bin
 - Low- p_T increase is because leakage increases λ
 - Slight high- p_T decrease is because background determination

2) KNO-scaling within jets

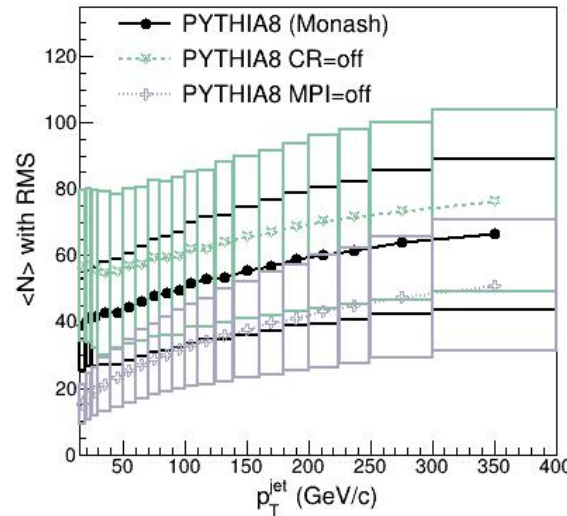
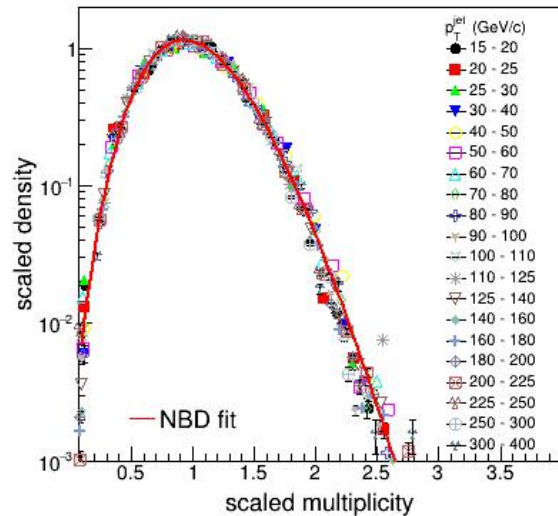
- KNO scaling: the multiplicity distribution scales with \sqrt{s}
Koba-Nielsen-Olesen, NPB 40, 317 (1972); Polyakov, Sov.Phys.JETP 32, 296 (1971)
- The KNO scaling breaks down at high \sqrt{s}
- KNO may be violated by the presence of multiple-parton interactions or overlapping color strings
Walker PRD 69, 034007 (2004); Abramovsky et al., arXiv:0706.3358



- **Is KNO-scaling valid within a single jet?**
- **How is affected by MPI and CR?**
- **Is there a connection of KNO to radial scaling?**



KNO within jet: multiplicity scaling with p_T^{jet}



Phys.Rev.D 103 (2021) 5, L051503
[arXiv:2012.01132]

- Multiplicity (dominated by the jet multiplicity) vs. jet momentum p_T^{jet}
- Parametrized with a NBD
- Distributions at all p_T^{jet} fit well on a single NBD curve
- **KNO-like scaling observed within a jet**
 - In the following we quantify how well it is fulfilled

$$P_N = \frac{\Gamma(Nk + a)}{\Gamma(a)\Gamma(Nk + 1)} p^{Nk} (1 - p)^a$$

Multiplicity vs. p_T^{jet} : moments

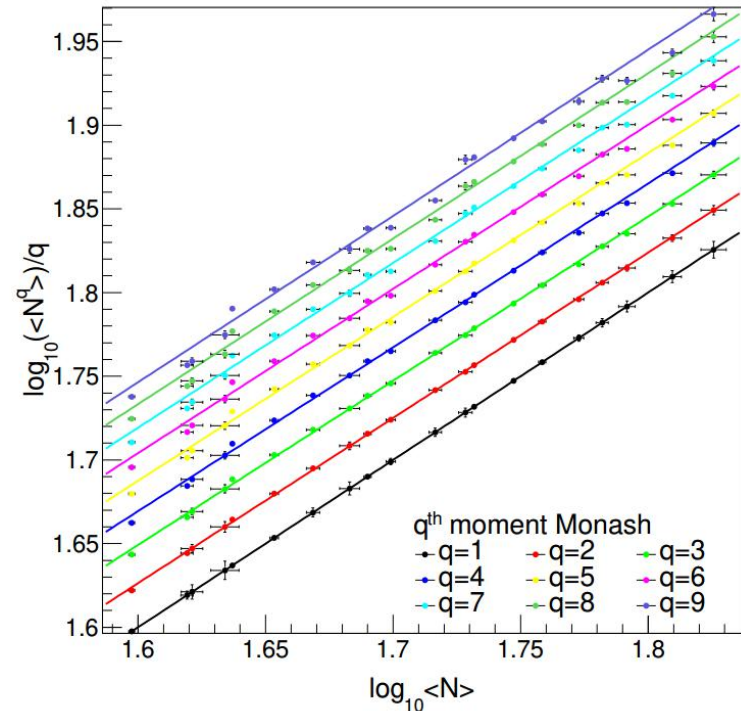
- q^{th} statistical moment

$$\langle N^q \rangle = \sum_{N=1}^{\infty} P_N N^q$$

- sensitive to goodness of scaling
- insensitive to fluctuations
- no need to parametrize and fit

- Scaling:

$$\langle N^q(p_T^{\text{jet}}) \rangle = \lambda^q(p_T^{\text{jet}}) \langle N^q(p_0) \rangle \quad \lambda(p_0) = 1$$



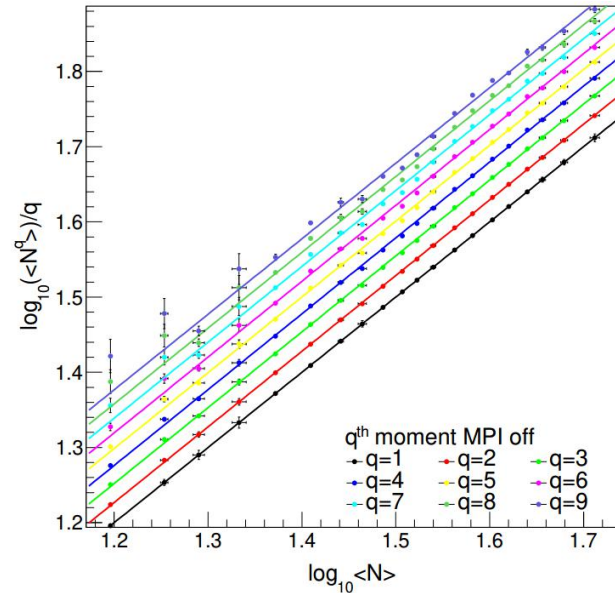
Phys.Rev.D 103 (2021) 5, L051503 [arXiv:2012.01132]

- $\log \langle N^q \rangle / q$ vs. $\log \langle N \rangle$ is a straight line with \sim unity slope
 - up to the 9th moment

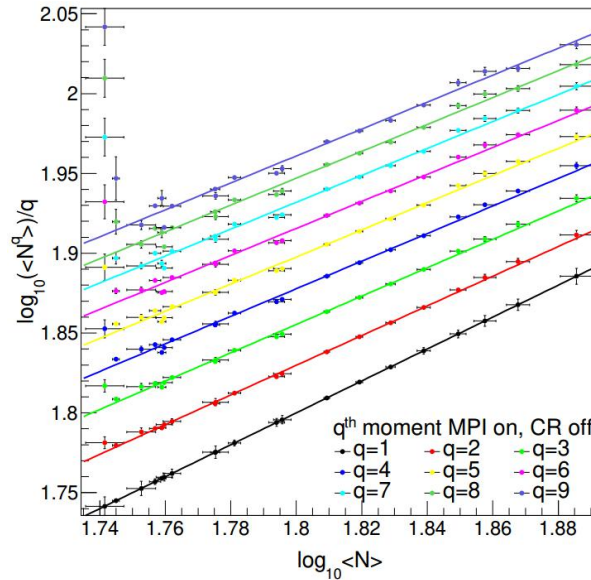
=> **scaling is fulfilled in the whole p_T^{jet} range**

Moments: Role of MPI and CR

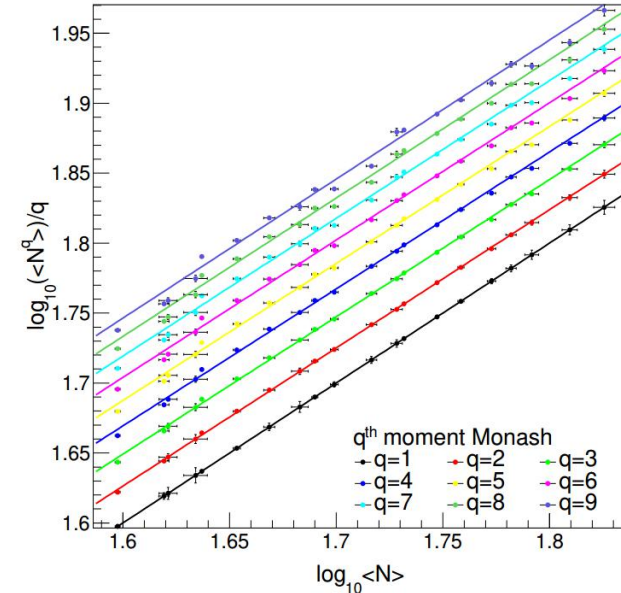
MPI off



CR off, MPI on



physical: CR on, MPI on

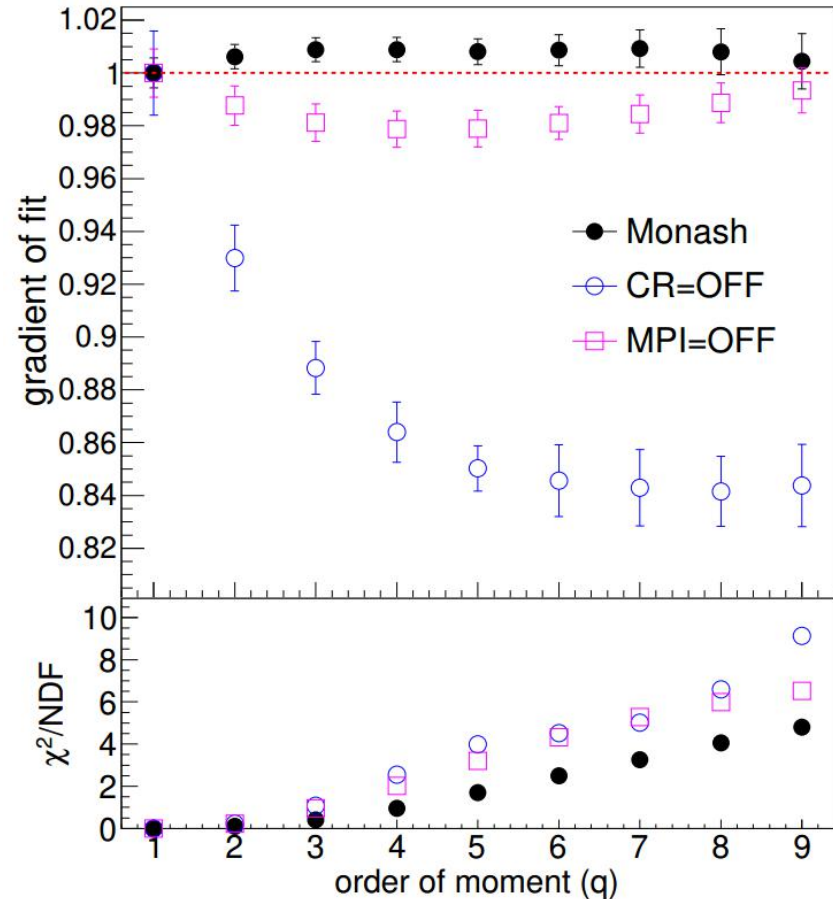


Phys.Rev.D 103 (2021) 5, L051503 [arXiv:2012.01132]

- **No multiple-parton interactions: scaling is present**
 - “possible physical” scenario producing low-activity events
- **No color reconnection: no scaling**
 - color-flow not handled, non-physical scenario

Slopes moment-by-moment

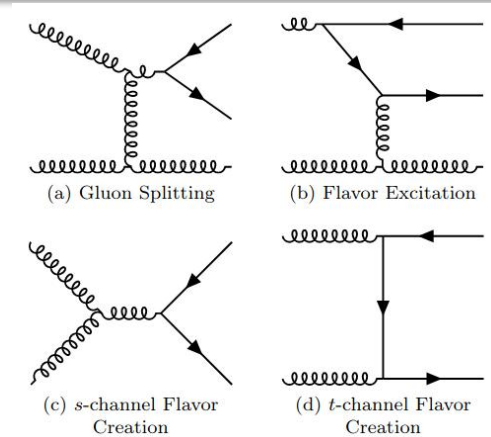
- Physical case (Monash): All 9 moments are consistent with unity, slope within $\sim 1\%$
 - Note*: scaling holds for different tunes & nPDFs (Monash, 4C, Monash*) and also for different jet algos (anti- k_T , C/A and k_T)
- No CR: Scaling is broken by $\sim 15\%$
- No MPI (also no CR by construction): Scaling is fulfilled to $\sim 2\%$.
- All fits are statistically good ($\chi^2/\text{NDF} < 8$, \sim proportional to the order of moment)
- The emerging picture is different from that of radial profile scaling, which holds for CR=off as well**



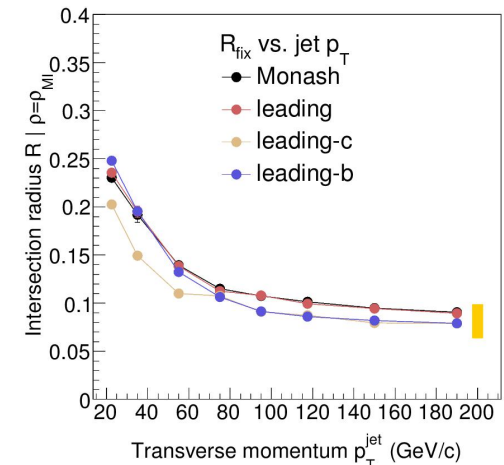
Phys.Rev.D 103 (2021) 5, L051503 [arXiv:2012.01132]

3) How do heavy-flavor jets scale?

- HF created via...
 - **LO** Flavor Creation
 - **NLO** Gluon Splitting and Flavor Excitation
- These contributions are of similar magnitudes
 Cao et al., *Phys.Rev.C* 93 (2016) 2, 024912
- Heavy-flavor jet production affected by:
 - Mass dependent effects: harder fragmentation, dead-cone effect
 - Color-dependent effects: HF initiated by quark jets only
 => HF jets are different than LF jets
- Comparison of scaling LO and NLO: sensitivity to its origin (hard QCD process vs. jet development)



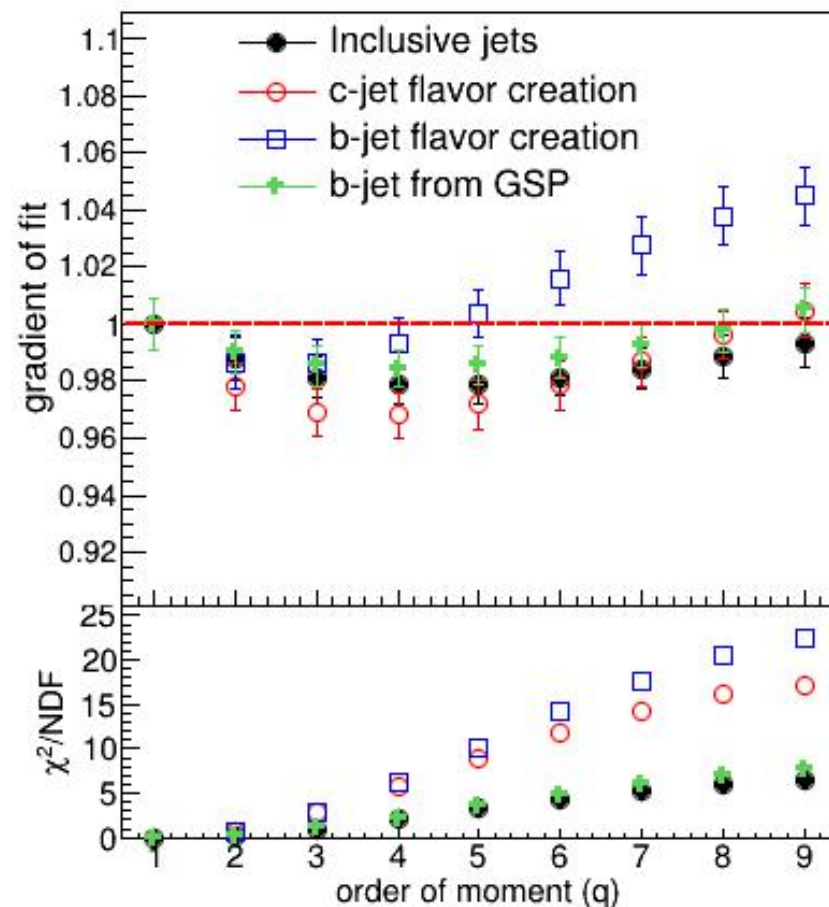
Ilten et al., *PRD* 96 (2017) 5, 054019



Varga et al., *Universe* 5 (2019) 5, 132

HF jets - production vs. fragmentation

- All slopes are around unity within 5%
- LO flavor-creation
 - Inferior quality fits (χ^2/ndf up to 22)
 - Deviation from inclusive jets, depending on the mass
- NLO gluon splitting
 - Follows inclusive jets (mostly gluon jets)
- **Scaling driven by initial hard process**
 - Direct HF quark pair creation djets
 - Later development of jets has less influence, as multiplicity is not driven by fragmentation



Summary

Radial jet-momentum profiles scale with multiplicity

Gribov-90 Memorial Volume, 81 (2021) [arXiv:2008.08500]

- Profiles can be parametrized with a Gamma dist. and scale with event multiplicity
- Scaling is present in a broad model class, regardless of settings
- **Fundamental statistical / thermodynamical property of jet development?**
- Cross-check with real data would be essential

KNO-like scaling within a jet: scaling of multiplicities with jet momentum

Phys.Rev.D 103 (2021) 5, L051503 [arXiv:2012.01132]

- Multiplicity distributions are NBD and can be collapsed into a single distribution
- This scaling holds without MPI but breaks down without CR
- **KNO scaling is likely violated by complex QCD processes outside the jet development, such as single and double-parton scatterings or softer MPI**
- This statement holds as long as the multiplicities are described. Testing for this scaling behavior can be an important element in model development

KNO-like scaling in heavy-flavor jets

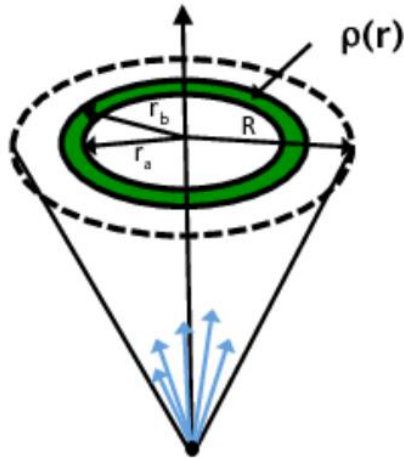
- Driven by the initial hard process

Thank you!

Special thanks to **Sándor Hegyi**
for fruitful discussions and guidance
and to **Zoltán Varga** for technical help

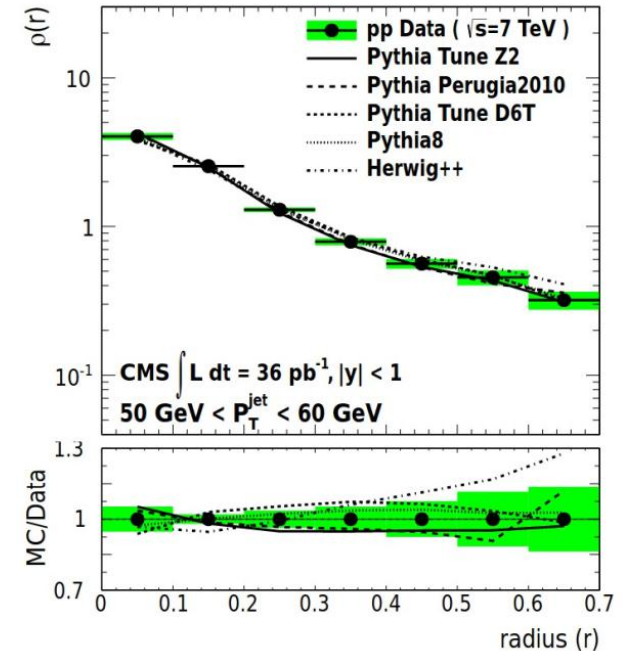
1) Radial jet profiles

- Differential jet shape



$$\rho(r) = \frac{1}{\delta r} \frac{1}{p_T^{\text{jet}}} \sum_{r_a < r_i < r_b} p_T^i$$
$$r_i = \sqrt{(\phi_i - \phi_{\text{jet}})^2 + (\eta_i - \eta_{\text{jet}})^2}$$

CMS, JHEP 06, 160 (2012)



- CMS@LHC pp collisions, $\sqrt{s} = 7$ TeV
- $R=0.7$ jets, $50 < p_T^{\text{jet}} < 60$ GeV/c, $|y| < 1$

- **Currently available LHC data are either multiplicity or transverse-momentum inclusive**

Scaling of the jet profiles - log scale

- Scaling assumption: profiles at all multiplicities collapse into a single distribution,

$$\rho_N(r) = \lambda(N) f\left(\frac{r}{\kappa(N)}\right)$$

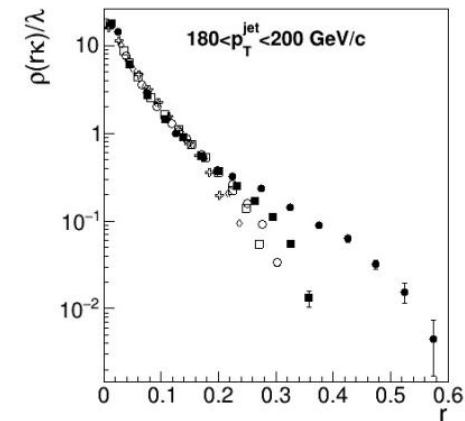
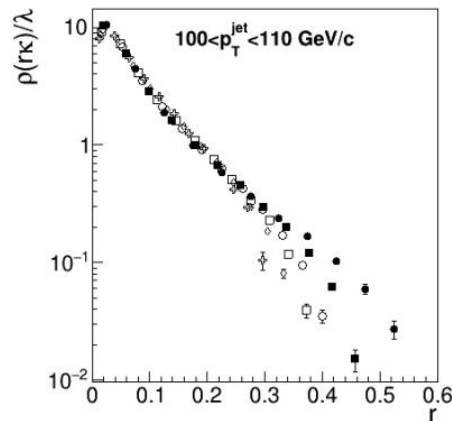
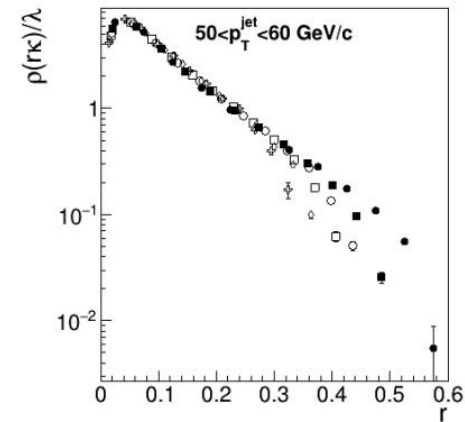
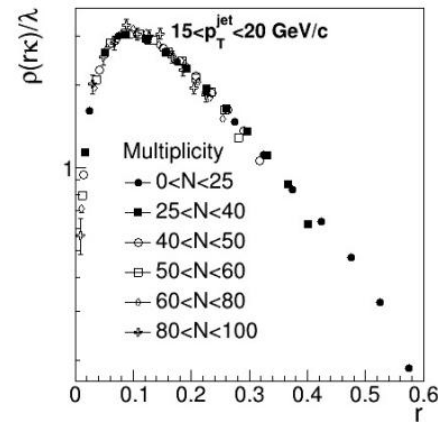
Note: Ideally, $\lambda=1/\kappa$, however...

“leakage” (distribution is cut-off at high r before normalization)

- Scaling is determined based on the Gamma distribution fits

- Chosen “good” mid-multiplicity fits, then others scaled to it minimizing χ^2

- The scaling works within 5-10% in the peak region**



How good are the fits?

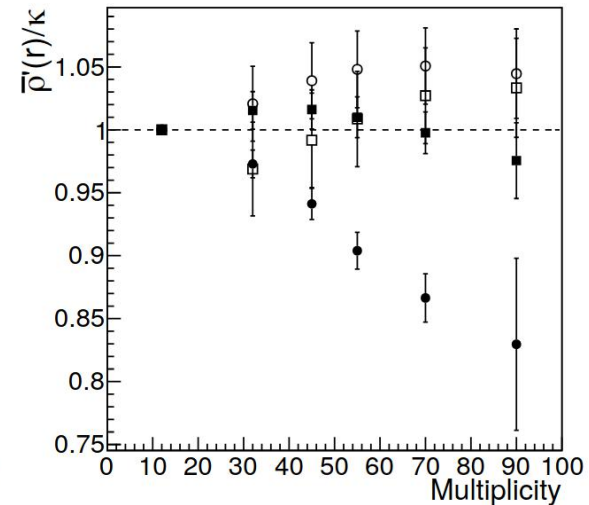
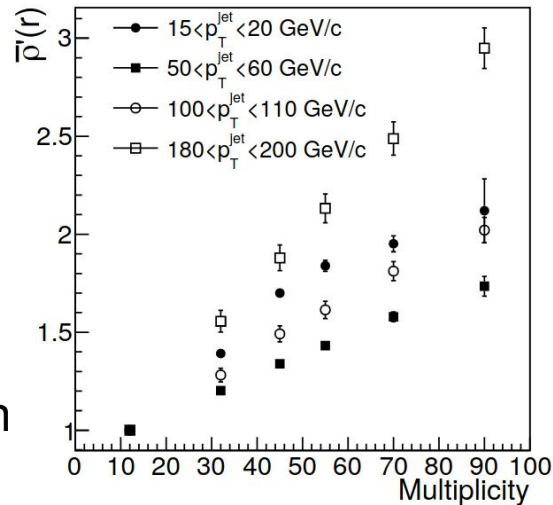
- Fitted distribution mean:

$$\bar{\rho}(r) = \frac{\gamma + 1}{\alpha}$$

- Ideally, it should scale:

$$\kappa / \bar{\rho}' \sim 1$$

where $\bar{\rho}'$ is the rescaled mean



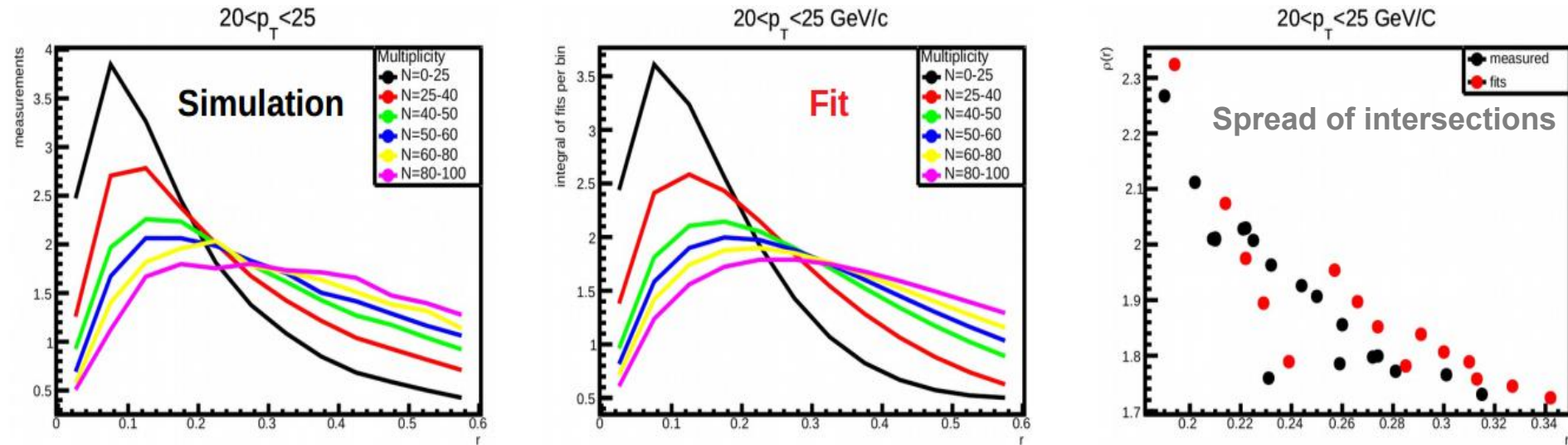
- The mean approximately scales linearly with multiplicity
- Except for the lowest p_T bin, $\kappa / \bar{\rho}' \sim 1$ within 5%
- Hence,

» **Radial profiles scale with multiplicity**

» **The gamma distribution is an adequate description**

Gribov-90 Memorial Volume, 81 (2021) [arXiv:2008.08500]

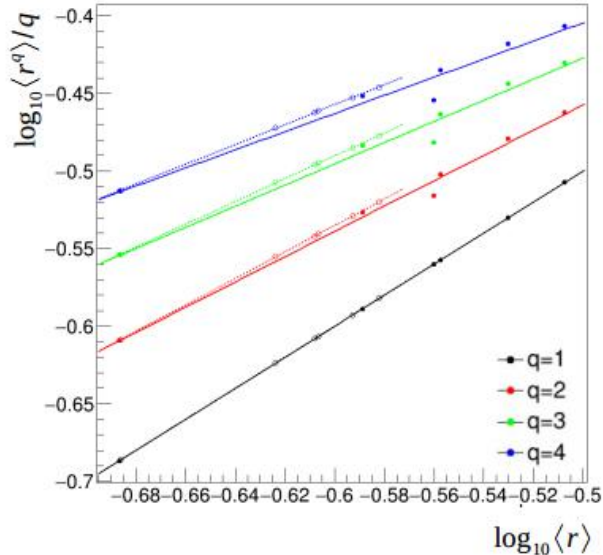
Is there really an R_{fix} ?



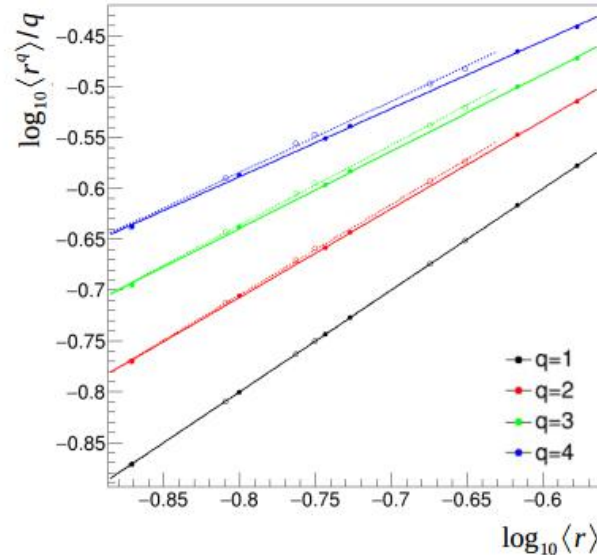
- Based on the parametrization of the Gamma distribution, R_{fix} is an approximate consequence of the scaling
- Note: R_{fix} would be exact if $\rho(r)$ fell linearly in the given region

Effects of finite-size bins (jet profiles)

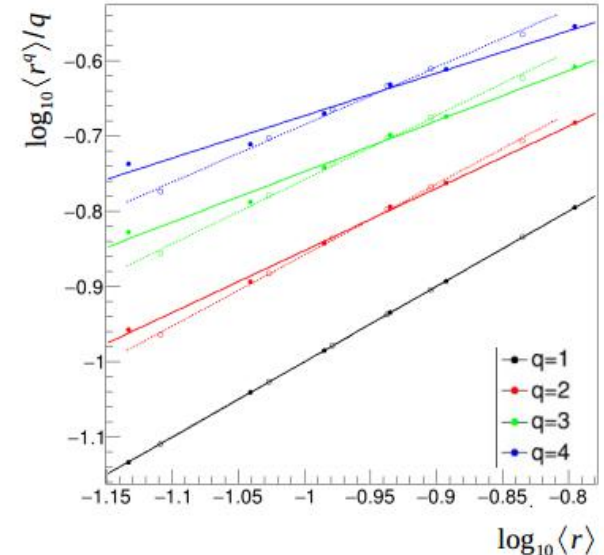
$15 < p_T < 20$



$30 < p_T < 40$

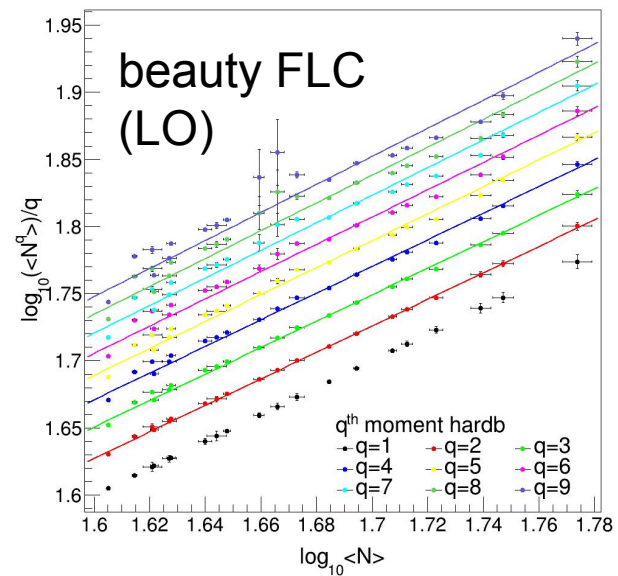
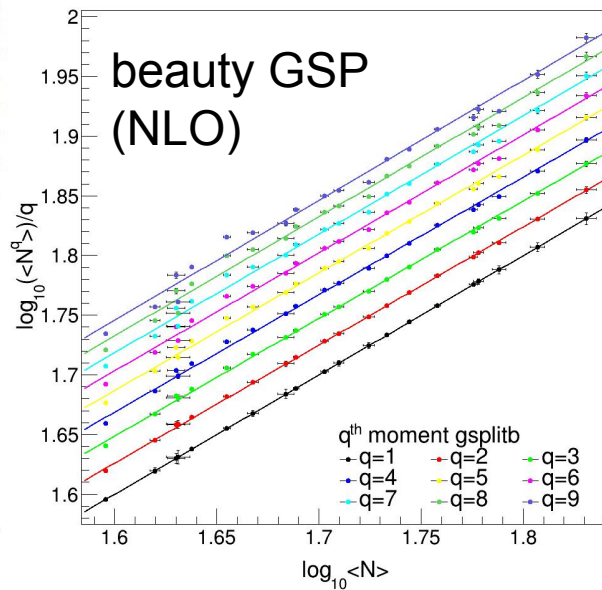
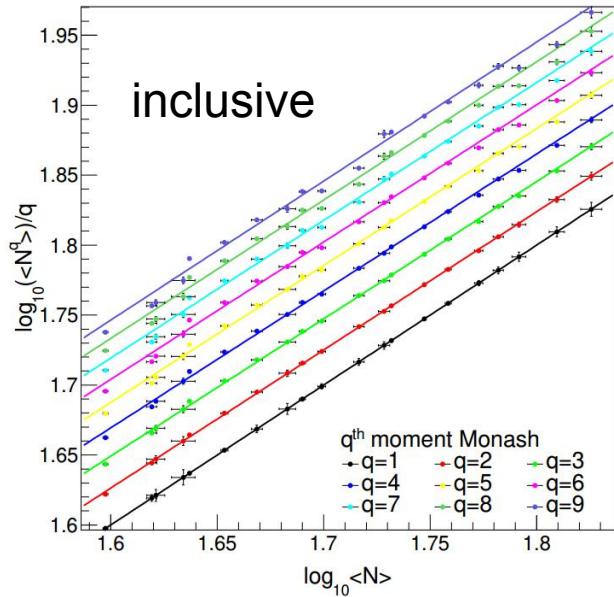


$100 < p_T < 110$



Dotted lines: effect of binning on analytical curves.
Qualitatively explains the behavior seen in the simulations.

3) KNO-like scaling: Heavy Flavor



Beauty-jets