Scaling properties of jets in high-energy pp collisions

Róbert Vértesi[1,*], **Antal Gémes**[1,2], **Gergely Gábor Barnaföldi**[1] and **Gábor Papp**[3]

[1] Wigner Research Centre for Physics
Centre of Excellence of the Hungarian Academy of Sciences

[2] Trinity College, University of Cambridge

[3] Institute of Physics, Eötvös Loránd University

*vertesi.robert@wigner.hu

This work has been supported by the Hungarian NKFIH OTKA FK131979 as well as the NKFIH 2019-2.1.11-TÉT-2019-00078, 2019-2.1.11-TÉT-2019-00050, 2019-2.1.6-NEMZKI-2019-00011, 2020-1.2.1-GYAK-2020-00013 grants and THOR Cost Action CA15213.

Outline

- Scaling of jet-momentum profiles with multiplicity
  - **arXiv:2008.08500**
- KNO-like scaling within a jet in pp collisions
  - **arXiv:2012.01132**

Outline

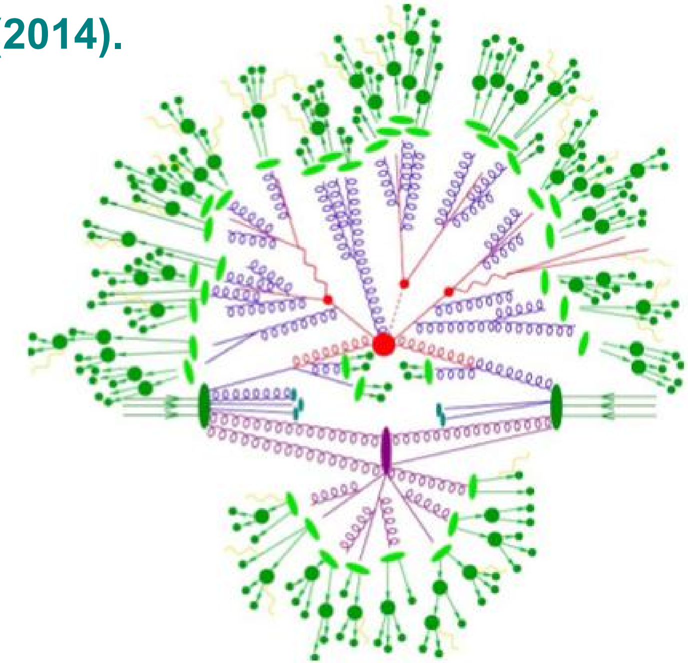
- Scaling of jet-momentum profiles with multiplicity
  - **arXiv:2008.08500**
- KNO-like scaling within a jet in pp collisions
  - **arXiv:2012.01132**

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)**

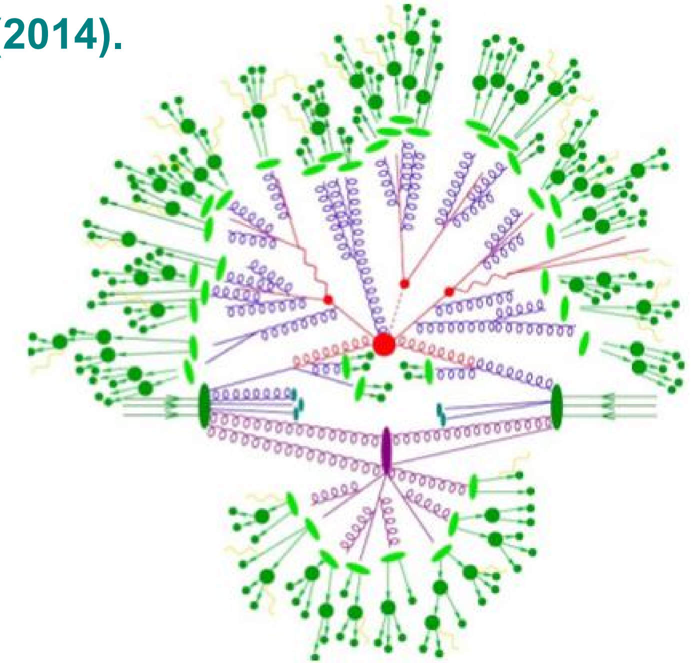
    eg. **Schlichting, arXiv:1601.01177**
  - and **color reconnection (CR)** [model element]

    eg. **Ortiz-Bencédi-Bello, J.Phys.G 44 (2017)**



Motivation

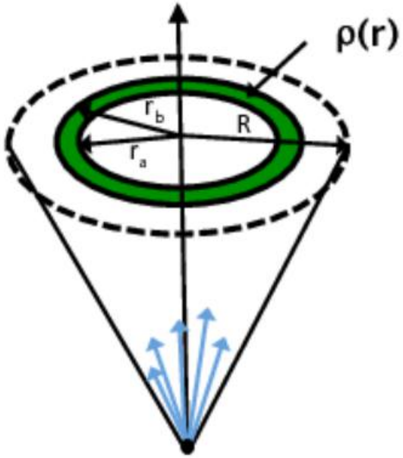
- **Collectivity in small systems with high-multiplicity at LHC**
  - Substantial v_n , eg. **Yan-Ollitrault, PRL 112, 082301 (2014).**
- Current understanding:
  - QGP is not necessary for collectivity
  - Vacuum-QCD effects at the soft-hard boundary: for instance **multiple-parton interactions (MPI)**
    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



Radial jet profiles

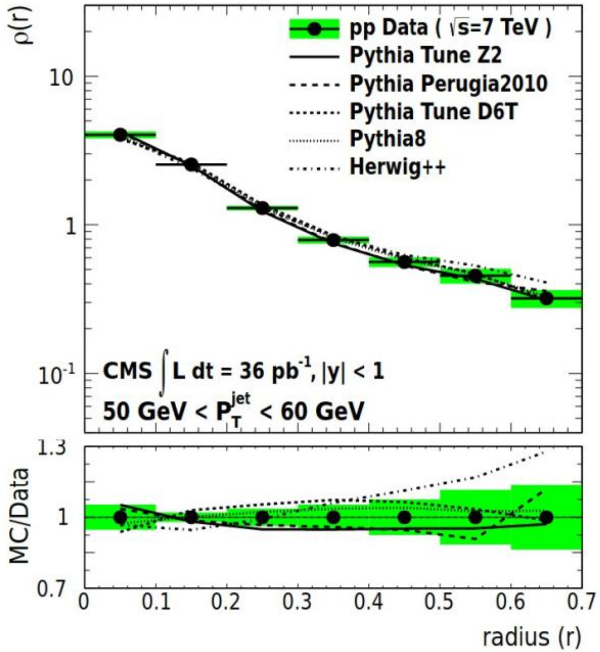
- Differential jet shape

CMS, JHEP 06, 160 (2012)



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

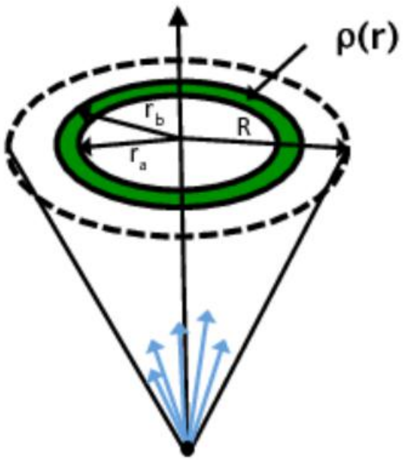
$$r_i = \sqrt{(\phi_i-\phi_{jet})^2+(\eta_i-\eta_{jet})^2}$$



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

Radial jet profiles

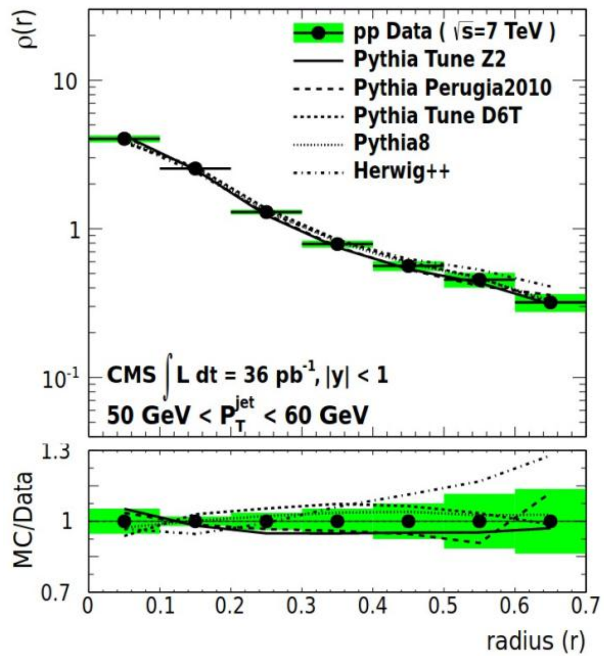
- Differential jet shape



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

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

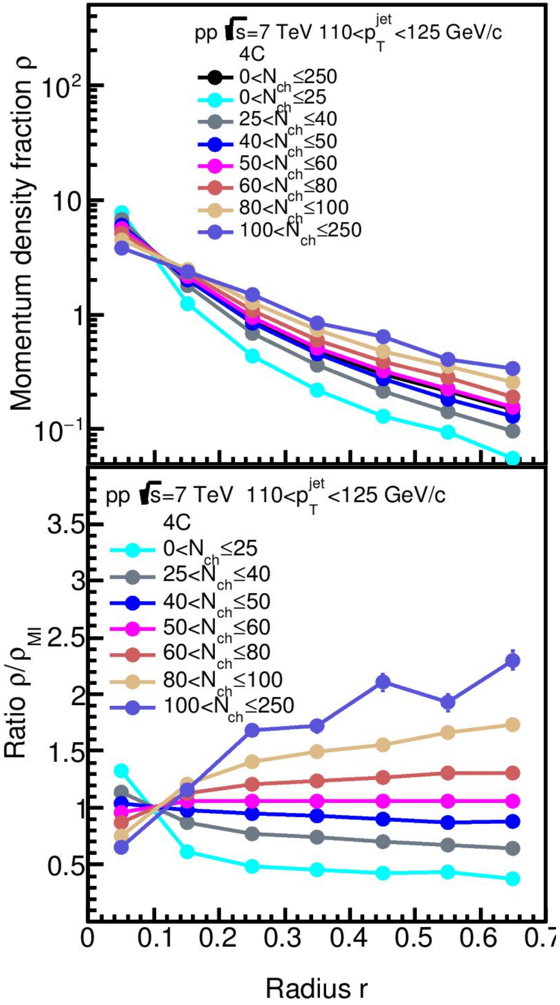
CMS, JHEP 06, 160 (2012)



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

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

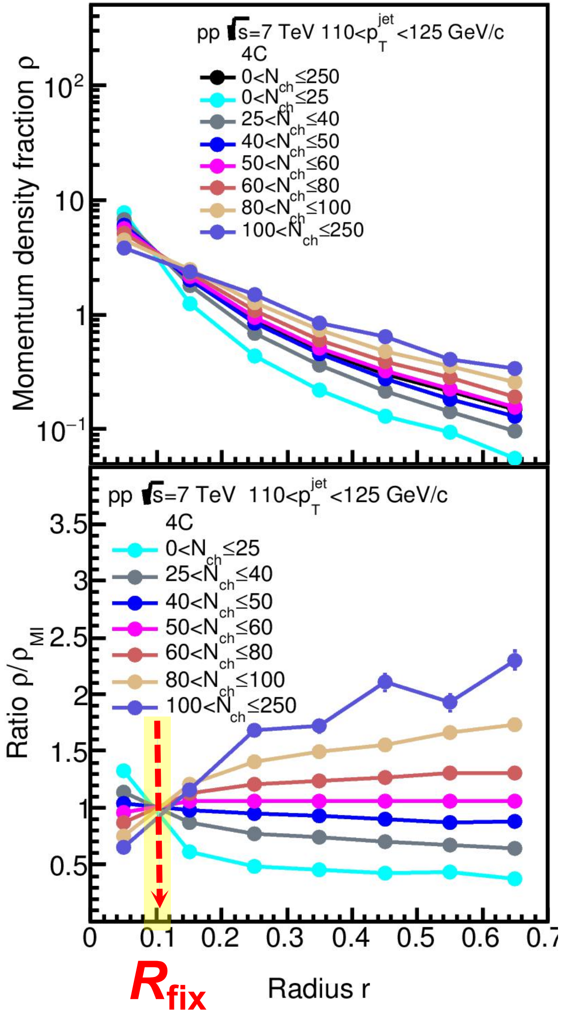
More multiplicity classes



- 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)**

More multiplicity classes

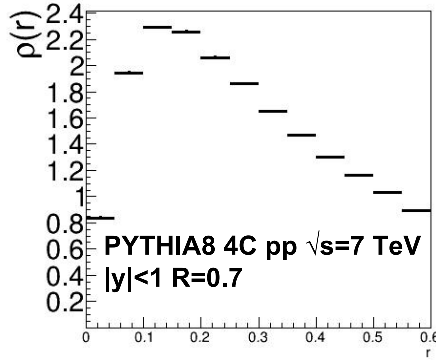


- PYTHIA 8.2 simulations (HardQCD)
  - pp collisions at √s = 7 TeV
  - *R*=0.7 jets, 50<p_T^{jet}<60 GeV/*c*, |*y*|<1
- **7 multiplicity classes:**
  jet profile curves intersect at a given point R_{fix}
  in any given p_T^{jet} window
- ***R_{fix}* independent of**
  - **generator**: Pythia, Hijing++
  - **tune**: 4C, Monash, Monash*
  - **nPDF** sets
  - **CR** scheme or **MPI**
  - **jet algorithm**: anti-k_T, C/A, k_T
- **Is it a scaling behavior?**

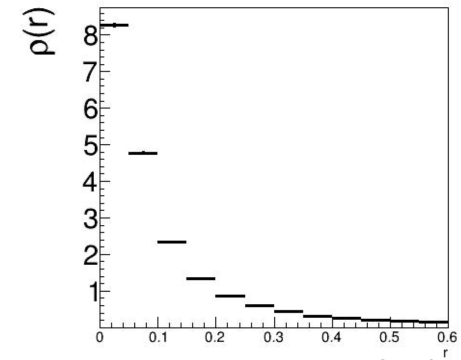
Z. Varga, R.V, G.G.B,
Adv.HEP 2019, 6731362 (2019)

Parametrizing the jet profiles

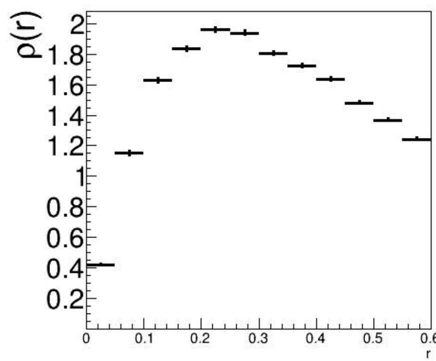
- Detailed PYTHIA 8 simulations (4C)
  - Jet radius: 12 bins up to r=0.6
  - Multiplicity 6 bins up to N=100
  - Momentum: 20 bins up to p_T^{jet}=400



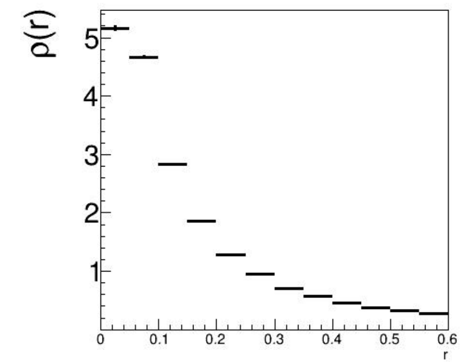
25<N<40, 15<p_T^{jet}<20 GeV/c



25<N<40, 100<p_T^{jet}<110 GeV/c



60<N<80, 15<p_T^{jet}<20 GeV/c



60<N<80, 100<p_T^{jet}<110 GeV/c

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
- Statistically motivated distributions:
  - **Poissonian distribution**

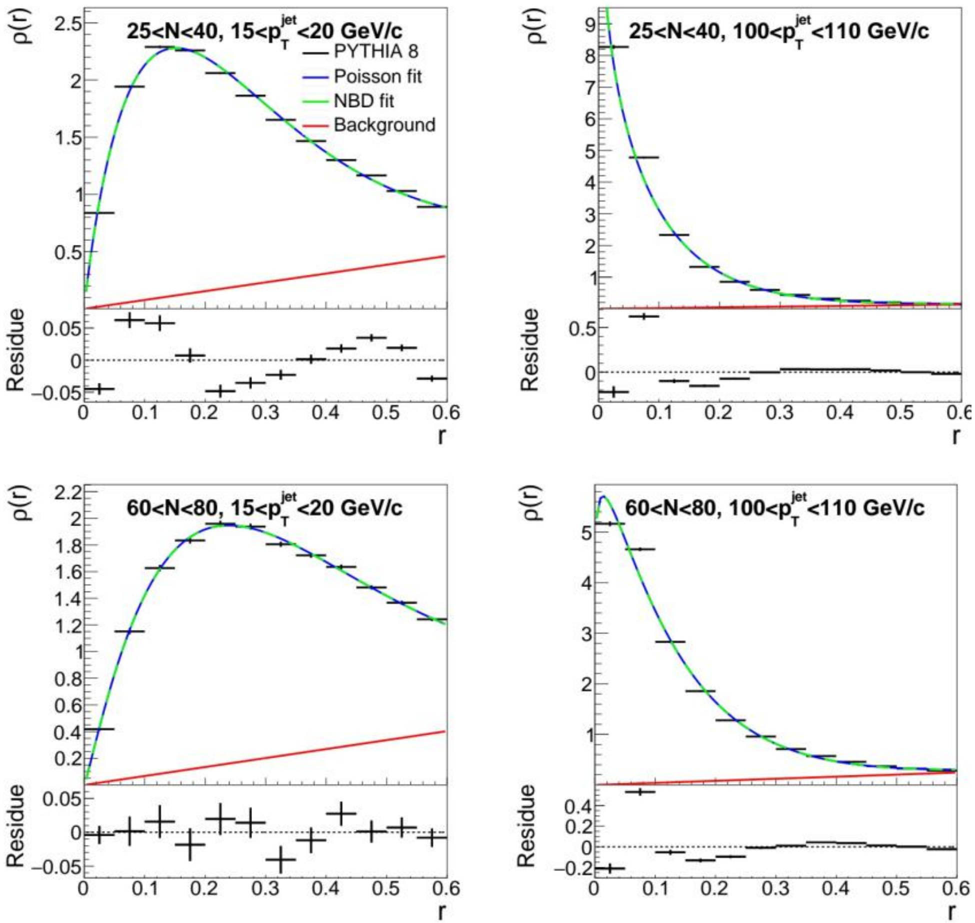
$$\rho(r) = C r^{\gamma} e^{-\alpha r}$$

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

- Simultaneous fit with a $\sim br$ background



arXiv:2008.08500

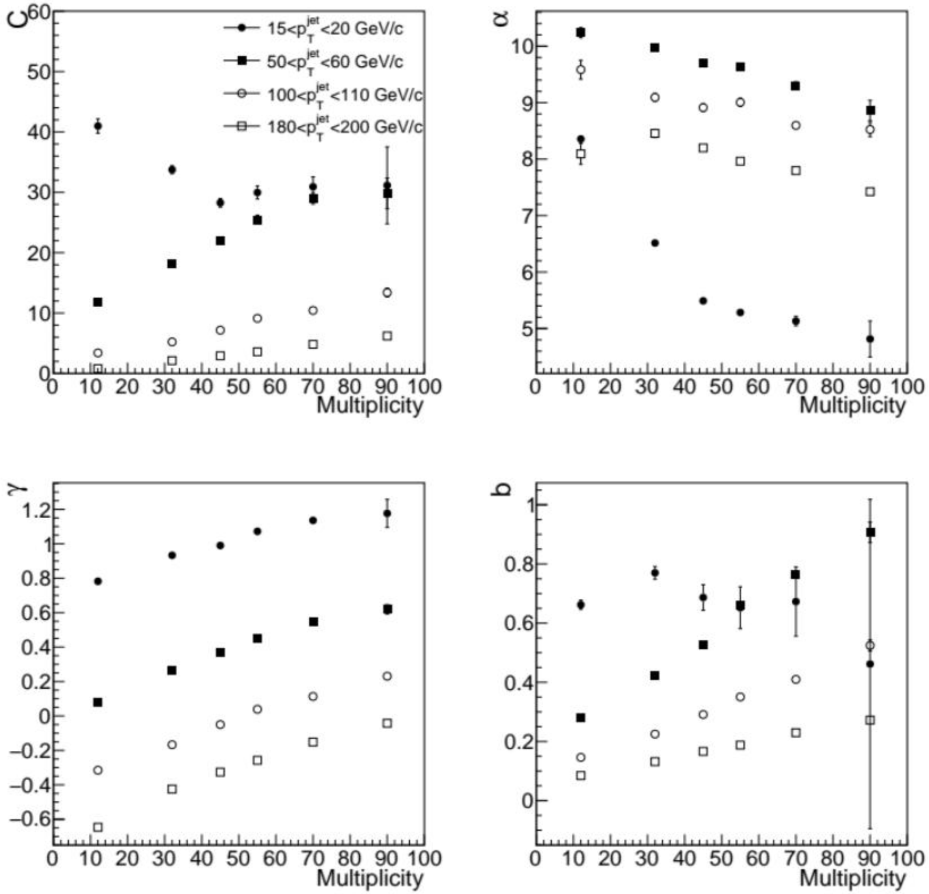
Parameters of the Poissonian fits

- Poissonian with background

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

- Monotonic trends observable

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



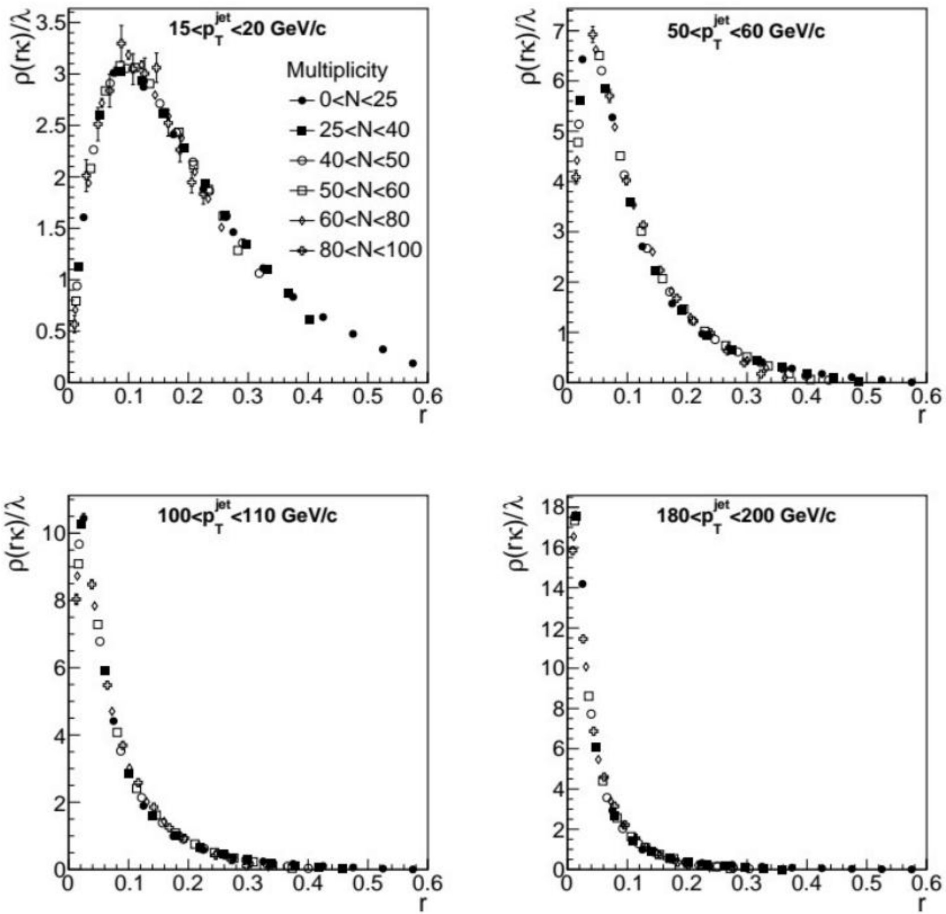
arXiv:2008.08500

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



arXiv:2008.08500

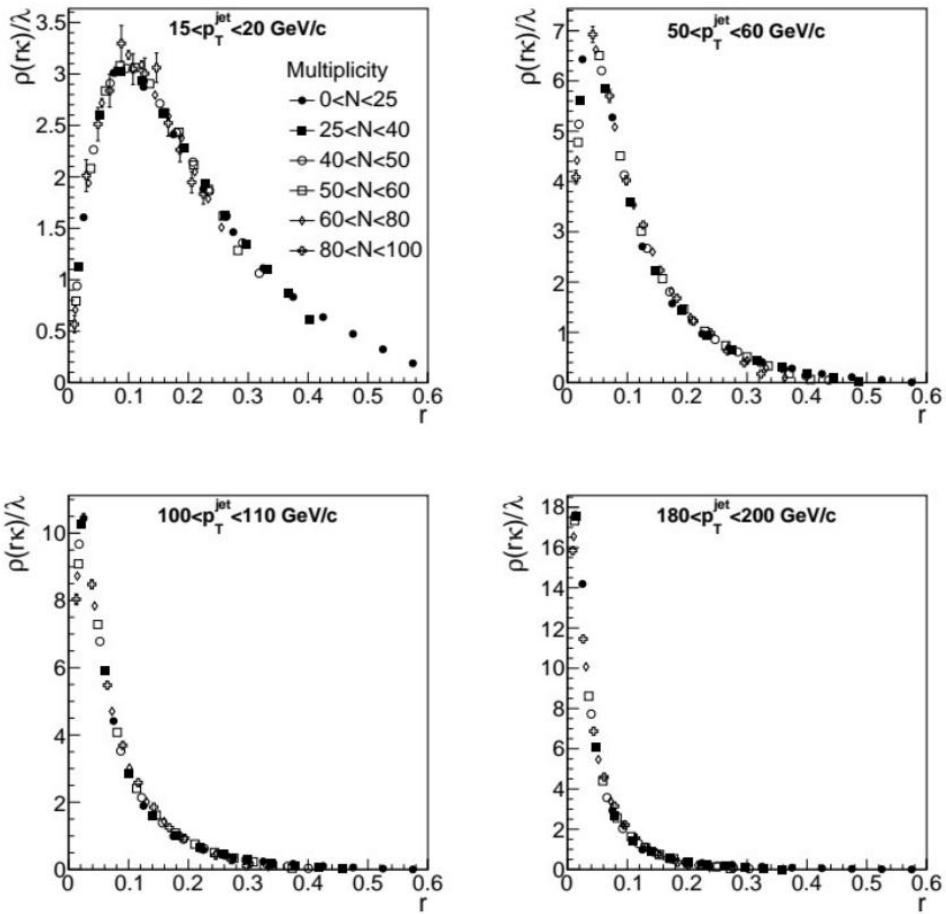
Scaling of the jet profiles

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

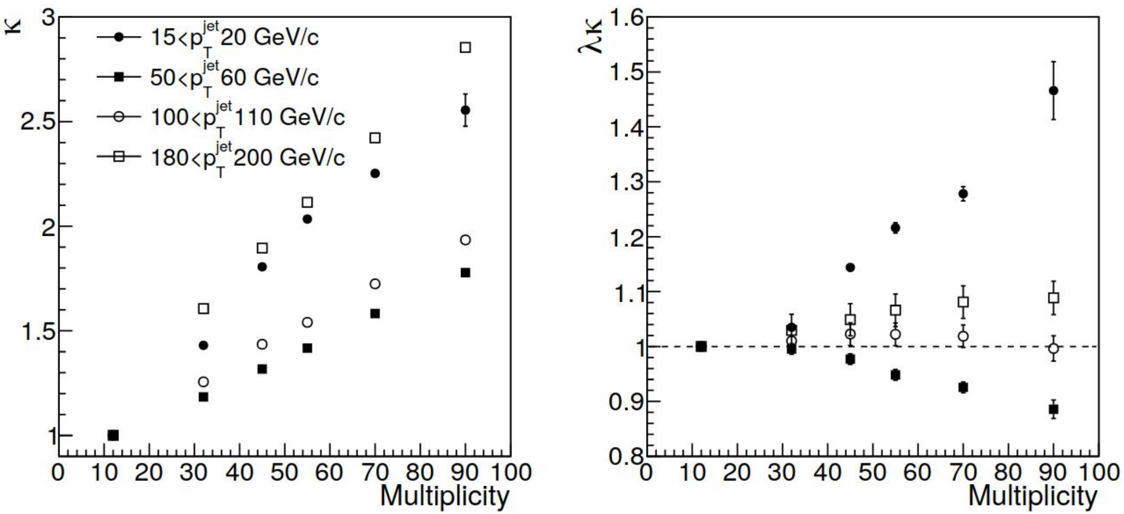
- **The scaling works within 5-10% in the peak region**



arXiv:2008.08500

Scaling factors

arXiv:2008.08500



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

- 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 Poisson fits?

- Poissonian mean:

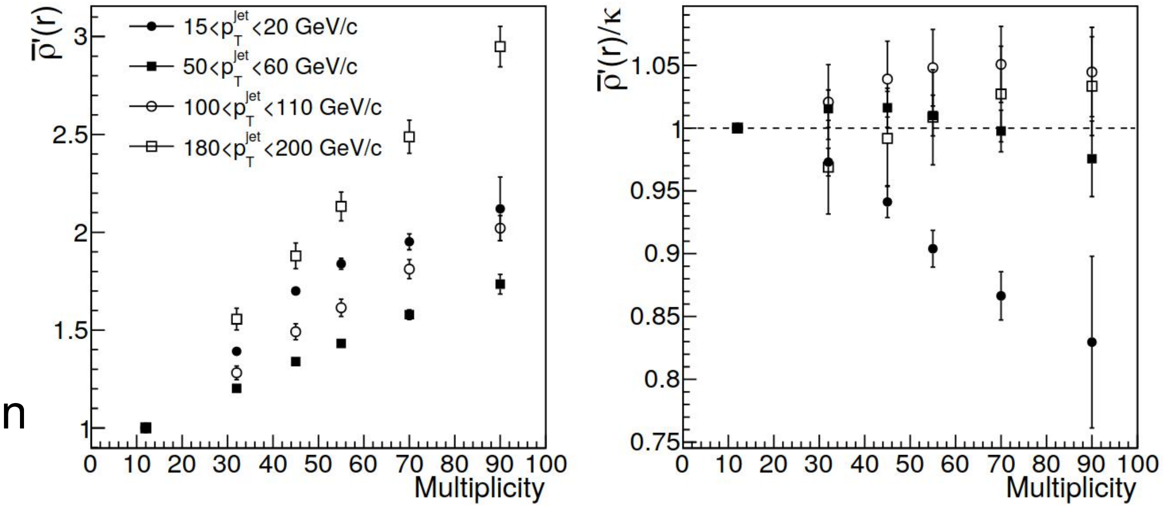
$$\bar{\rho}(r) = \frac{\gamma + 1}{\alpha}$$

- Ideally, it shoud scale:

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

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

arXiv:2008.08500



How good are the Poisson fits?

arXiv:2008.08500

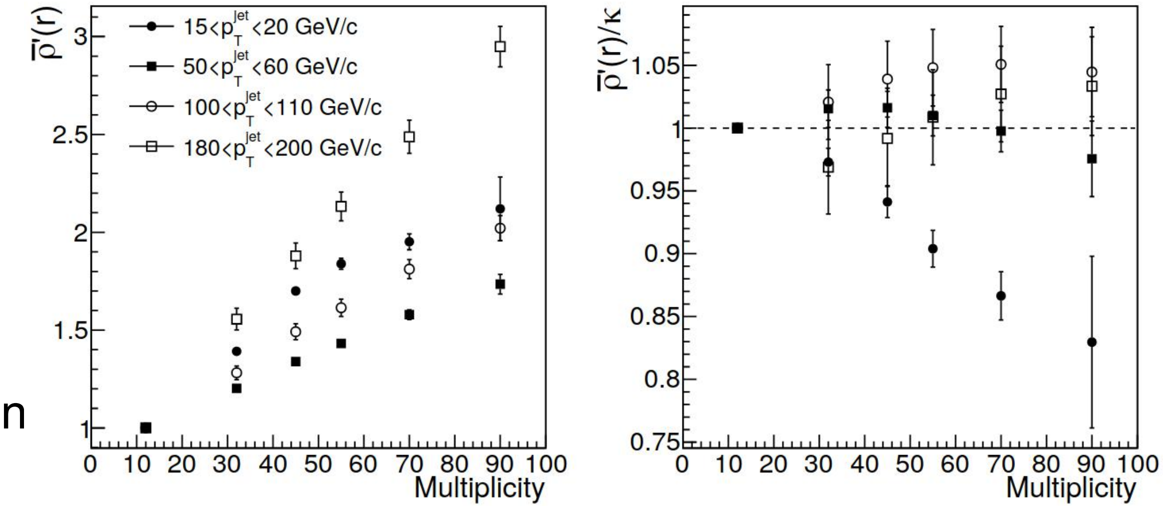
- Poissonian mean:

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

- Ideally, it shoud scale:

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

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

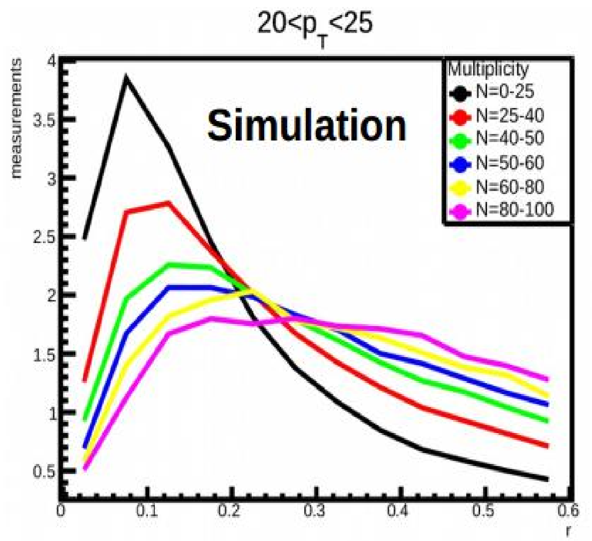


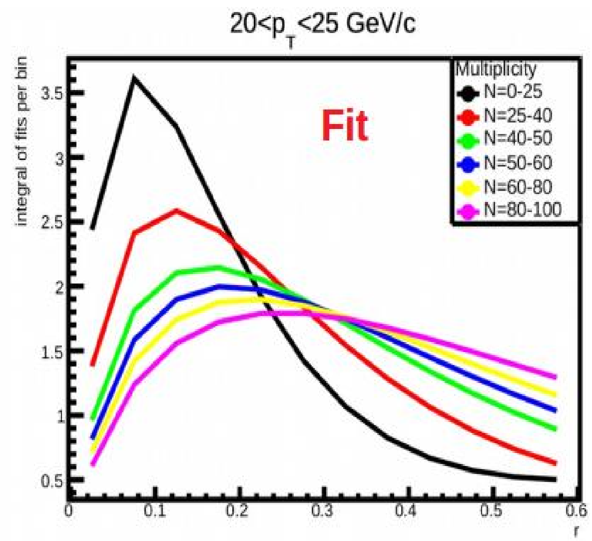
- The mean approximately scales linearly with multiplicity
- Except for the lowest p_T bin, $\kappa/\overline{\varrho}' \sim 1$ within 5%
- Hence,

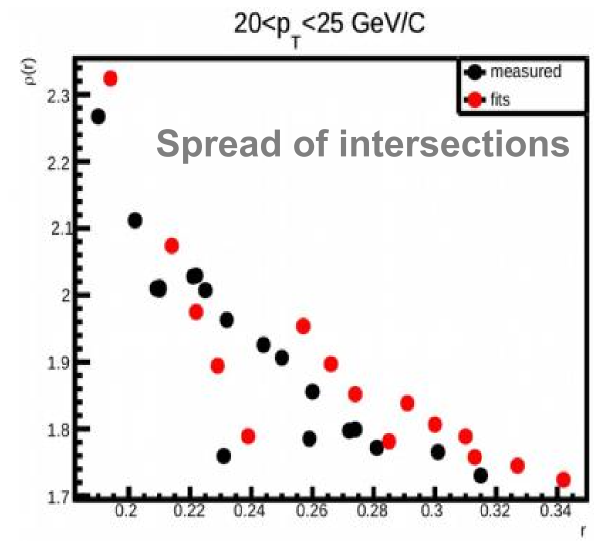
» **Radial profiles scale with multiplicity**

» **Poissonian is an adequate description**

Is there really an R_{fix}?







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

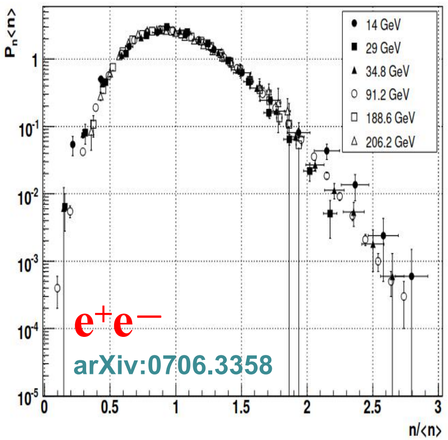
Outline

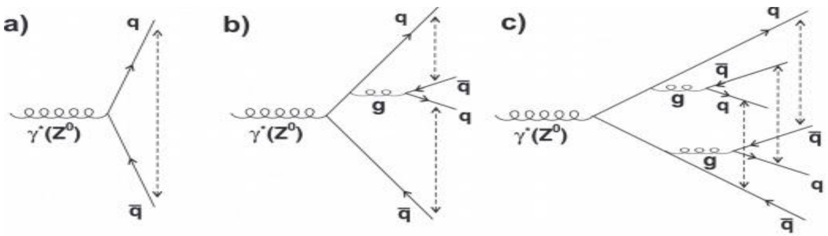
- Scaling of jet-momentum profiles with multiplicity
  - **arXiv:2008.08500**

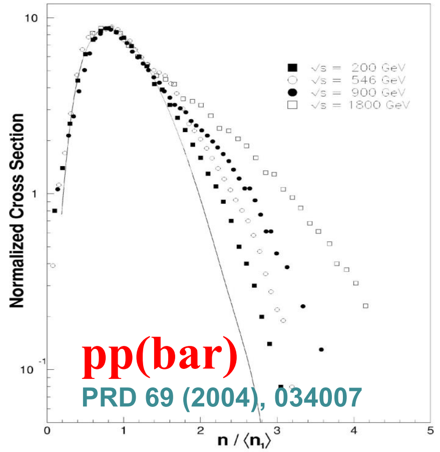
- KNO-like scaling within a jet in pp collisions
  - **arXiv:2012.01132**

KNO-scaling and its violation

- 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

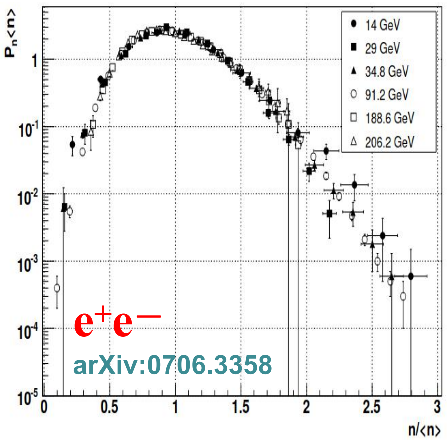


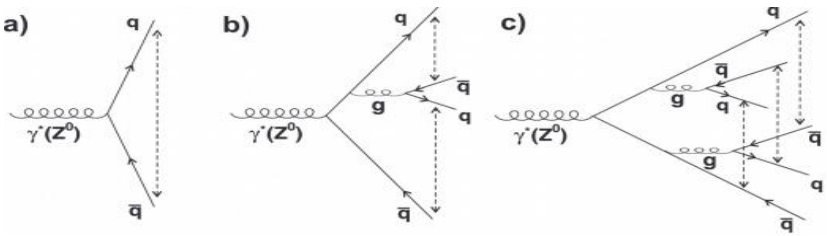


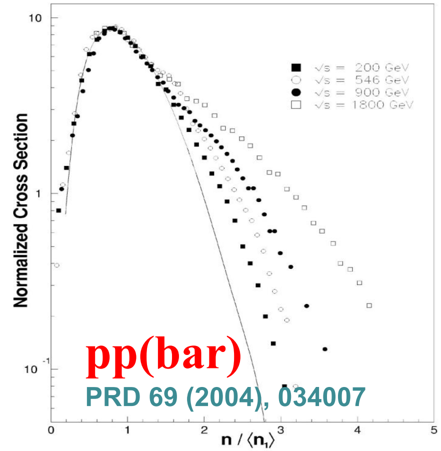


KNO-scaling and its violation

- 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

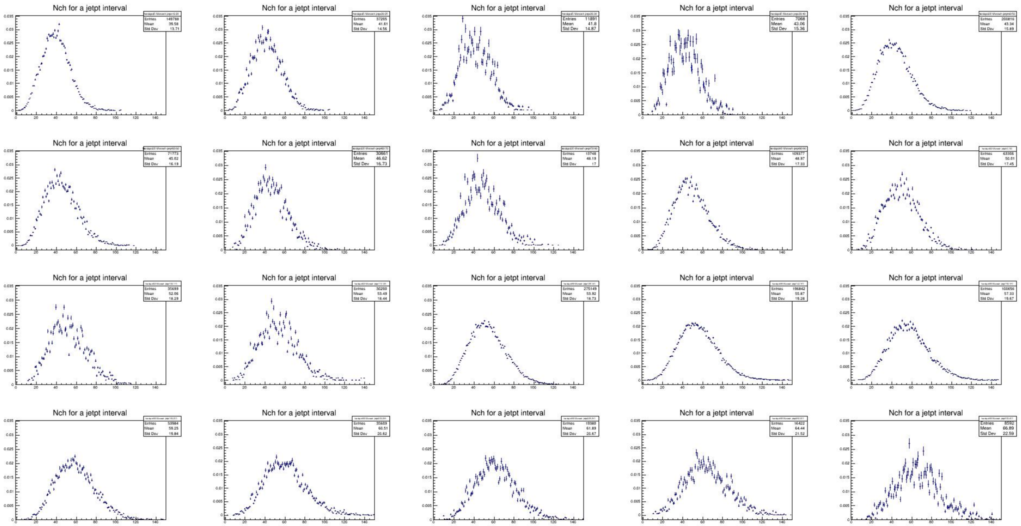


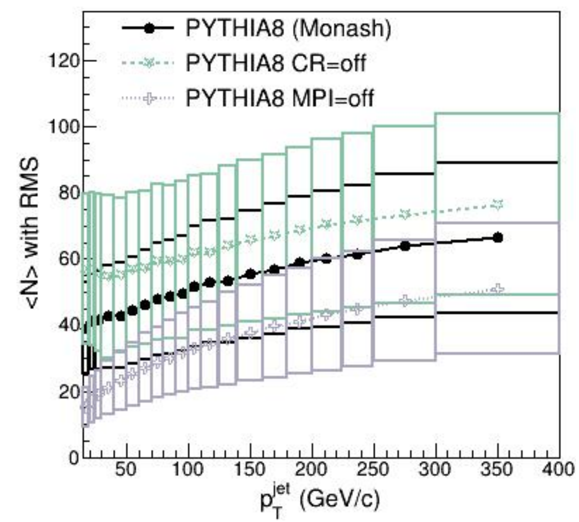




- **Is KNO-scaling valid within a single jet?**
- **How is affected by MPI and CR?**
- **Is there a connection of KNO to radial scaling?**

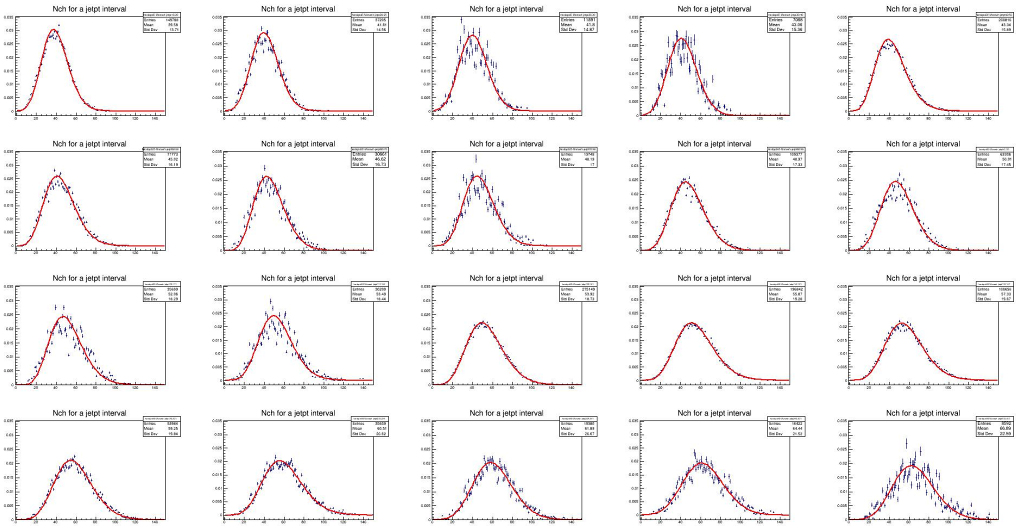
KNO within jet: multiplicity scaling with p_T^{jet}

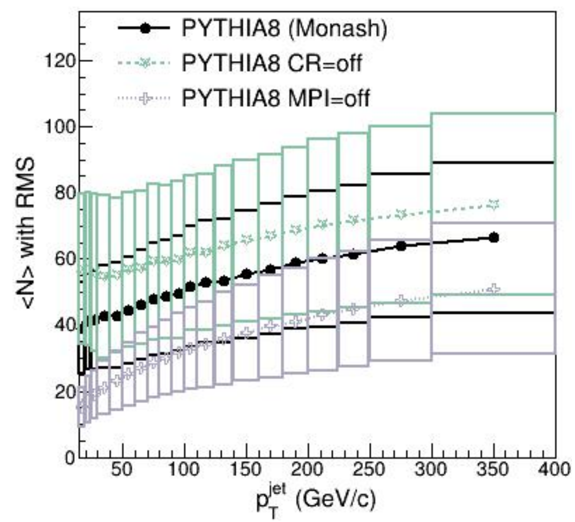




- Multiplicity (dominated by the jet multiplicity) vs. jet momentum p_T^{jet}

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

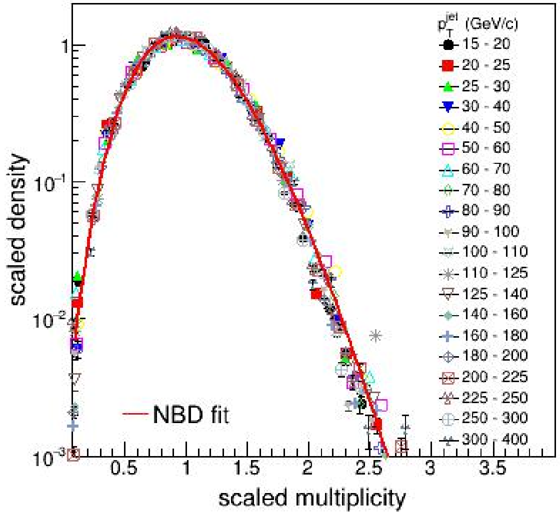


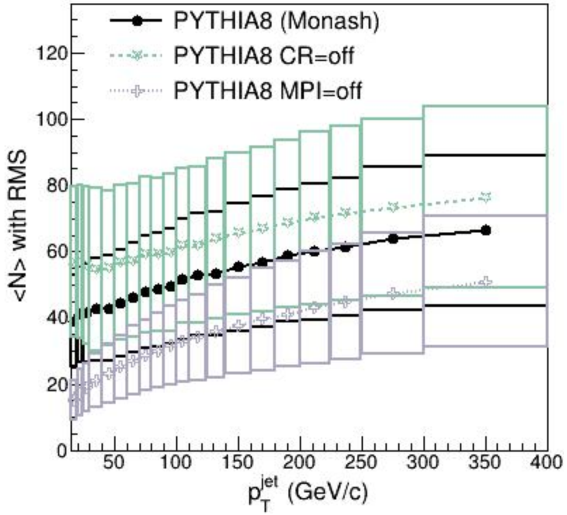


- Multiplicity (dominated by the jet multiplicity) vs. jet momentum p_T^{jet}
- Parametrized with a NBD

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

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





- 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

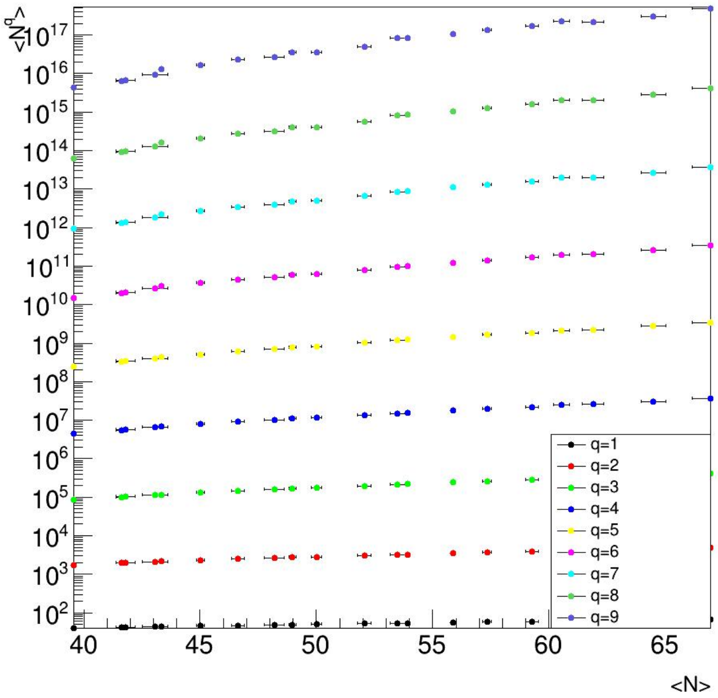
- q^{th} statistical moment

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

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

- Scaling:

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



Multiplicity vs. p_T^{jet}: moments

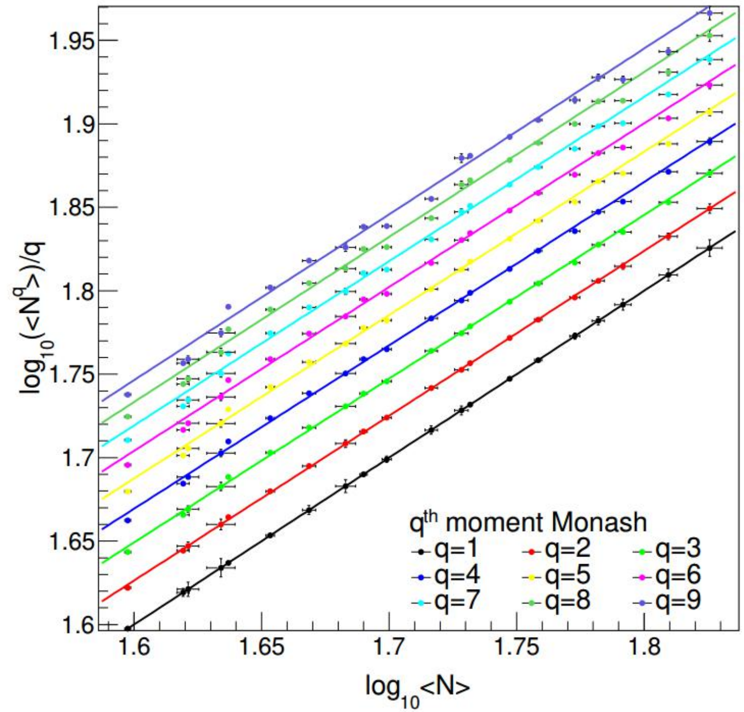
- q^{th} statistical moment

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

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

- Scaling:

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

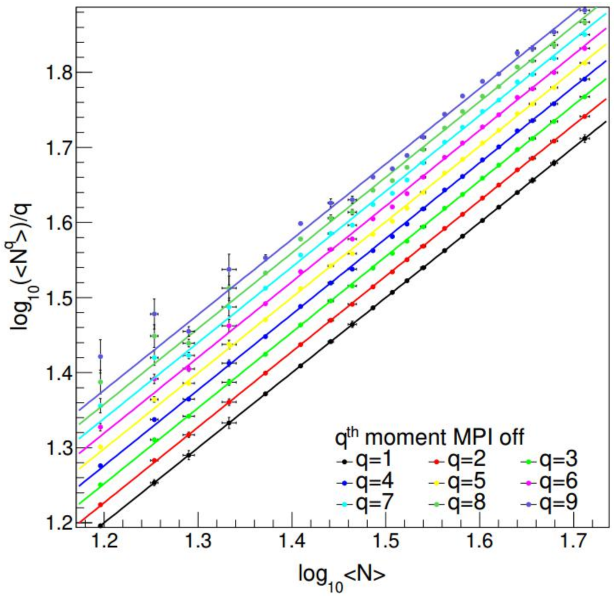


- log$\langle N^q \rangle / q$ vs. log$\langle N \rangle$ is a straight line with ~unity slope
  - up to the 9th moment

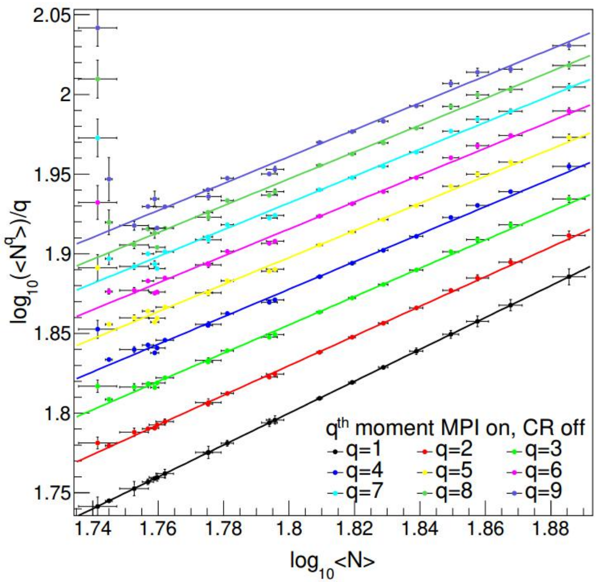
=> **scaling is fulfilled in the whole p_T^{jet} range**

Moments: Role of MPI and CR

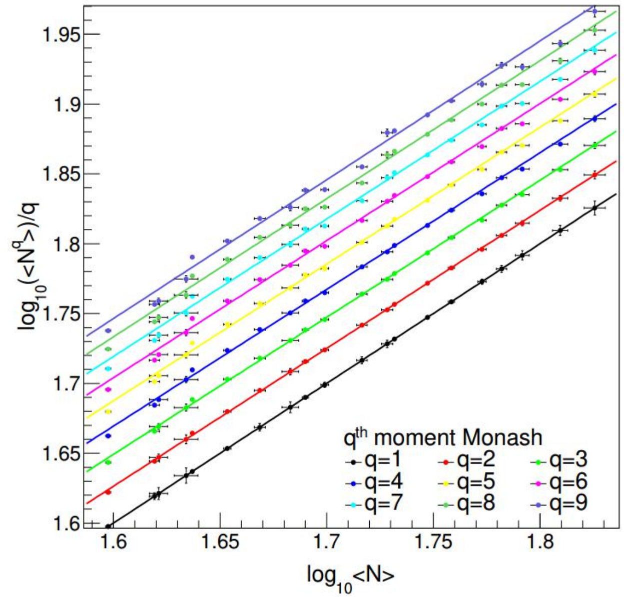
MPI off



CR off, MPI on



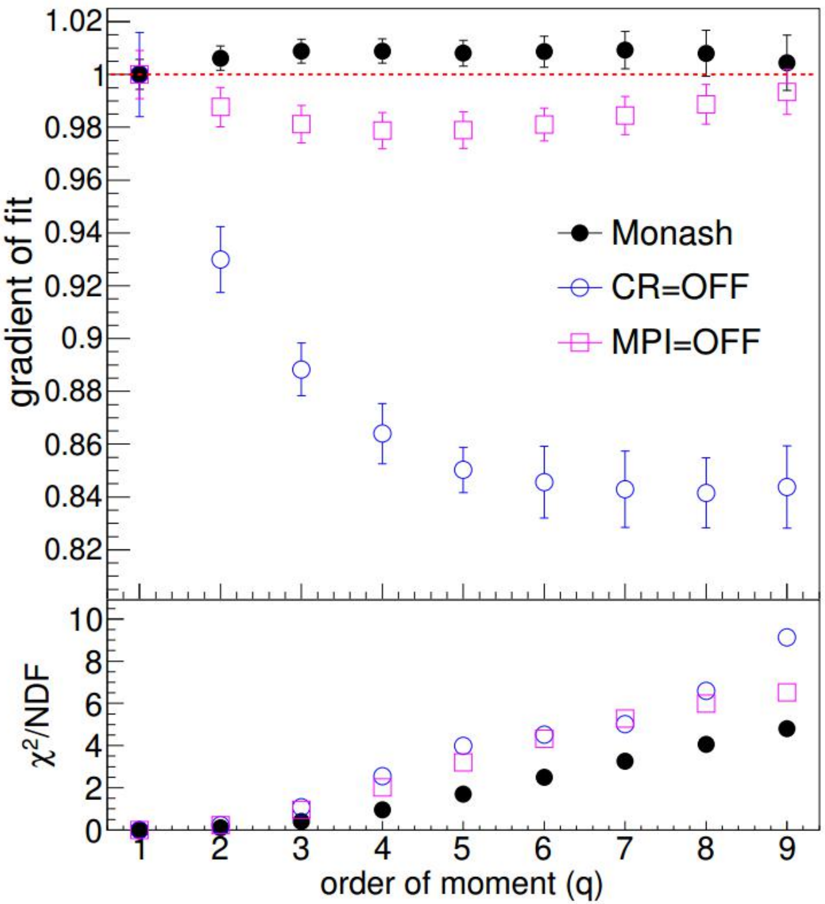
physical: CR on, MPI on



- **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

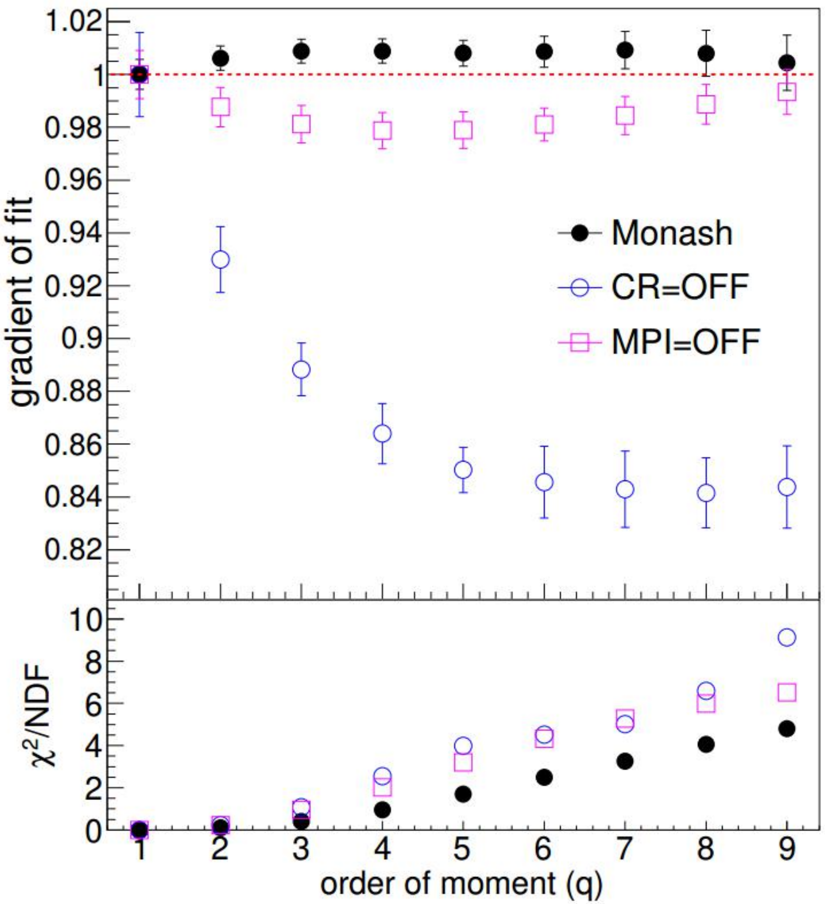
Slopes moment-by-moment

- 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)



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)
- **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 Poissonian, 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?**
  - Cross-check with real data would be essential

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 Poissonian, 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?**
  - Cross-check with real data would be essential
- **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.

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 Poissonian, 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?**
  - Cross-check with real data would be essential
- **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.

Thank you!

Special thanks to Sándor Hegyi
for fruitful discussions and guidance

This work has been supported by the Hungarian NKFIH OTKA FK131979 as well as the NKFIH 2019-2.1.11-TÉT-2019-00078, 2019-2.1.11-TÉT-2019-00050, 2019-2.1.6-NEMZKI-2019-00011, 2020-1.2.1-GYAK-2020-00013 grants and THOR Cost Action CA15213.

Scaling of the jet profiles - log scale

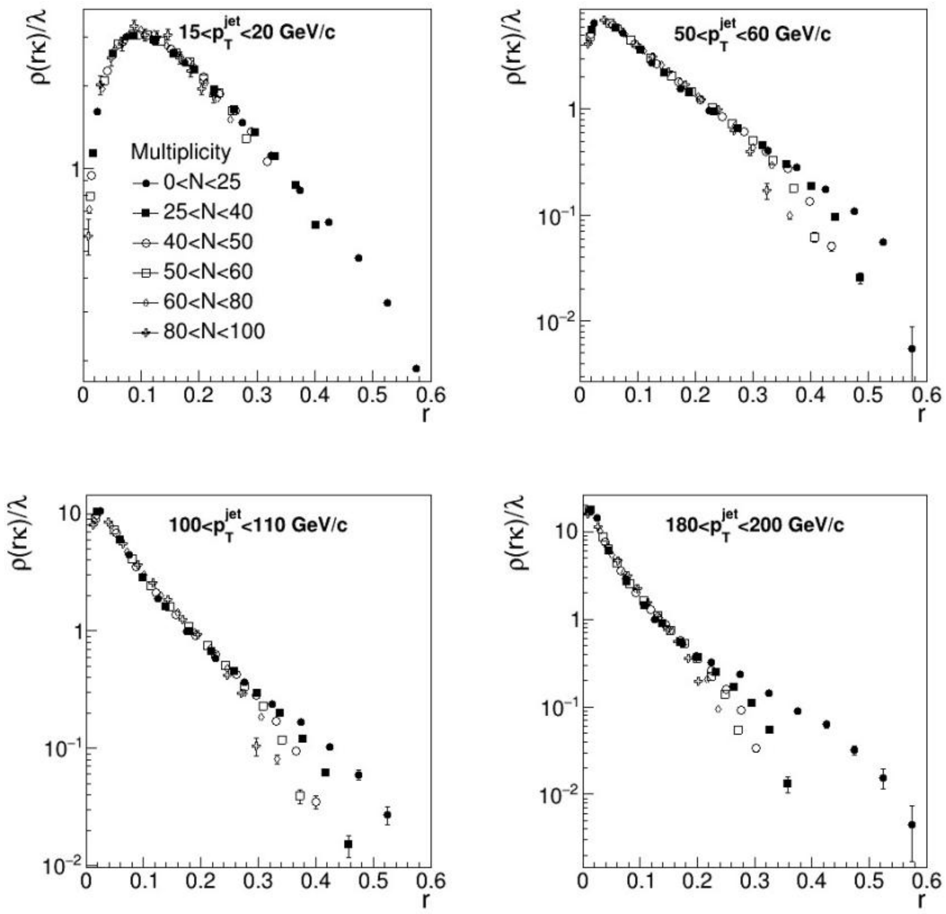
- Scaling assumption: profiles at all multiplicities collapse into a single distribution,

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

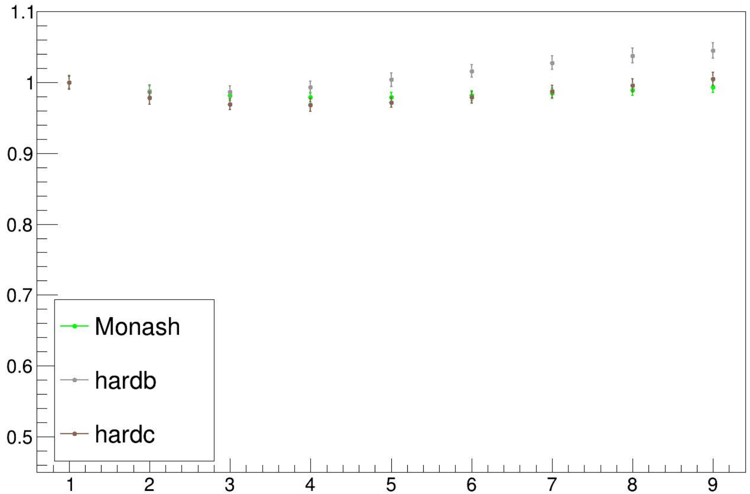
  Note: Ideally, $\lambda = 1/\kappa$, however... "leakage" (distribution is cut-off at high *r* before normalization)

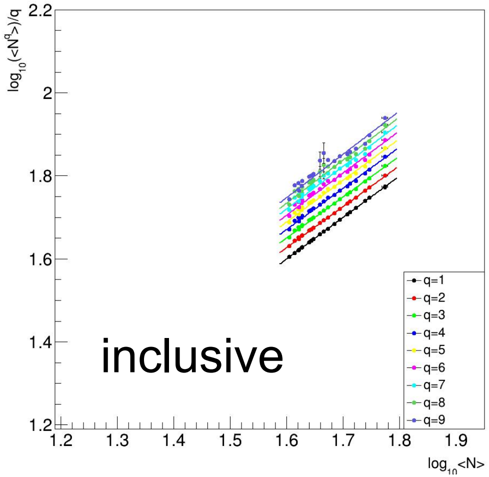
- Scaling is determined based on Poissonian fits
  - Chosen "good" mid-multiplicity fits, then others scaled to it minimizing χ^2

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

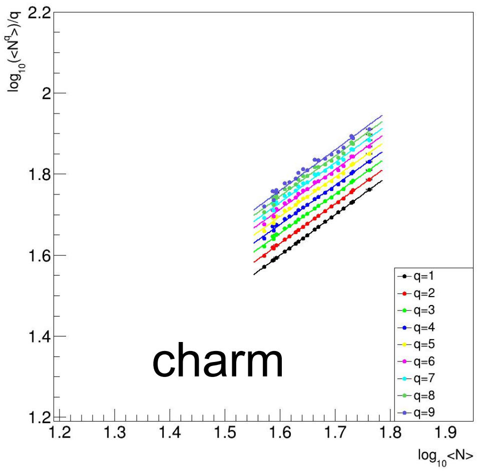


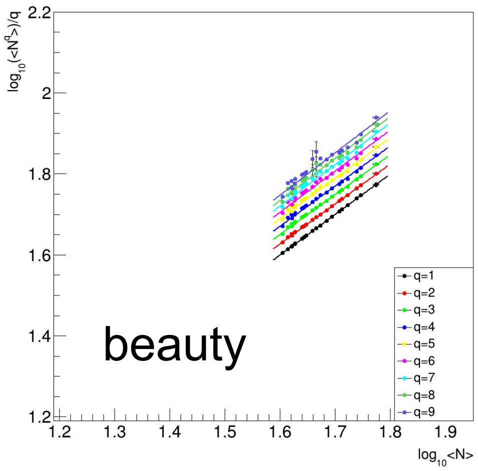
KNO-like scaling: Heavy Flavor



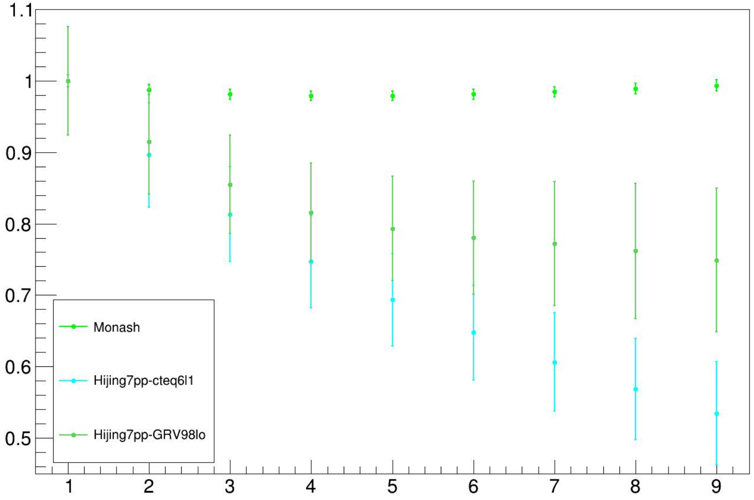


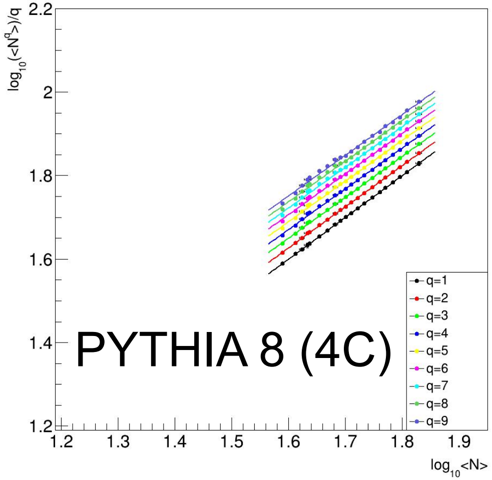
- Heavy-flavor jets also show KNO-like scaling



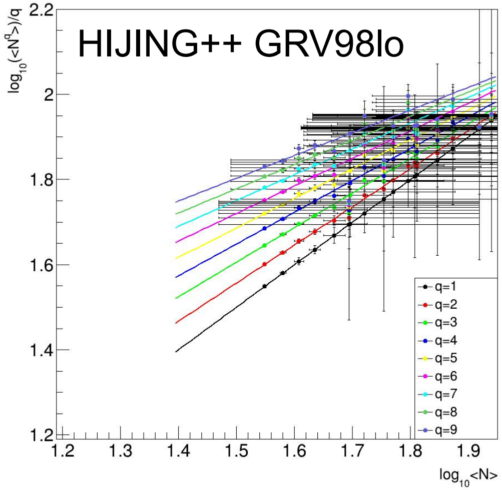


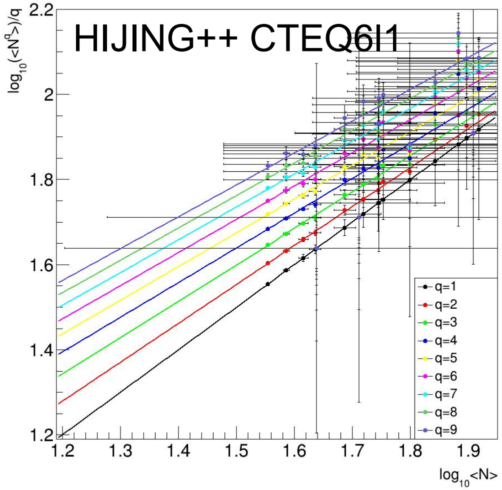
KNO-like scaling: Hijing++



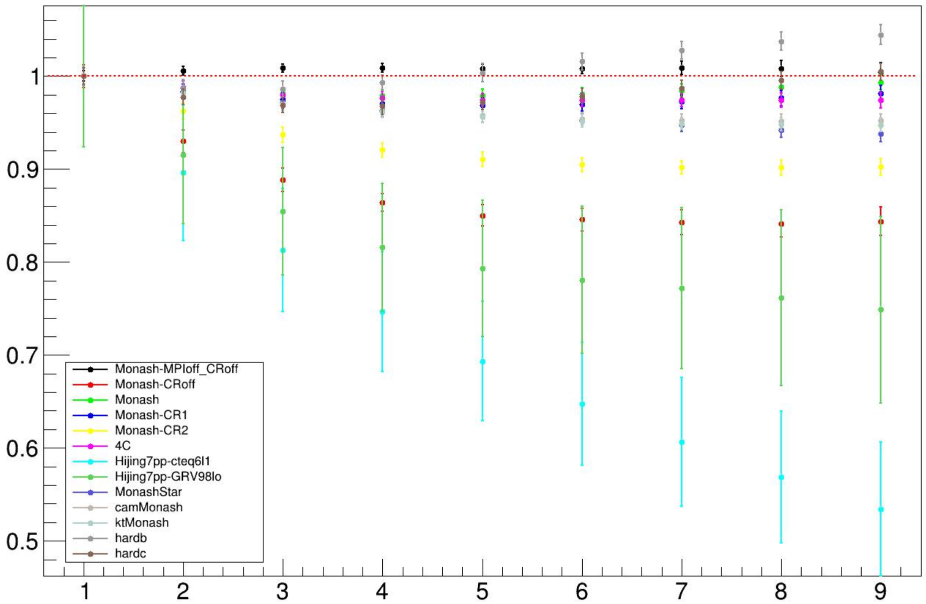


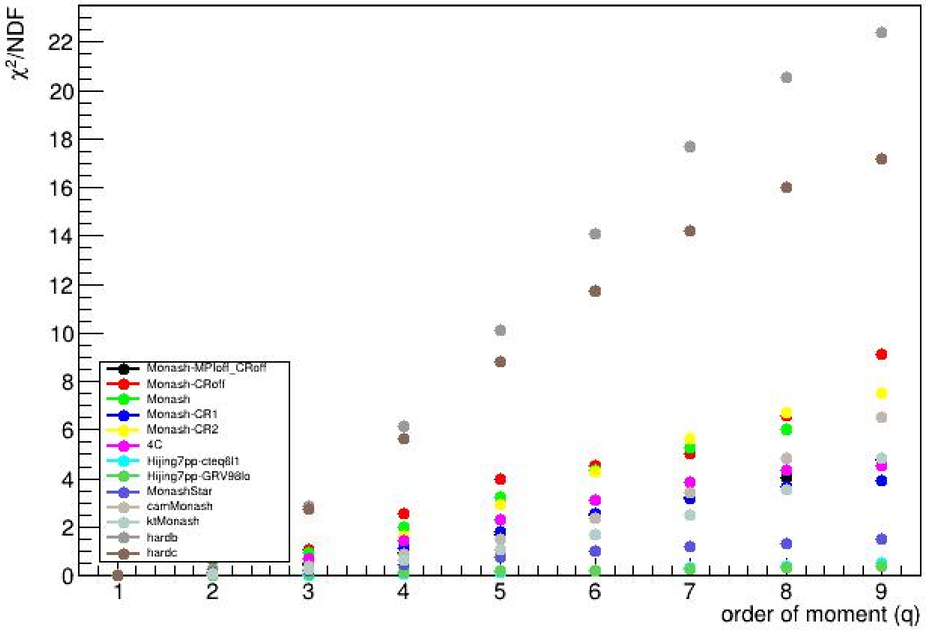
- Hijing++ does not exhibit the scaling





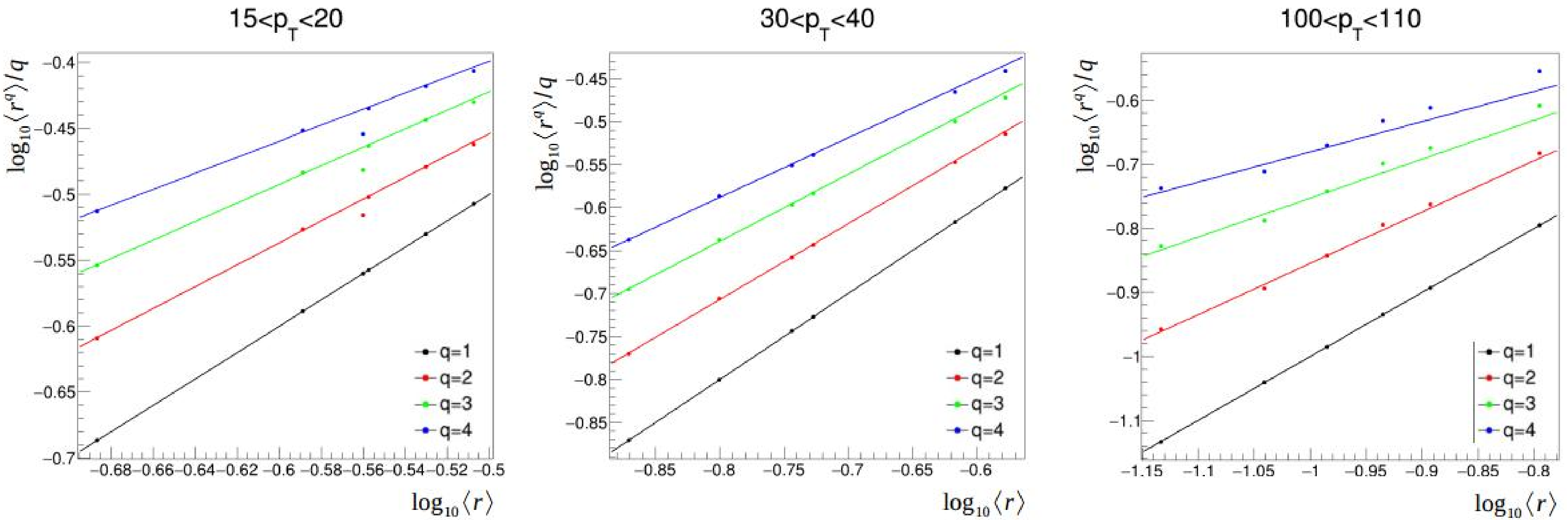
KNO-like scaling: summary





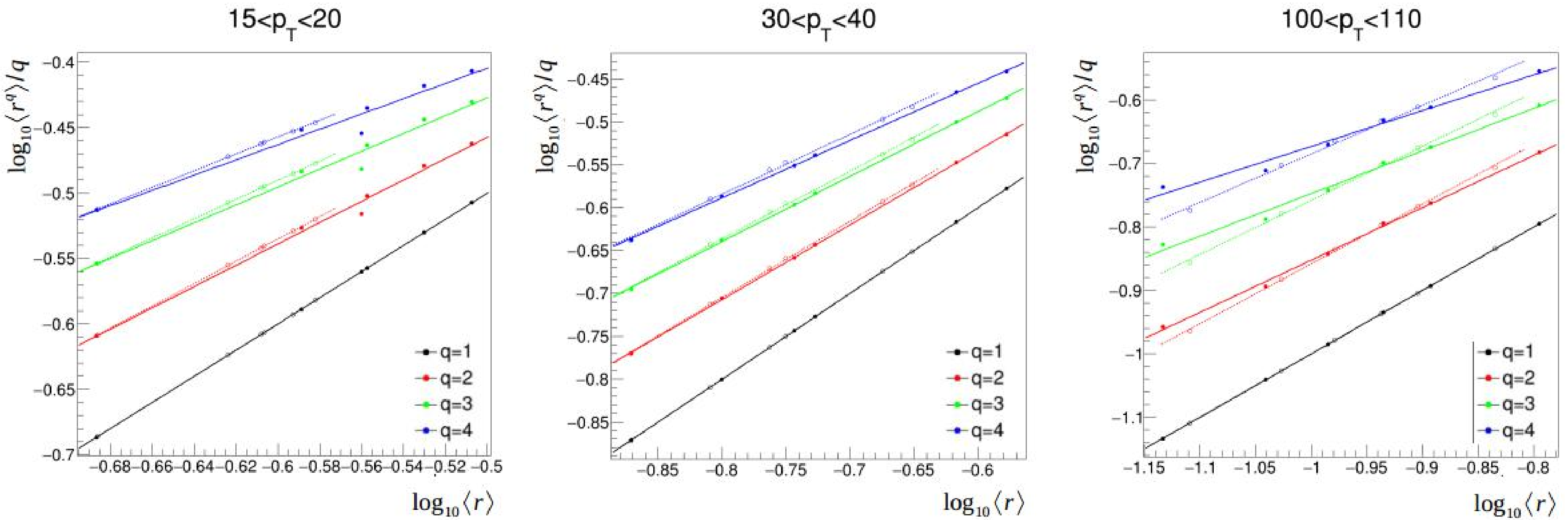
Statistical moments of jet profiles

(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.