Scaling properties of jets in high-energy pp collisions

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Outline

- Scaling of jet-momentum profiles with multiplicity

  in *Gribov-90 Memorial Volume: Algebraic Methods in QFT*
  arXiv:2008.08500

- KNO-like scaling within a jet in pp collisions

  Phys. Rev. D 103, 051503 (2021)
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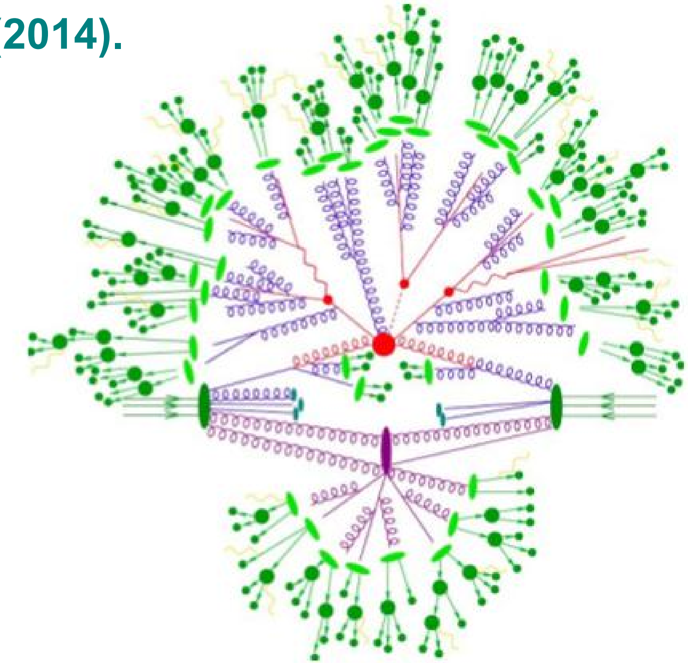
Motivation

- **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)**



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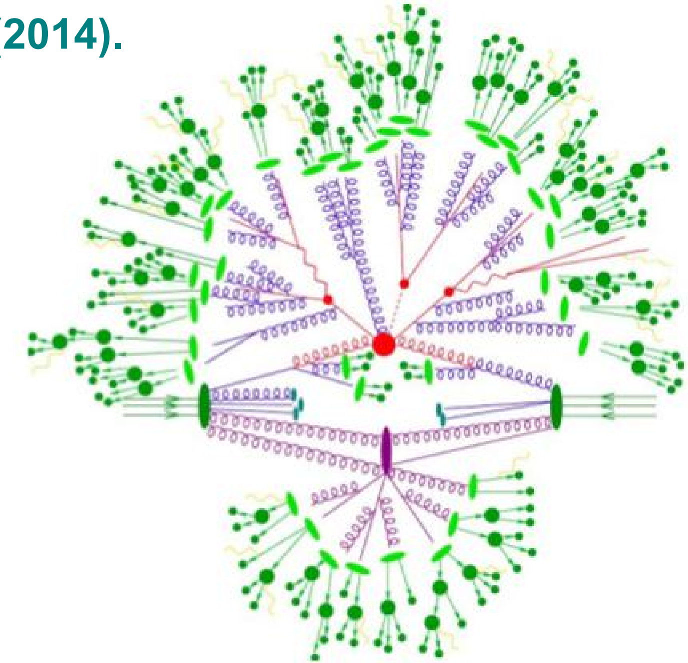
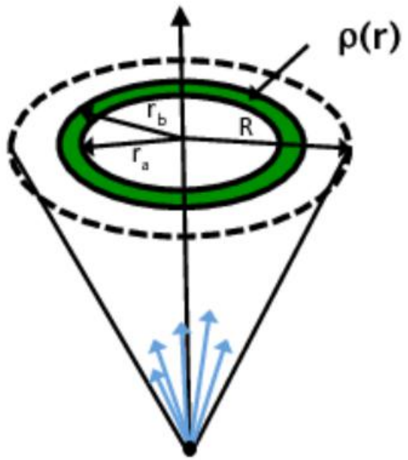
- **Jets:**
  - **A-A**: sensitive probe of nuclear modification.
  - **pp**: No suppression expected.
    However: soft and hard processes are related by MPI
    => jets can serve to study this connection



Radial jet profiles

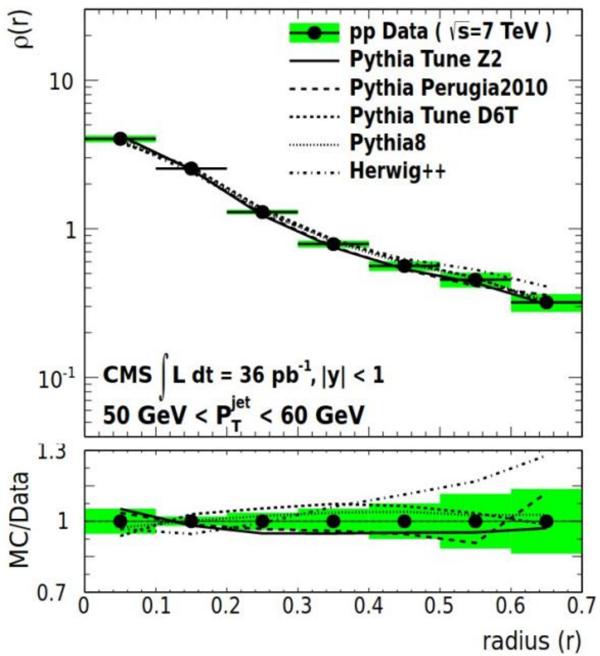
- Differential jet shape



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

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

CMS, JHEP 06, 160 (2012)



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

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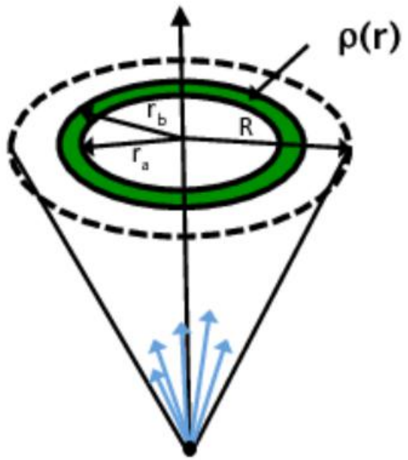

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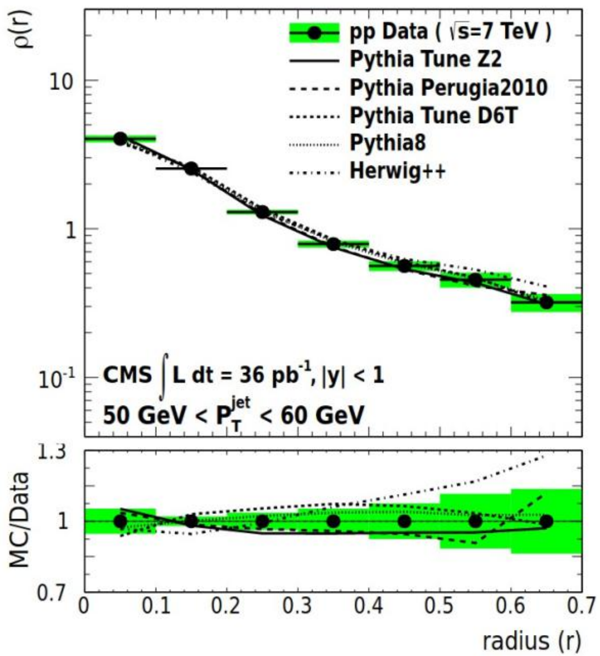
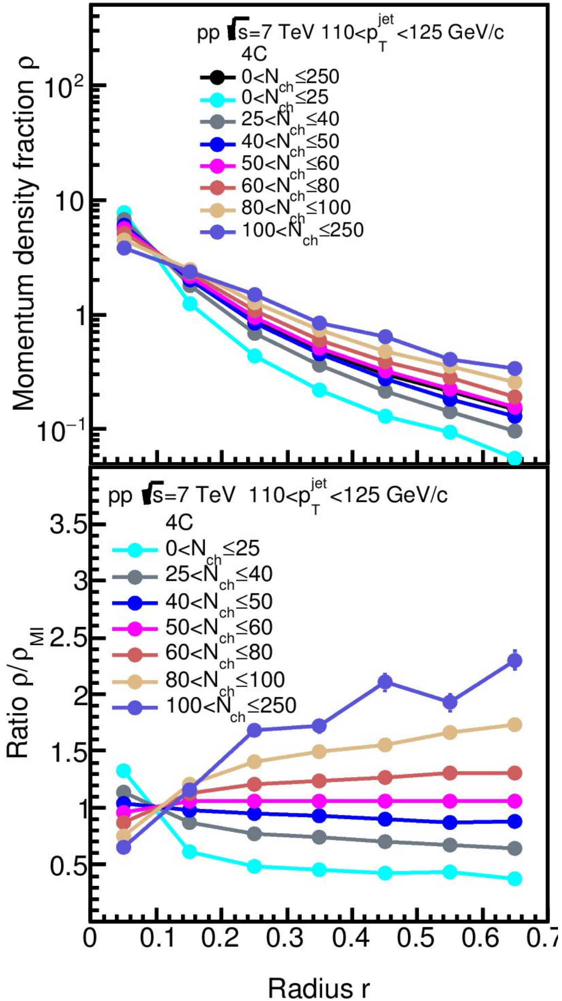


- CMS@LHC pp collisions, $\sqrt{s}$ = 7 TeV
- R=0.7 jets, 50<p_T^{jet}<60 GeV/c, $|y|$<1

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

More multiplicity classes



- PYTHIA 8.2 simulations (HardQCD)
  - pp collisions at $\sqrt{s}$ = 7 TeV
  - *R*=0.7 jets, 50<p_T^{jet}<60 GeV/*c*, |*y*|<1

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

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

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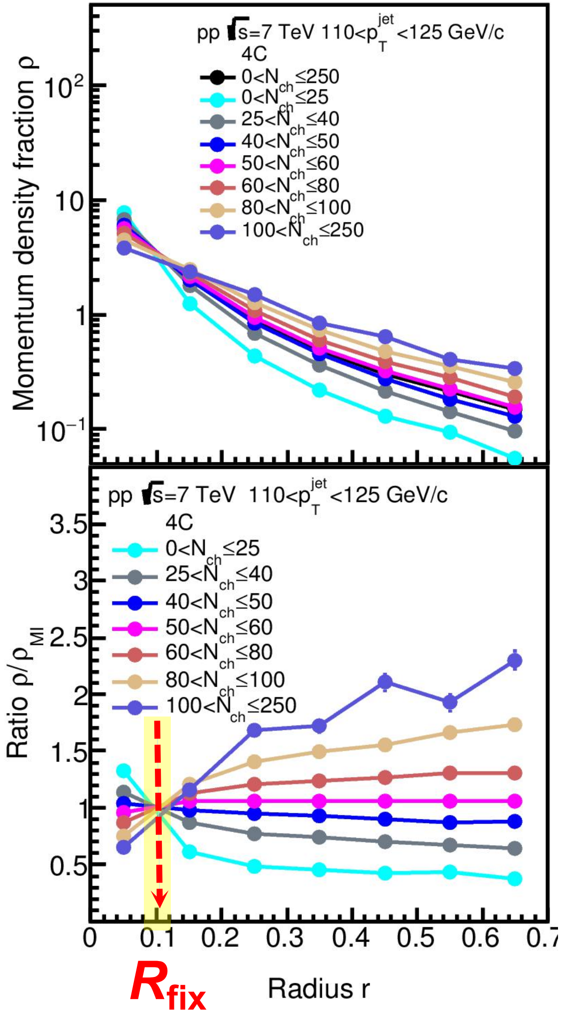
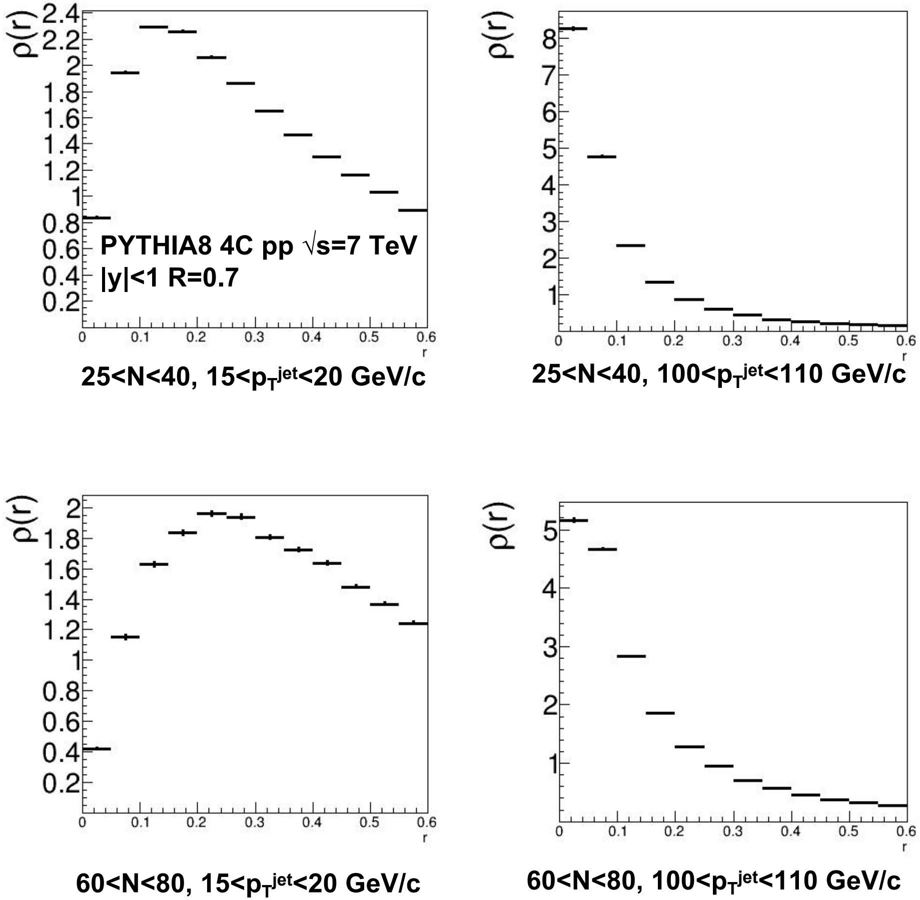


- PYTHIA 8.2 simulations (HardQCD)
  - pp collisions at $\sqrt{s}$ = 7 TeV
  - R=0.7 jets, 50<p_T^{jet}<60 GeV/c, |y|<1
- **7 multiplicity classes:**
  jet profile curves intersect at a given point R_{fix}
  in any given p_T^{jet} window
- ***R_{fix}* independent of**
  - **generator**: Pythia, Hijing++
  - **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^{jet}=400



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  - Jet radius: 12 bins up to r=0.6
  - Multiplicity 6 bins up to N=100
  - Momentum: 20 bins up to p_T^{jet}=400
- Statistically motivated distributions:
  - **Gamma distribution**

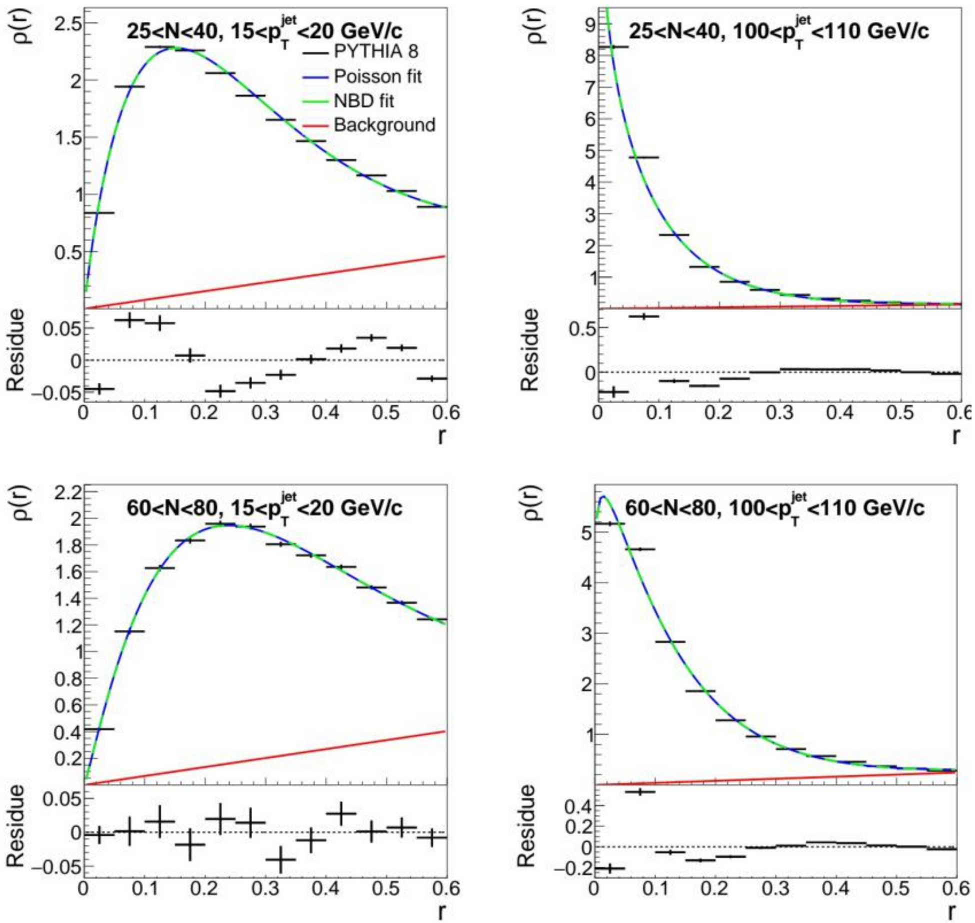
$$\rho(r)=Cr^{\gamma}e^{-\alpha r}$$

  - **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 ($p\to1$) and narrow-jet limit ($\gamma\to-1$), NBD reduces to a Gamma

- Simultaneous fit with a $\sim br$ background



arXiv:2008.08500

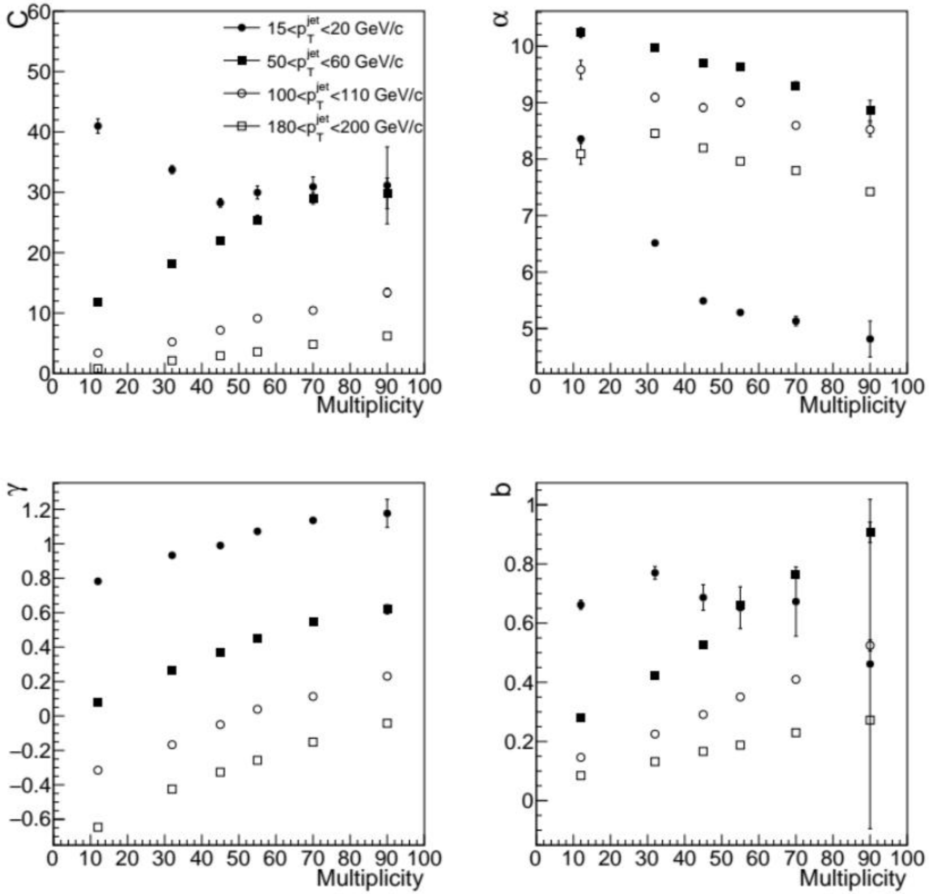
Parameters of the fits

- Gamma distribution with background

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

- Monotonic trends observable

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



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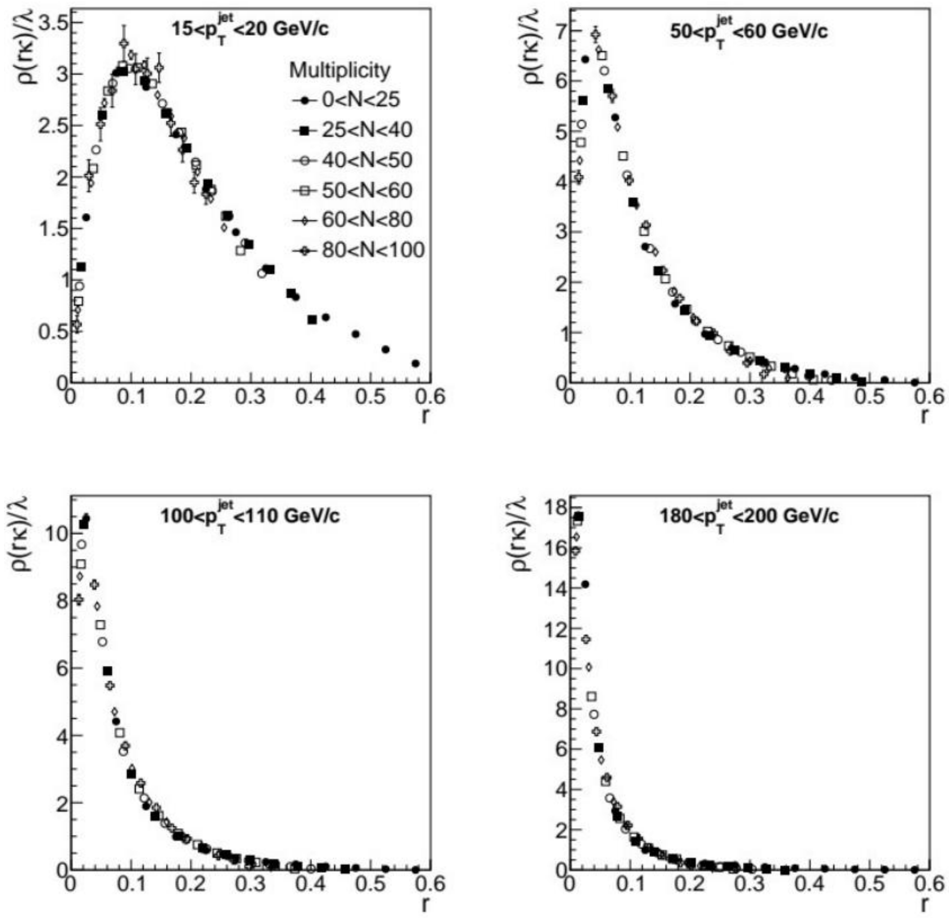
Scaling of the jet profiles

- 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



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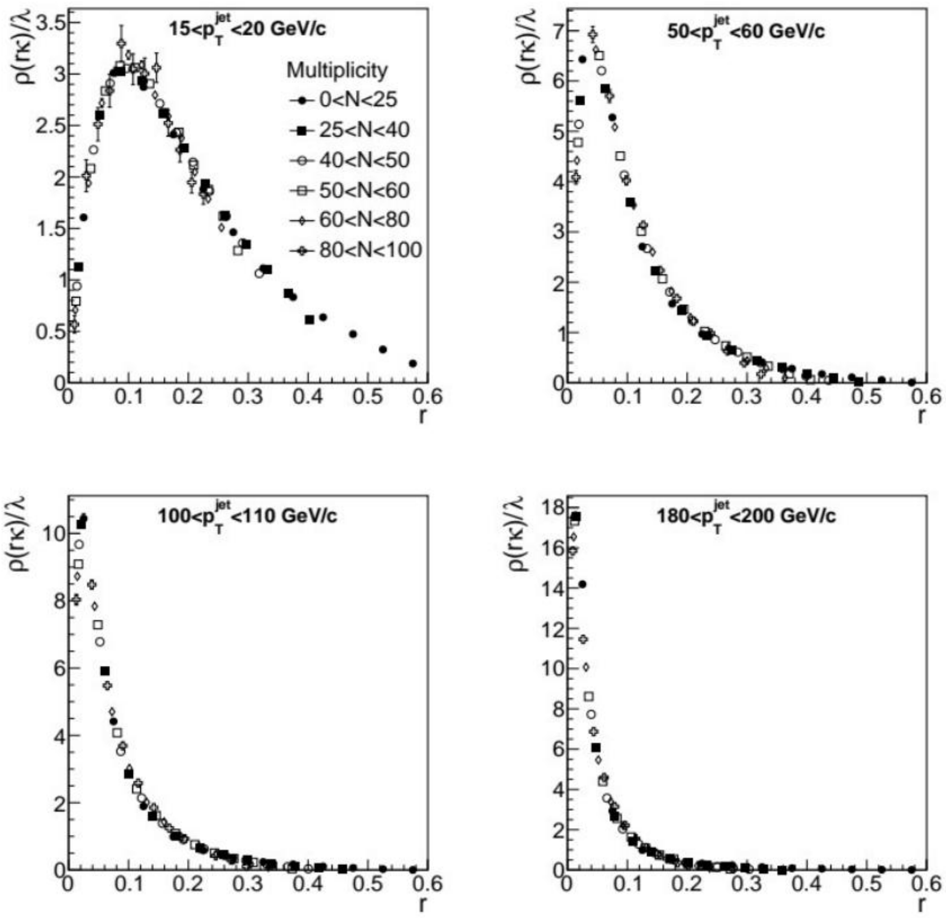
- **The scaling works within 5-10% in the peak region**



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Scaling factors

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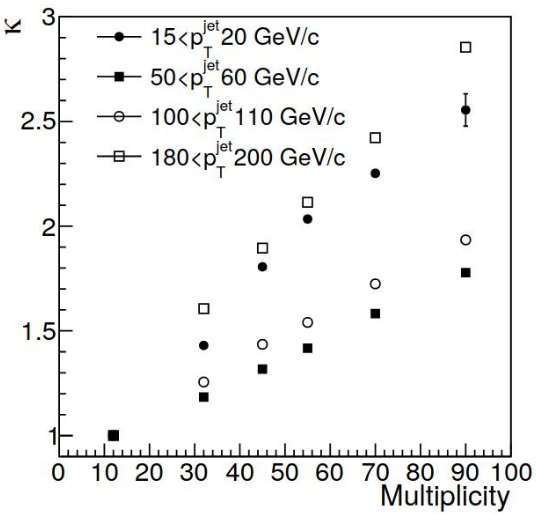
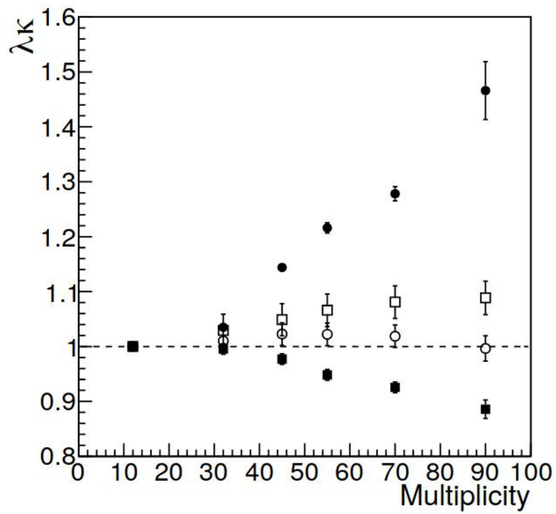




$$\rho_N(r) = \lambda(N) f\left(\frac{r}{\kappa(N)}\right)$$

- 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

How good are the fits?

arXiv:2008.08500

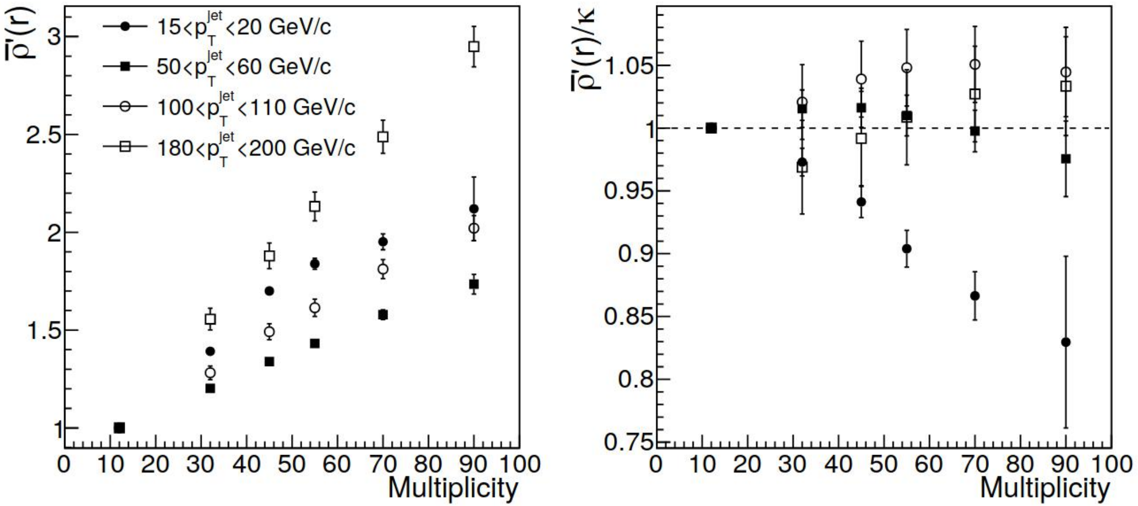
- Fitted distribution mean:

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

- Ideally, it shoud scale:

$$\kappa / \overline{\varrho}' \sim 1$$

where $\overline{\varrho}'$ is the rescaled mean



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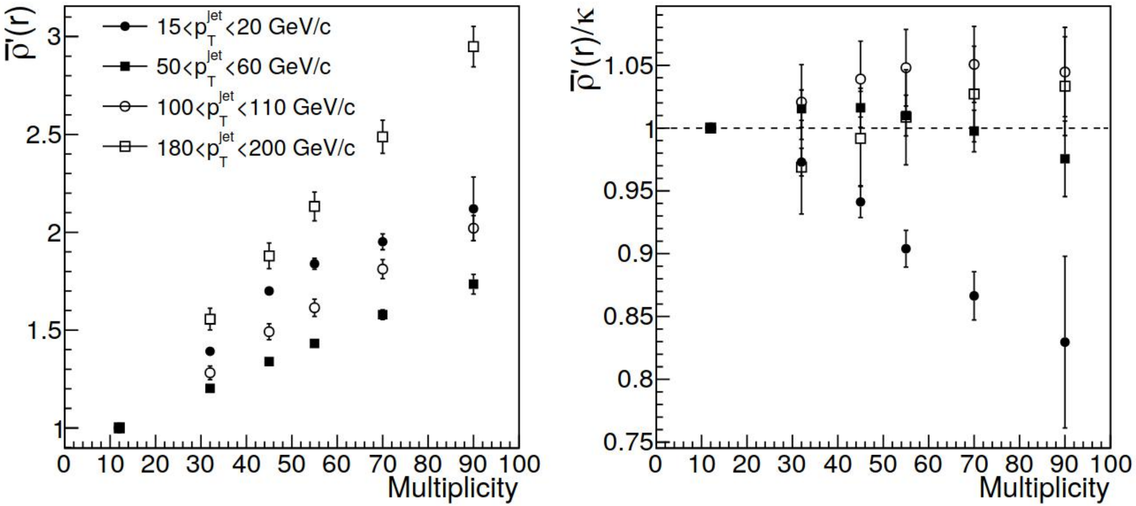
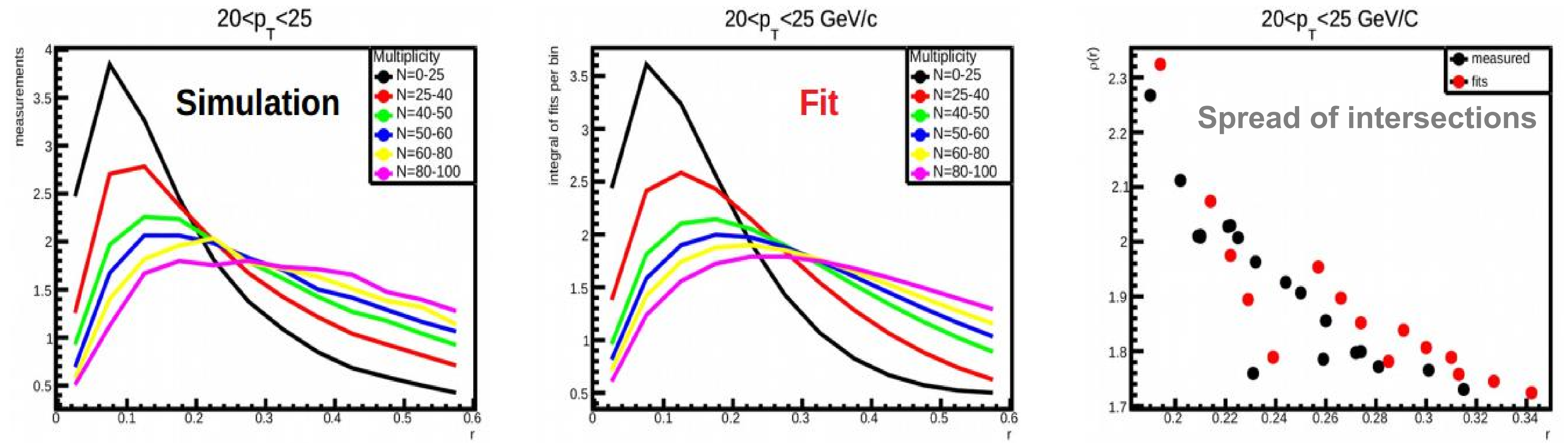


- The mean approximately scales linearly with multiplicity
- Except for the lowest p_T bin, $\kappa/\bar{\varrho}' \sim 1$ within 5%
- Hence,

» **Radial profiles scale with multiplicity**

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

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*

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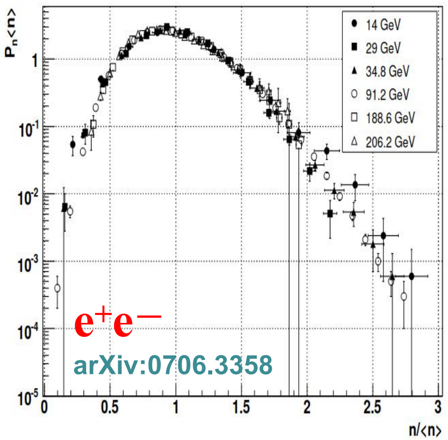
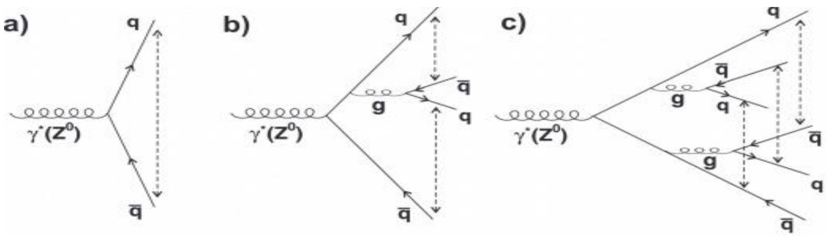
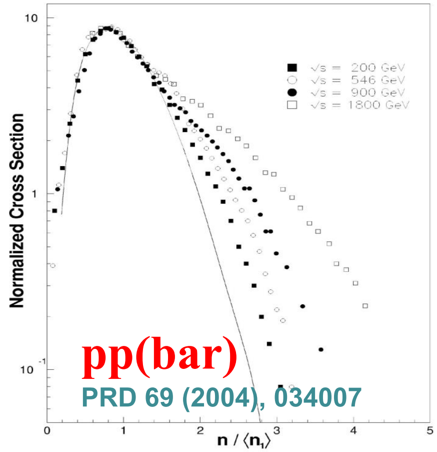
KNO-scaling and its violation

- KNO scaling: the multiplicity distribution scales with √*s*
  Koba-Nielsen-Olesen, NPB 40, 317 (1972); Polyakov, Sov.Phys.JETP 32, 296 (1971)
- The KNO scaling breaks down at high √*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







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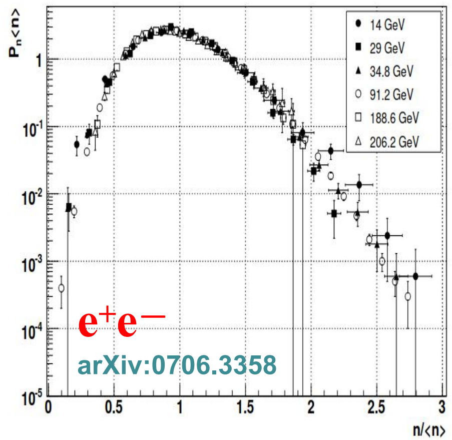
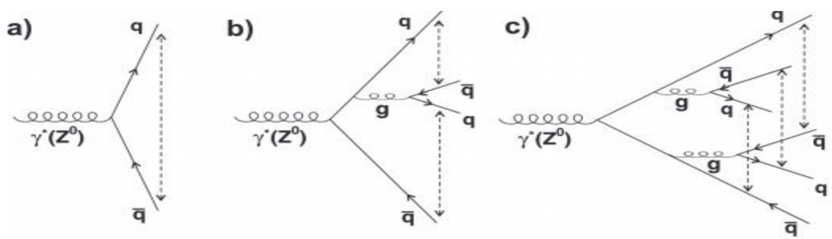
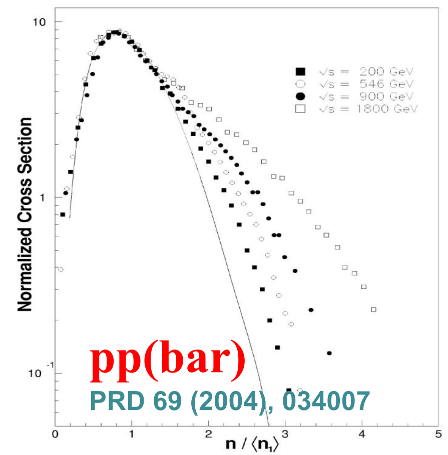
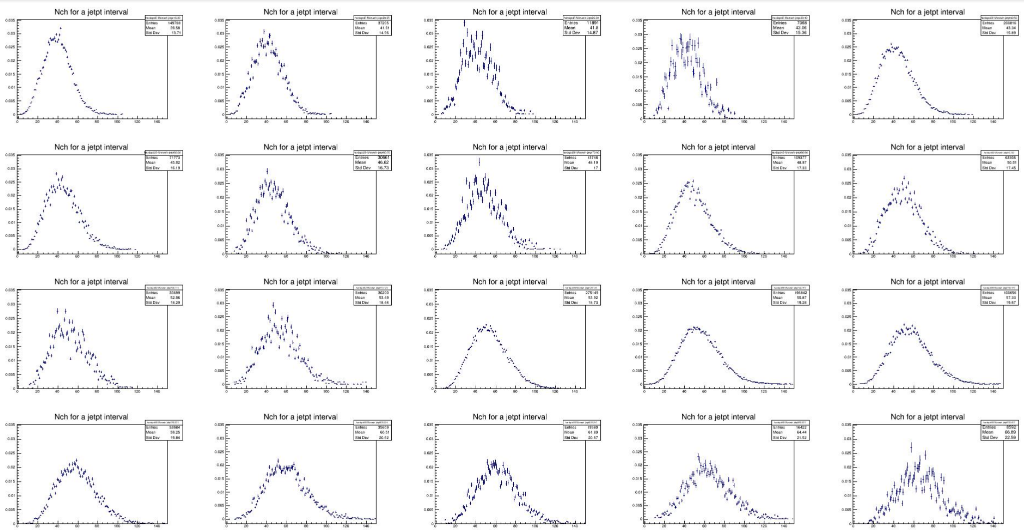


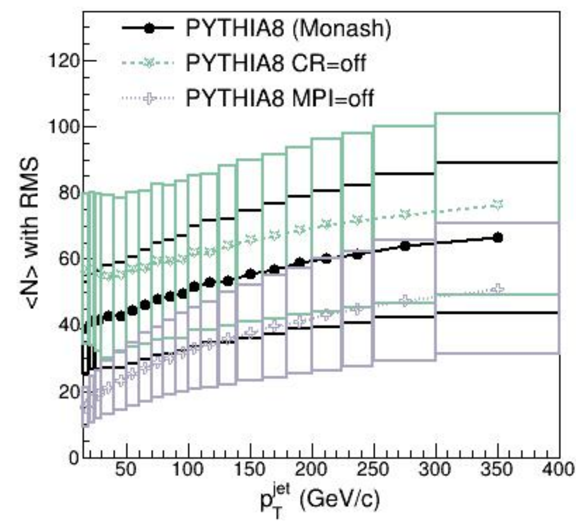




- **Is KNO-scaling valid within a single jet?**
- **How is affected by MPI and CR?**
- **Is there a connection of KNO to radial scaling?**

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





- Multiplicity (dominated by the jet multiplicity) vs. jet momentum p_T^{jet}

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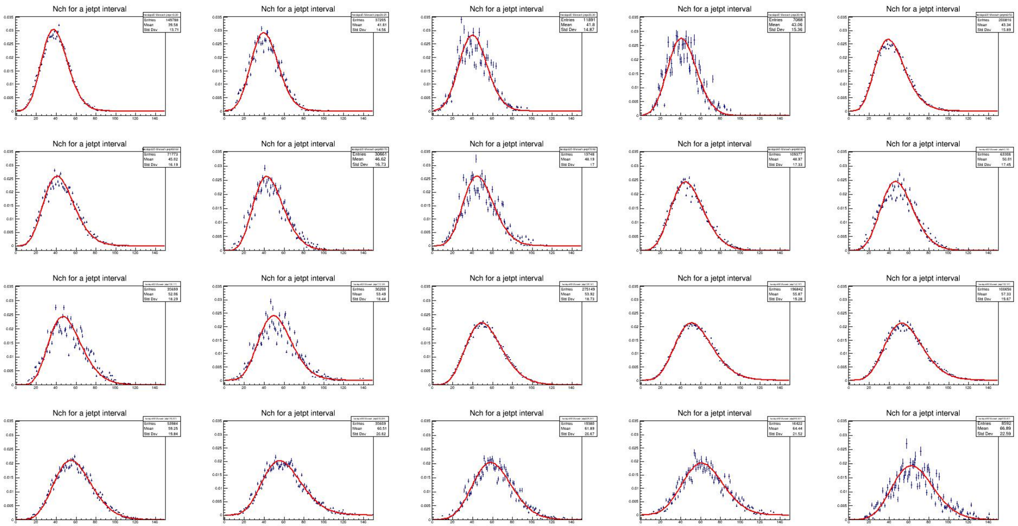

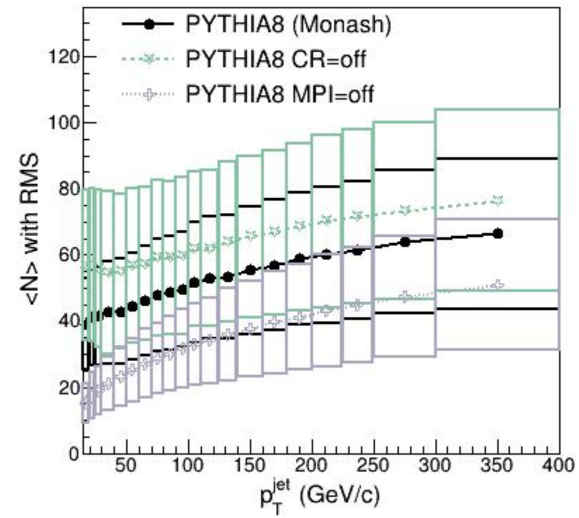

- Multiplicity (dominated by the jet multiplicity) vs. jet momentum p_T^{jet}
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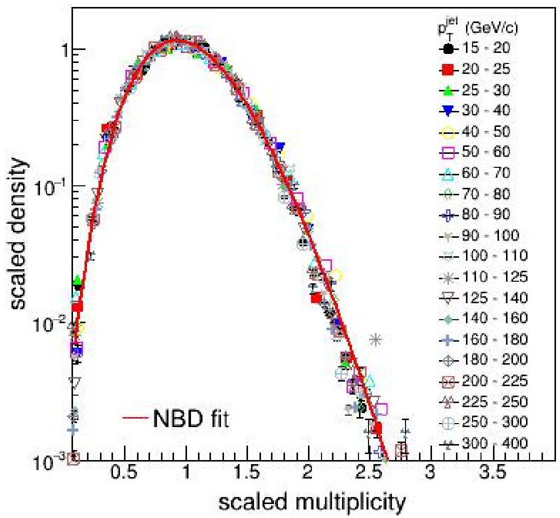
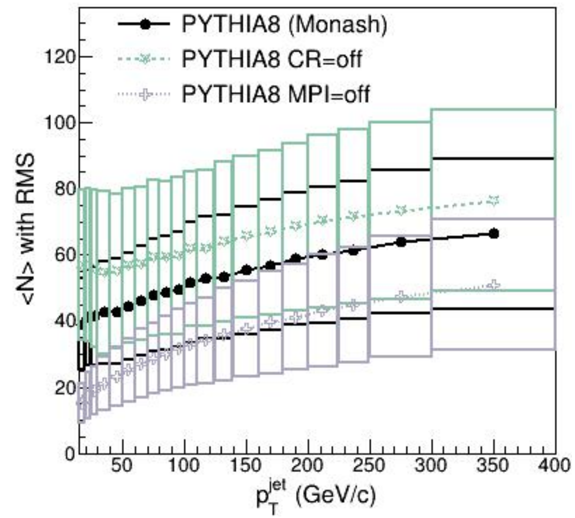




- Multiplicity (dominated by the jet multiplicity) vs. jet momentum p_T^{jet}
- Parametrized with a NBD $$P_N = \frac{\Gamma(Nk+a)}{\Gamma(a)\Gamma(Nk+1)} p^{Nk}(1-p)^a$$
- Distributions at all p_T^{jet} fit well on a single NBD curve
- **KNO-like scaling observed within a jet**
  - In the following we quantify how well it is fulfilled

Multiplicity vs. p_T^{jet}: moments

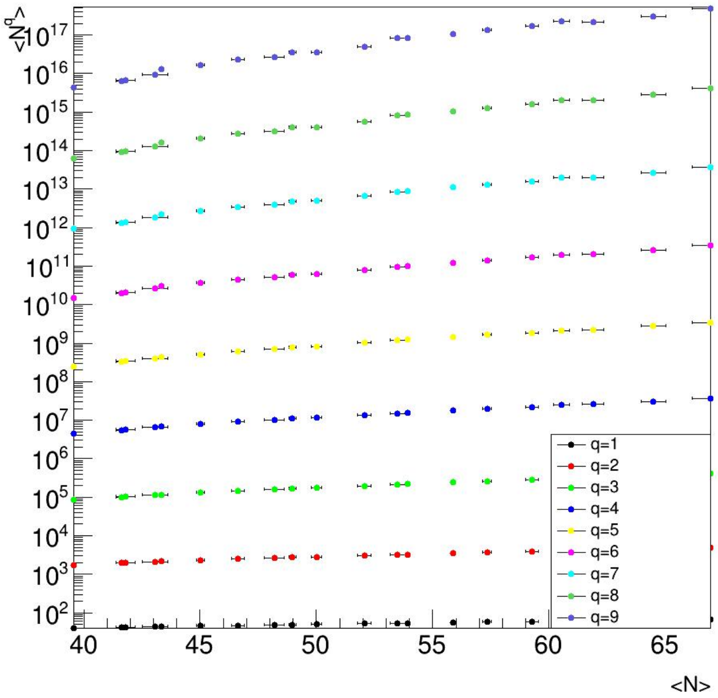
- q^{th} statistical moment

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

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

- Scaling:

$$\left\langle N^q(p_T^{jet}) \right\rangle = \lambda^q(p_T^{jet}) \left\langle N^q(p_0) \right\rangle \qquad \lambda(p_0) = 1$$



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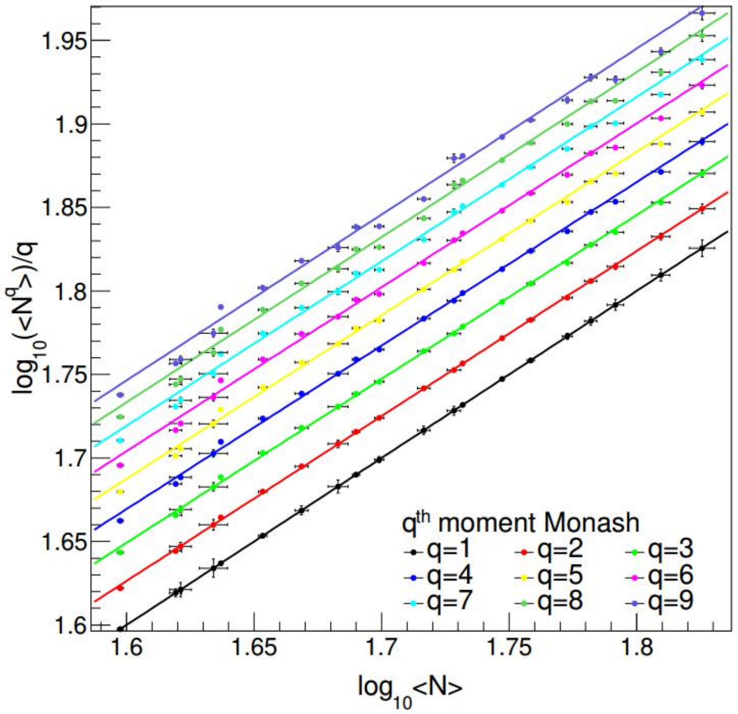
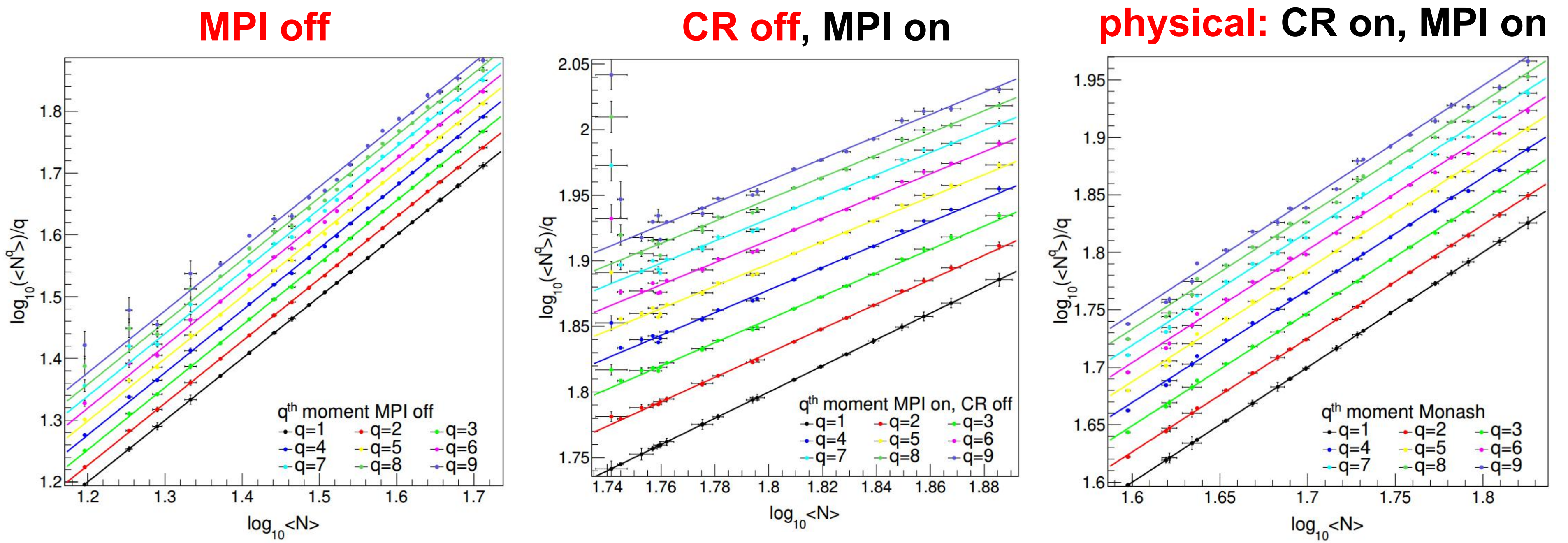


- log<N^q>/q vs. log<N> is a straight line with ~unity slope
  - up to the 9[th] moment

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

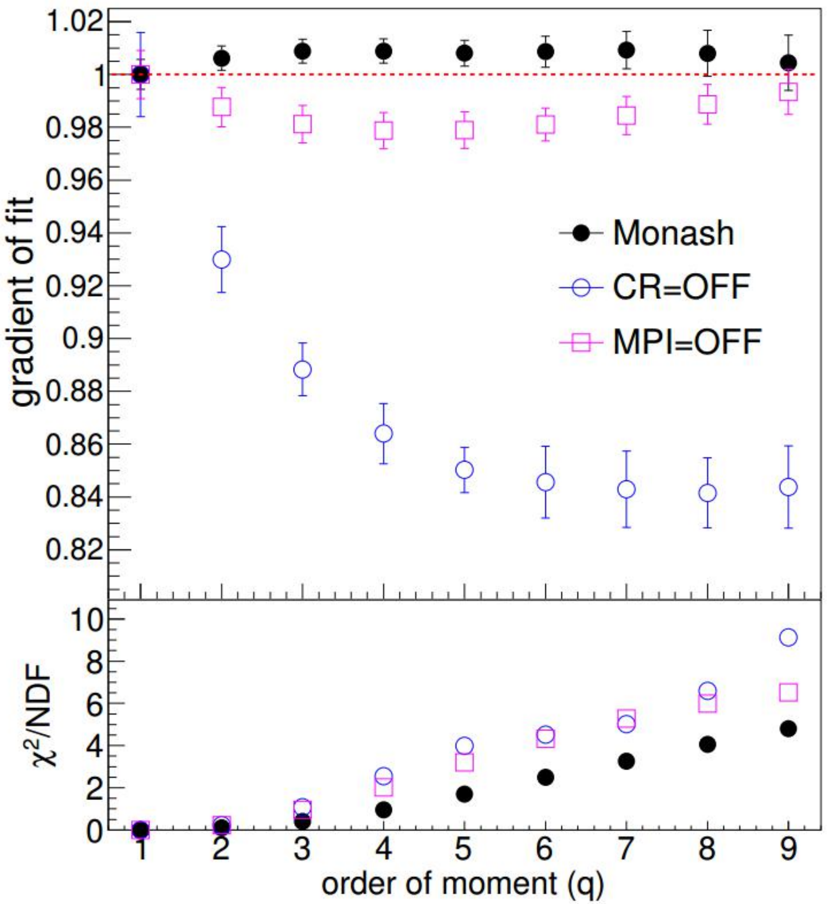
Moments: Role of MPI and CR



- **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 ~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 ~15%
- No MPI (also no CR by construction): Scaling is fulfilled to ~2%.
- All fits are statistically good (χ^2/NDF<8, ~proportional to the order of moment)



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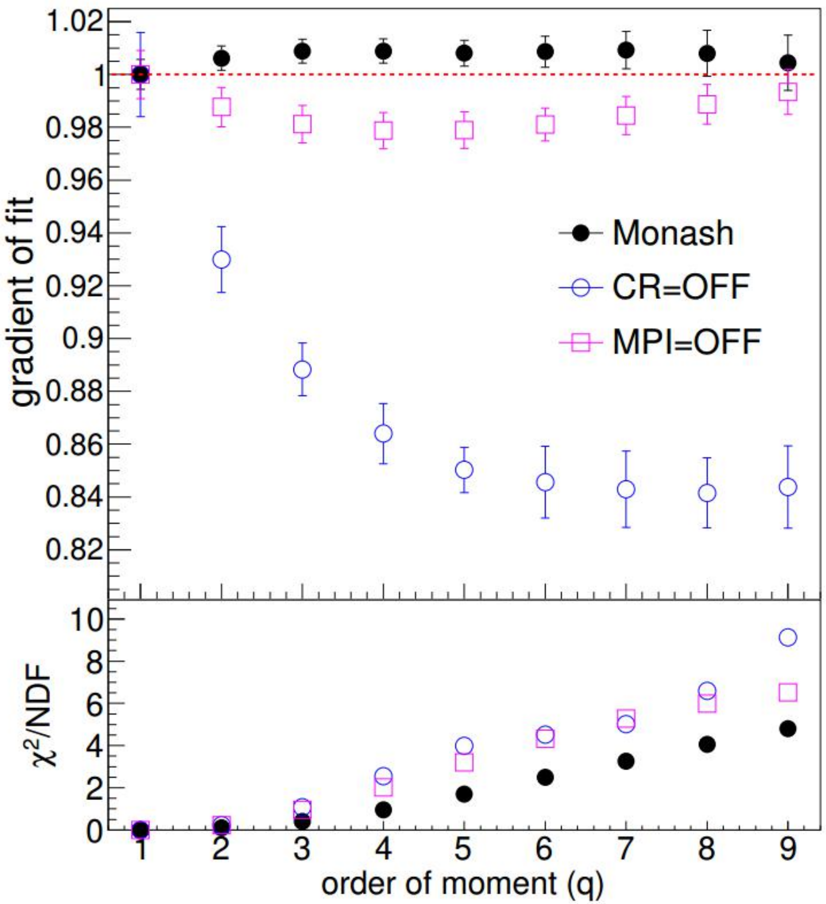
- **The emerging picture is different from that of radial profile scaling, which holds for CR=off as well**



Summary

- We observed scaling behavior in jets from 7 TeV pp collisions using MC
- **Radial jet-momentum profiles scale with multiplicity**
  - Profiles can be parametrized with a Gamma dist. and scale with event multiplicity
  - Scaling is present in a broad model class, regardless of settings (nPDF, CR, MPI settings, jet reconstruction, and even MC generator)
  - **Fundamental statistical / thermodinamical property of jet development?**
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- **KNO-like scaling within a jet**: scaling of multiplicities with jet momentum
  - 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.

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Scaling of the jet profiles - log scale

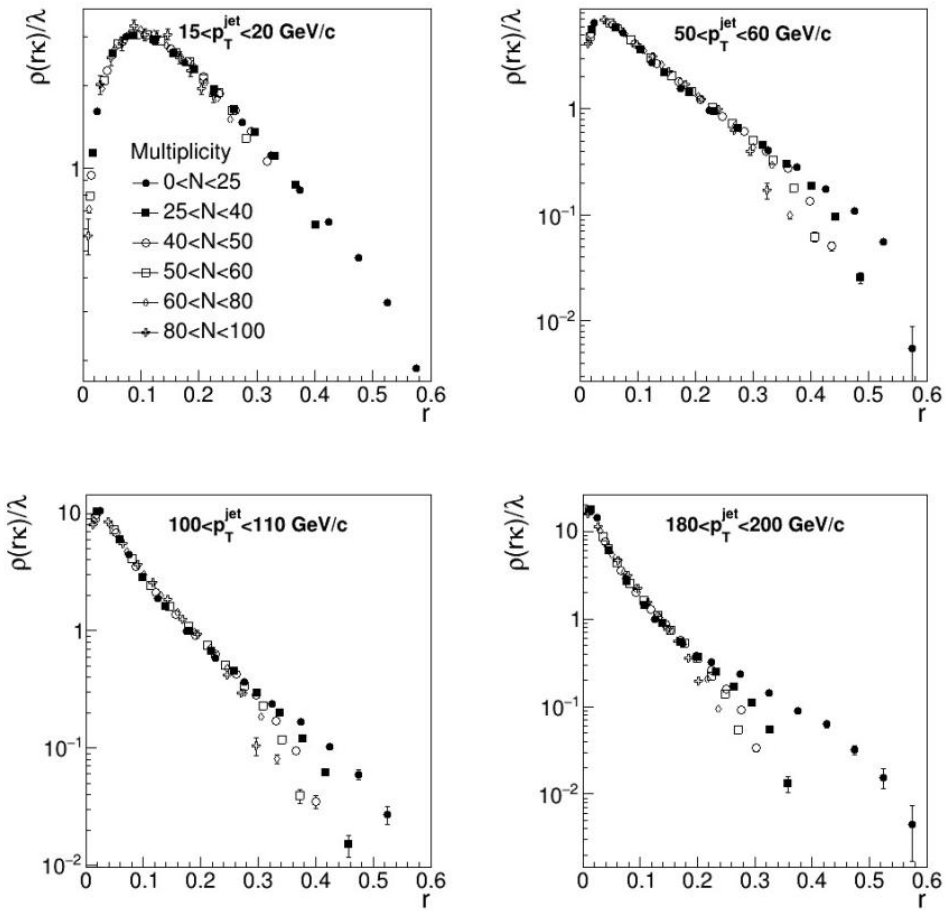
- Scaling assumption: profiles at all multiplicities collapse into a single distribution,

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

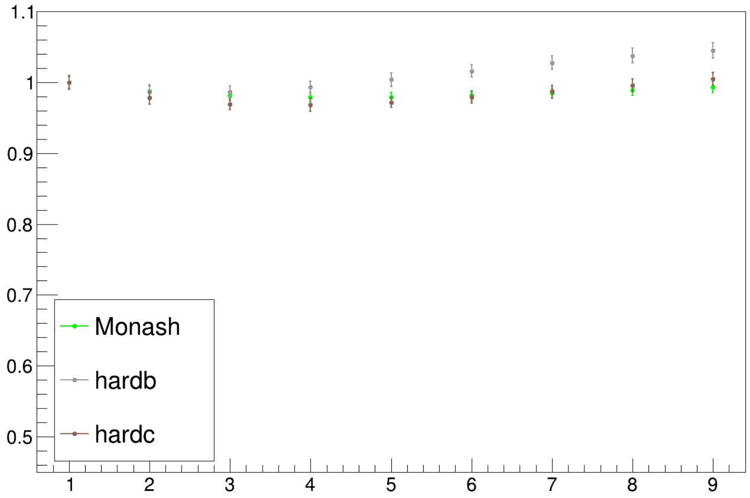
  Note: Ideally, $\lambda = 1/\kappa$, however...
  "leakage" (distribution is cut-off at high *r* before normalization)

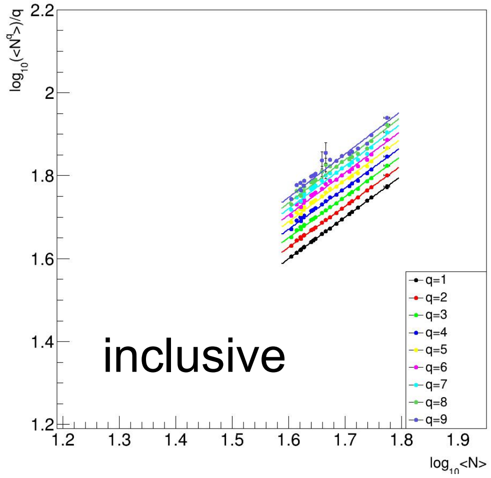
- Scaling is determined based on the Gamma distribution fits
  - Chosen "good" mid-multiplicity fits, then others scaled to it minimizing χ^2

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

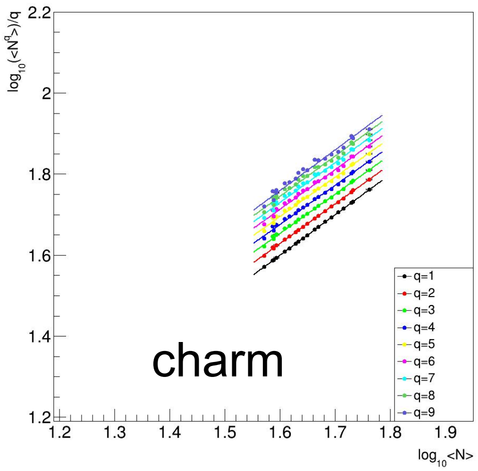


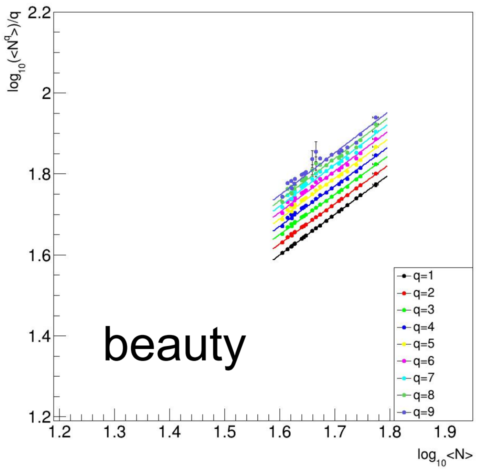
KNO-like scaling: Heavy Flavor



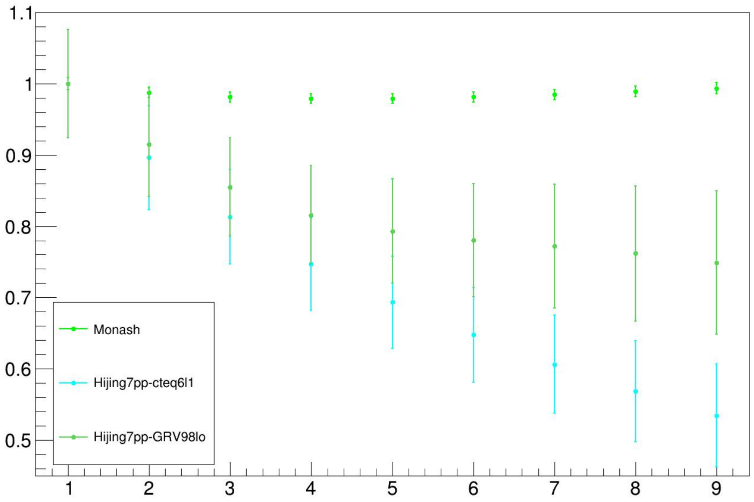


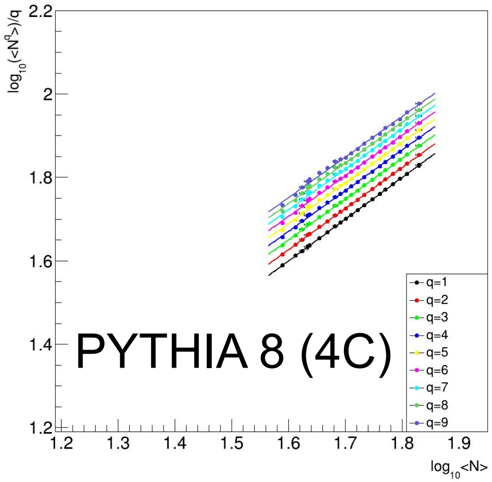
- Heavy-flavor jets also show KNO-like scaling



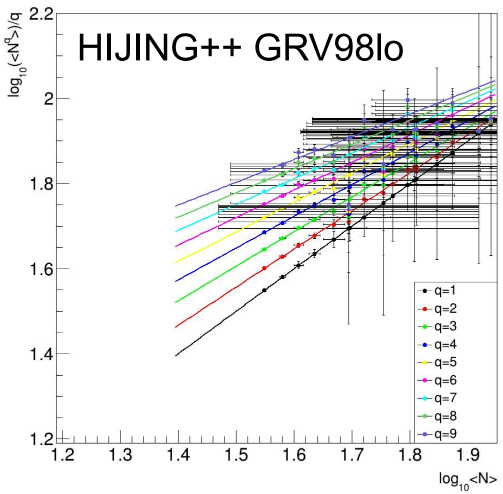


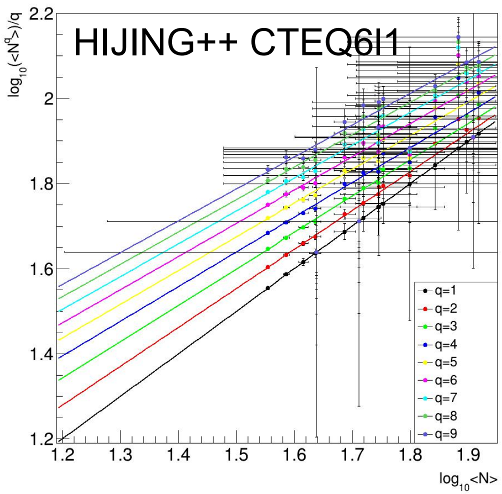
KNO-like scaling: Hijing++



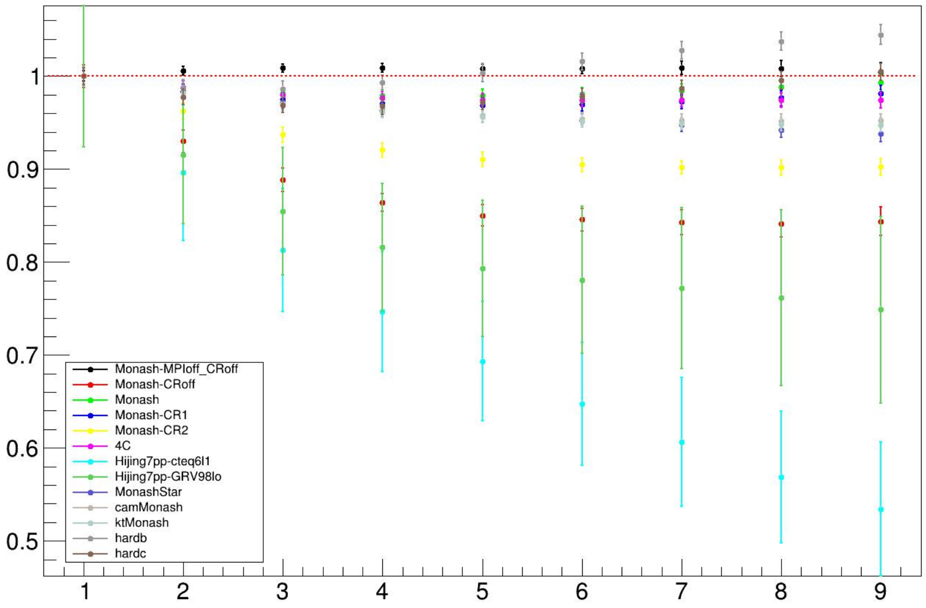


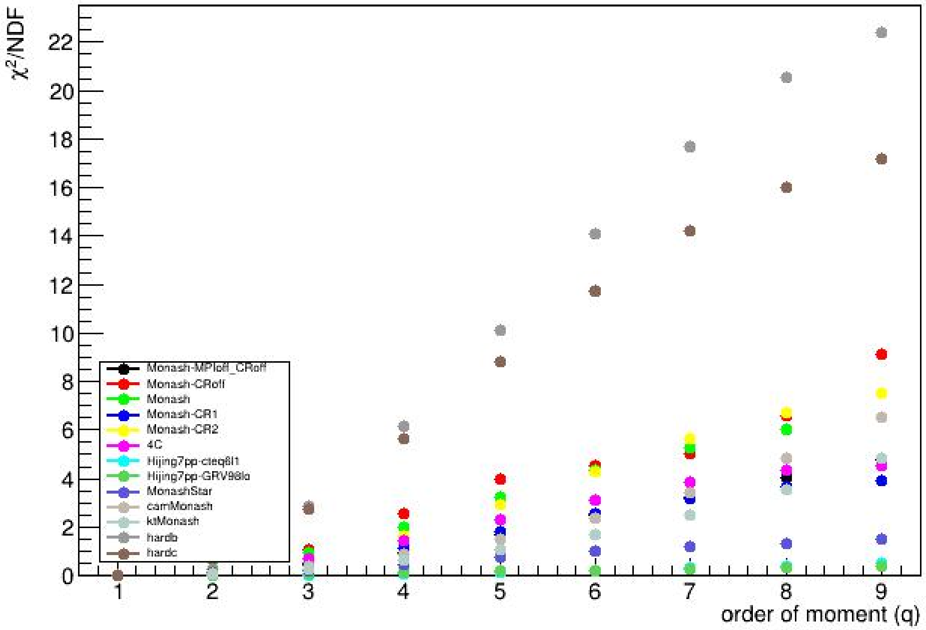
- Hijing++ does not exhibit the scaling



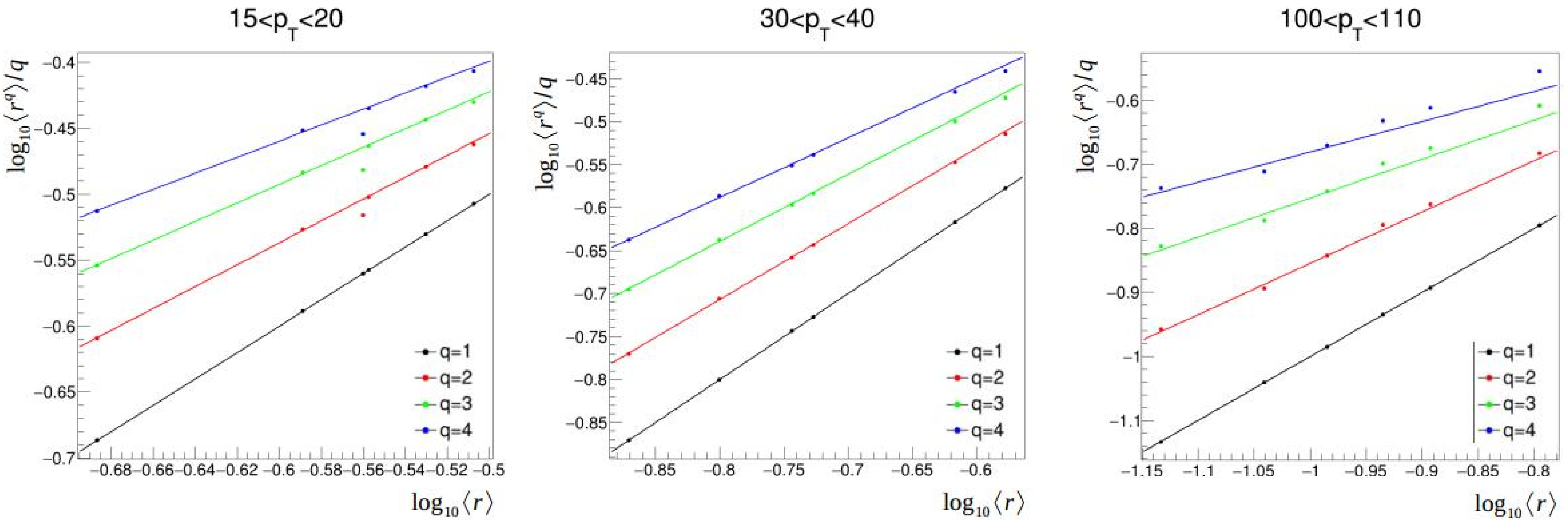


KNO-like scaling: summary



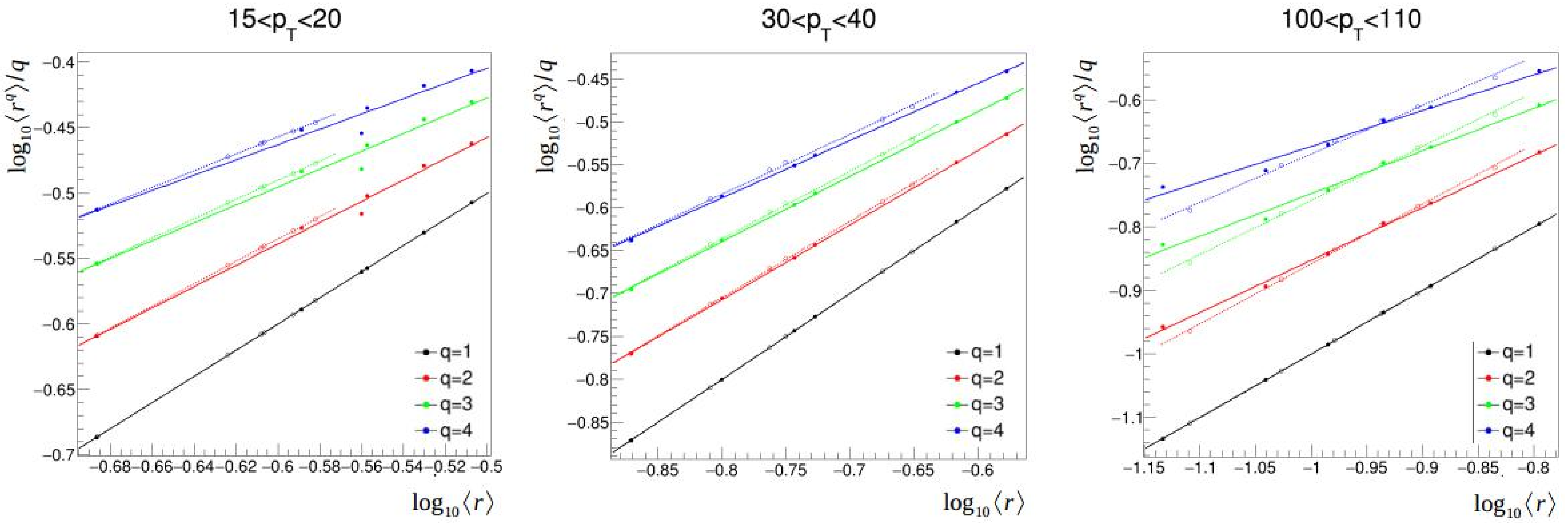


Statistical moments of jet profiles (Monash with MPI and CR)



The gradients are not 1, but it could be explained with the binning.

Effects of finite-size bins (jet profiles)



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