Scaling properties of jets in high-energy pp collisions

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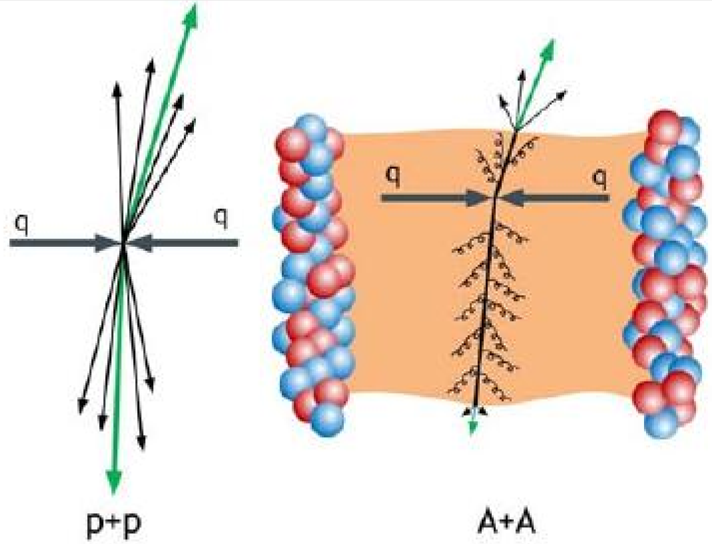
Outline

- Scaling of jet-momentum profiles with multiplicity
  - **arXiv:2008.08500**
    Gribov-90 Memorial Volume: Algebraic Methods in QFT
- KNO-like scaling within a jet in pp collisions
  - **arXiv:2012.01132**
    Submitted to Phys. Rev. D

QGP in A+A collisions

- Hard probes: **Jet quenching**
  - Tomography of the sQGP
    by early hard pQCD processes
  - **modification in the medium**



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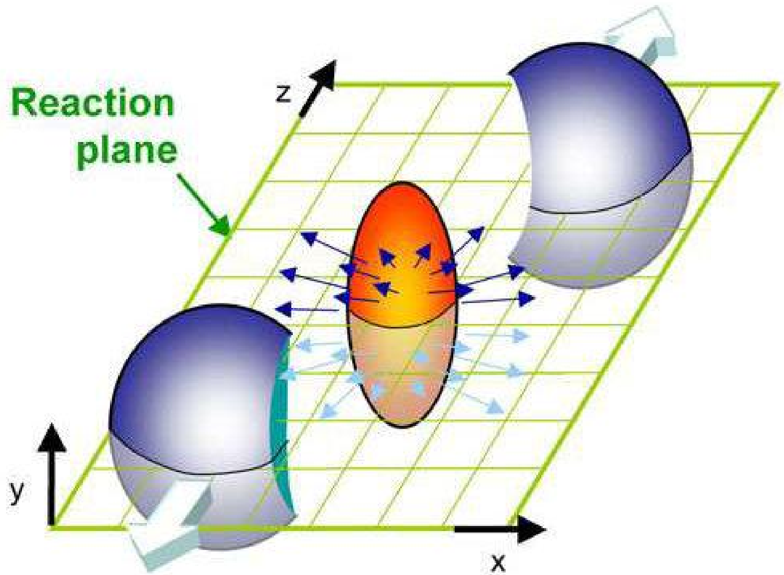
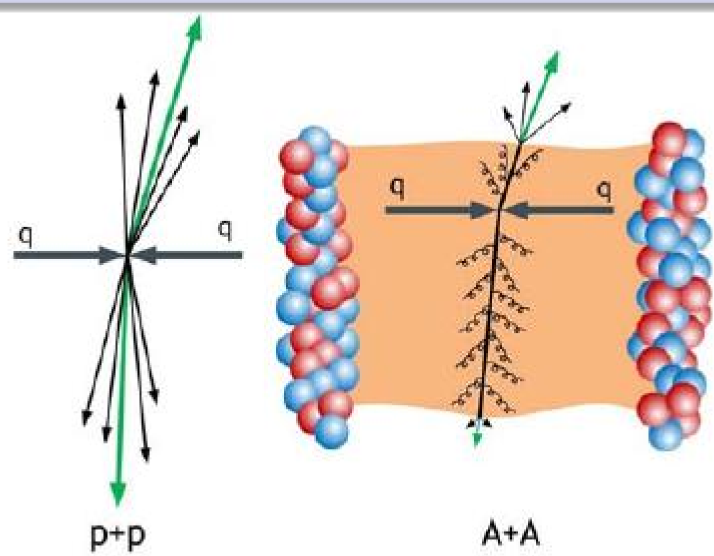


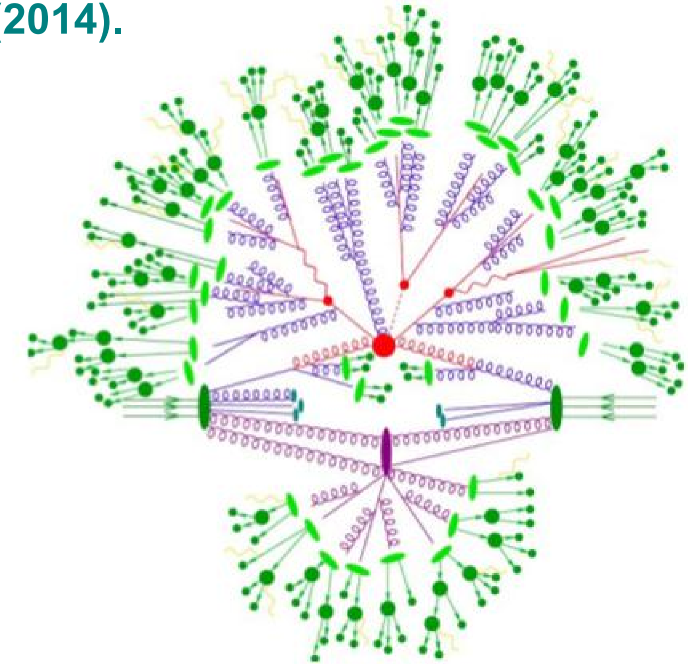


- Soft probes: **“Flow”**
  - **Collective dynamics** of the bulk final-state hadrons (v_2~0.2 ...)
  - D.O.F. are the constituent quarks
  - viscousless hydro description

=> Strongly coupled quark-gluon plasma

Collectivity in small systems

- **Collectivity in small systems with high-multiplicity at LHC**
  - Substantial v_n , eg. **Yan-Ollitrault, PRL 112, 082301 (2014).**
  - **Can sQGP be created in pp collisions?**



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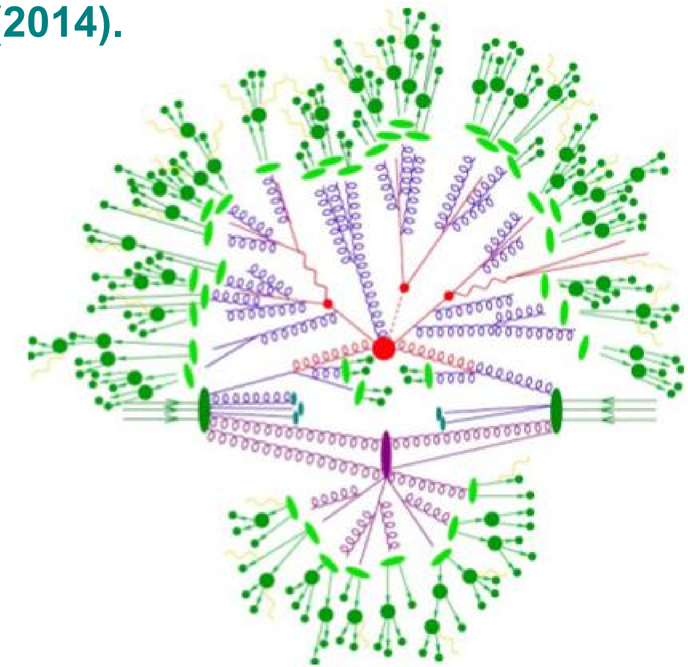

- Current understanding:
  - **QGP is not necessary for collectivity**
  - Vacuum-QCD effects at the soft-hard boundary: for instance **multiple-parton interactions (MPI)**

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

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

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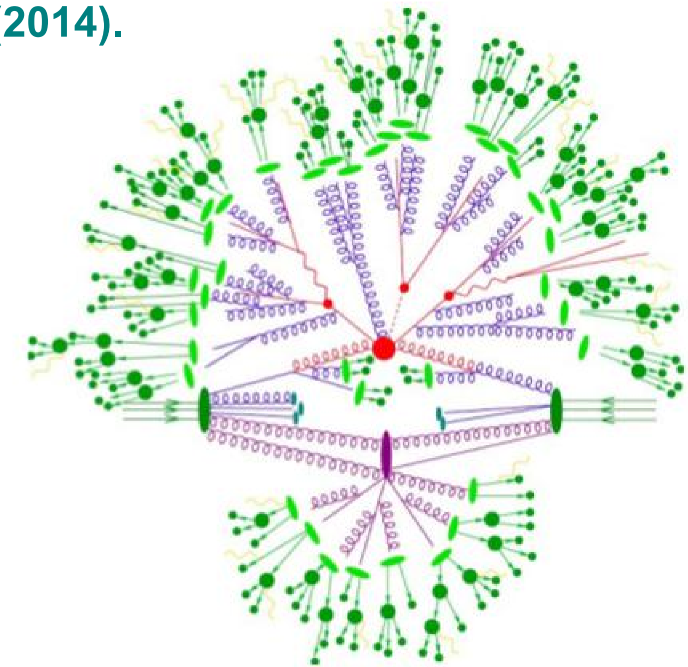

- **Jets:**
  - **A-A**: sensitive probe of nuclear modification.
  - **pp**: No suppression expected.
    However: **soft and hard processes are related by MPI**

⇨ **this connection may be explored with jets in high-multiplicity events**

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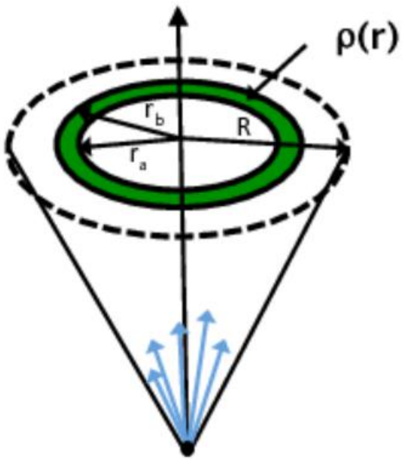
Radial jet profiles

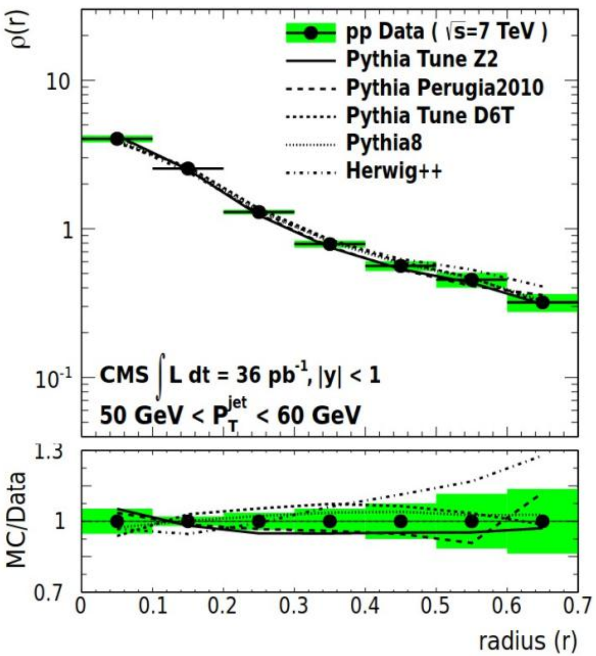
- Differential jet shape



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

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

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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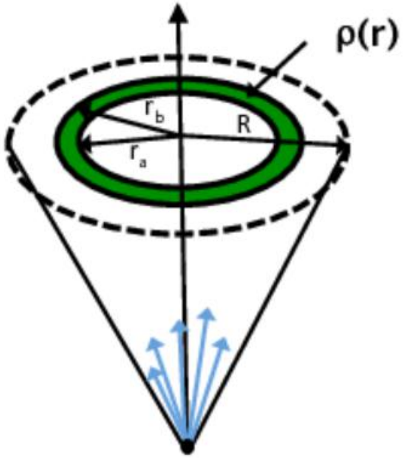

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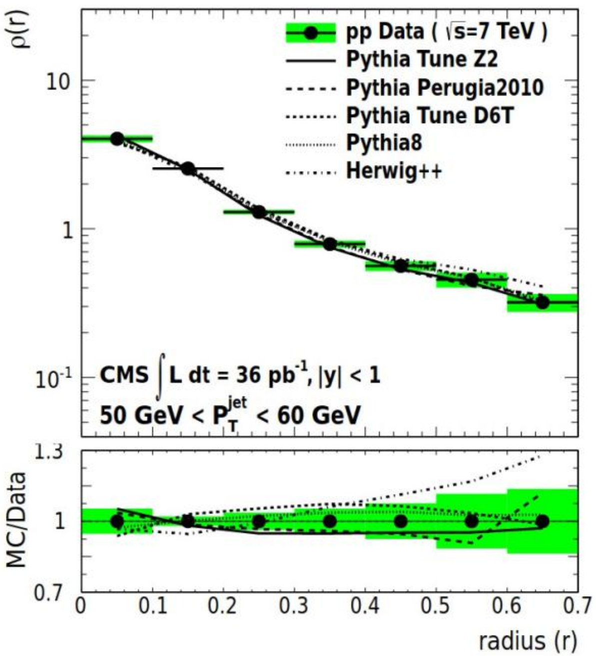

- CMS@LHC pp collisions, $\sqrt{s}$ = 7 TeV
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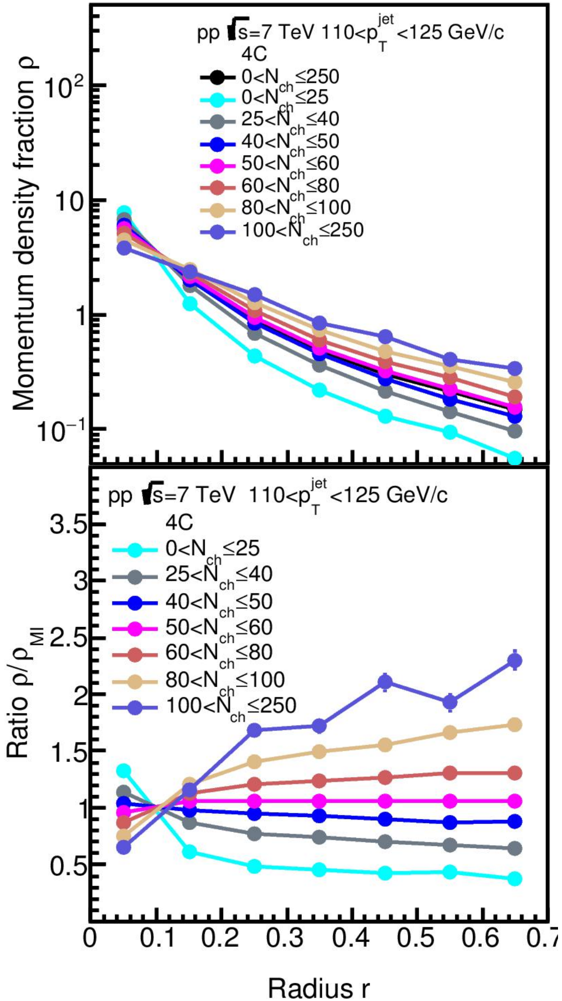
- **Currently available LHC data are either multiplicity or transverse-momentum inclusive**

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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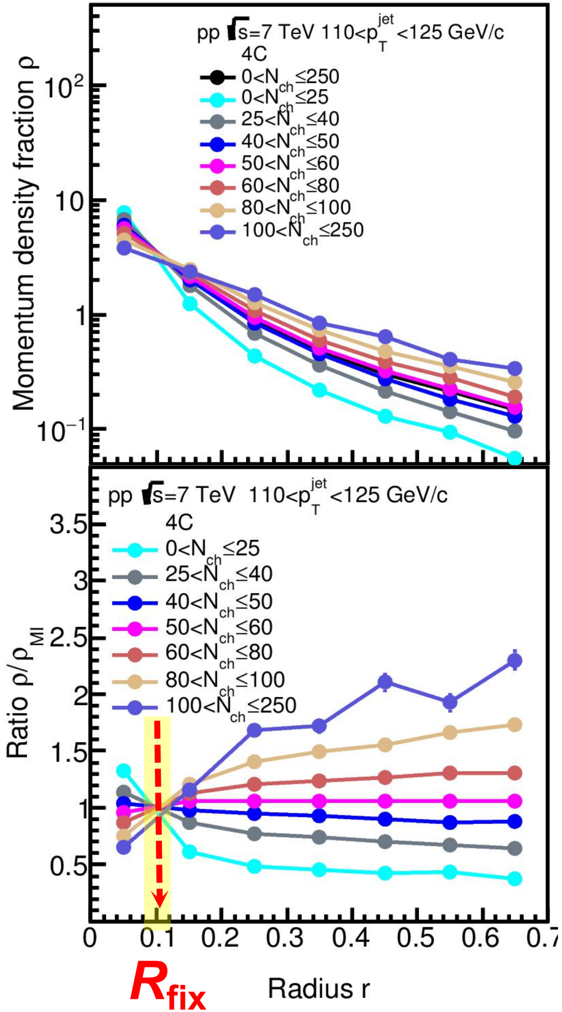
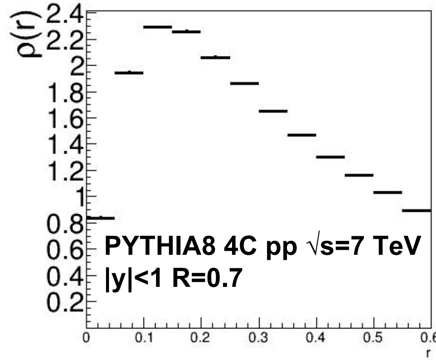


- PYTHIA 8.2 simulations (HardQCD)
  - pp collisions at $\sqrt{s}$ = 7 TeV
  - R=0.7 jets, 50<p_T^{jet}<60 GeV/c, |y|<1
- **7 multiplicity classes:**
  jet profile curves intersect at a given point R_{fix}
  in any given p_T^{jet} window
- ***R_{fix}* independent of**
  - **generator**: Pythia, Hijing++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

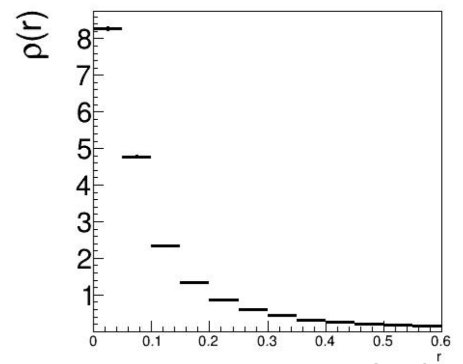
Z. Varga, R.V, G.G.B,
Adv.HEP 2019, 6731362 (2019)

Parametrizing the jet profiles

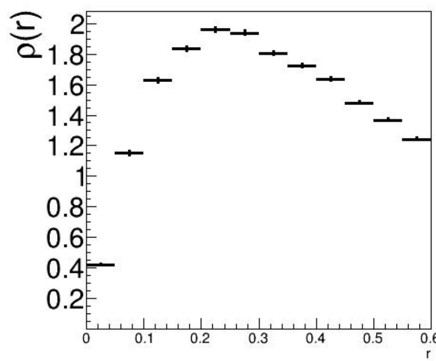
- Detailed PYTHIA 8 simulations (4C)
  - Jet radius: 12 bins up to r=0.6
  - Multiplicity 6 bins up to N=100
  - Momentum: 20 bins up to p_T^{jet}=400



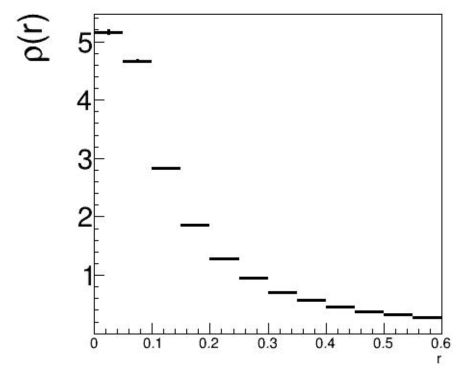
25<N<40, 15<p_T^{jet}<20 GeV/c



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



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



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- Detailed PYTHIA 8 simulations (4C)
  - Jet radius: 12 bins up to r=0.6
  - Multiplicity 6 bins up to N=100
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- Statistically motivated distributions:
  - **Poissonian distribution**

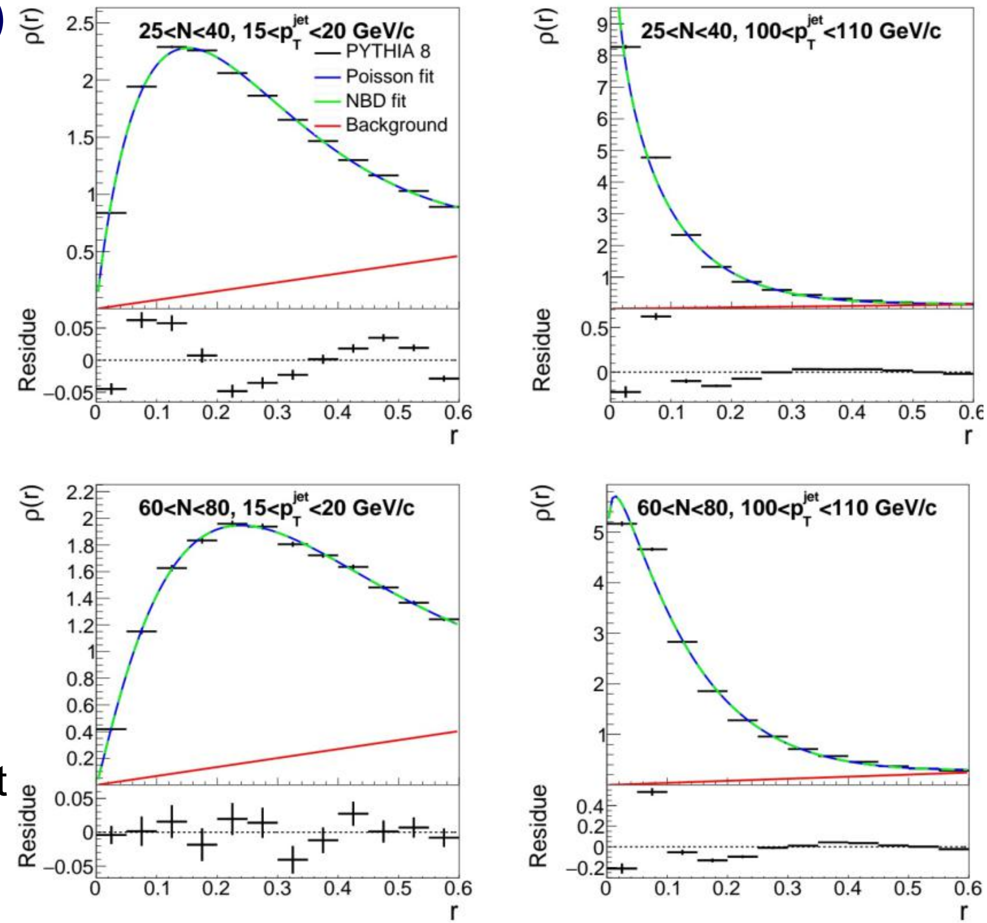
$$\rho(r) = C r^{\gamma} e^{-\alpha r}$$

  - **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

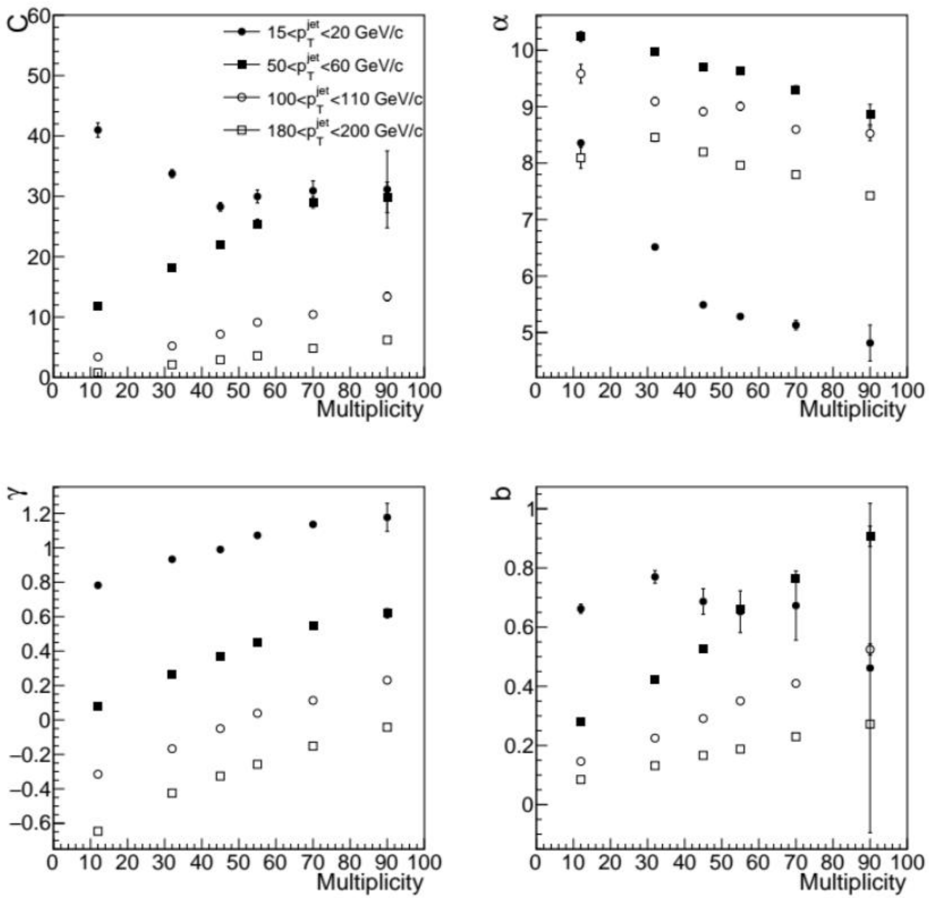
Parameters of the Poissonian fits

- Poissonian with background

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

- Monotonic trends observable

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



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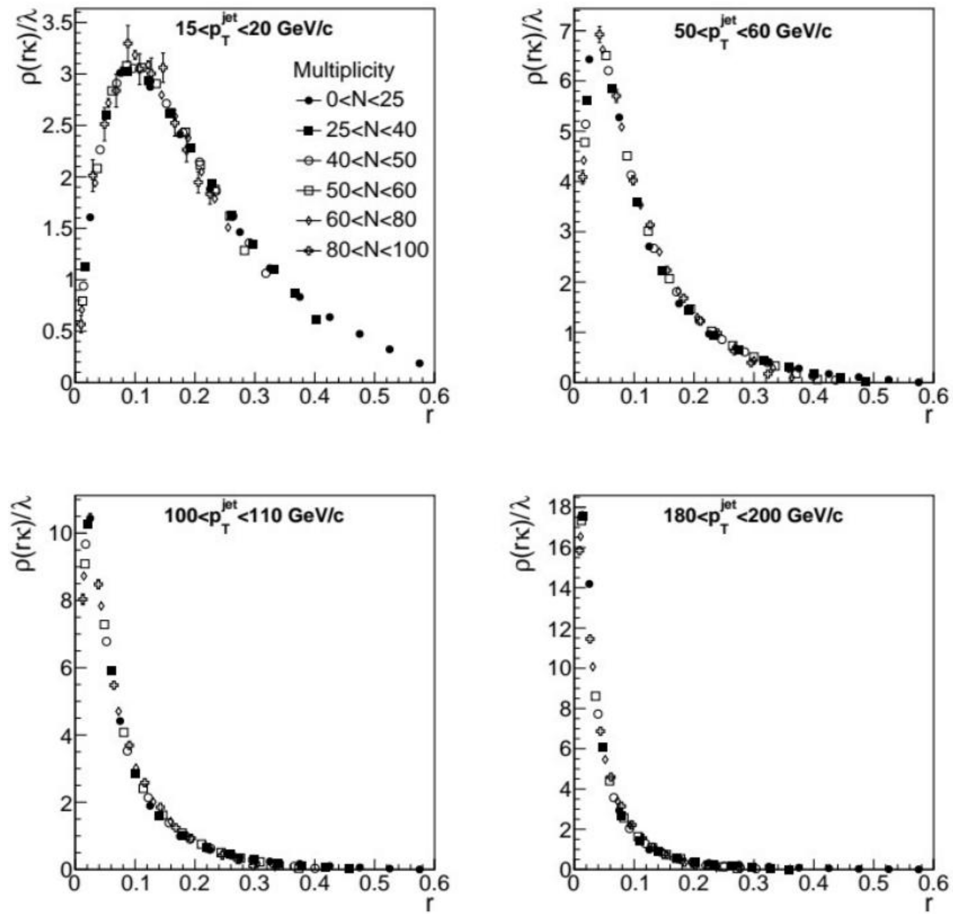
Scaling of the jet profiles

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



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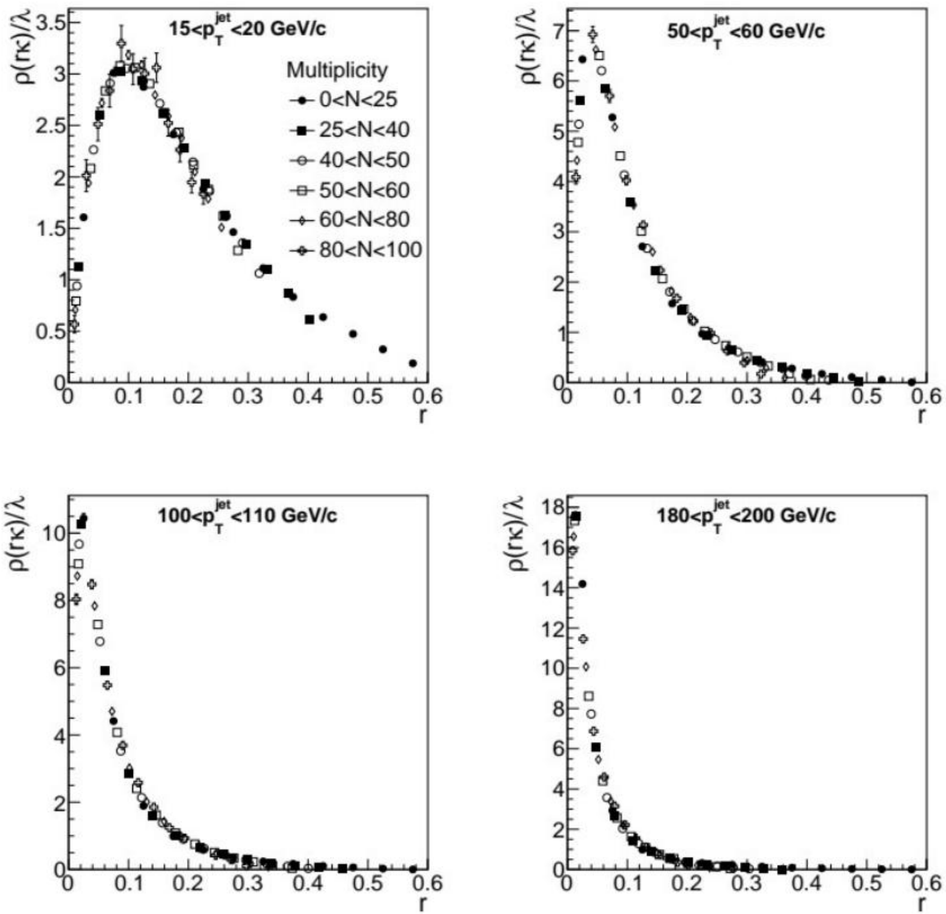
- **The scaling works within 5-10% in the peak region**



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Scaling factors

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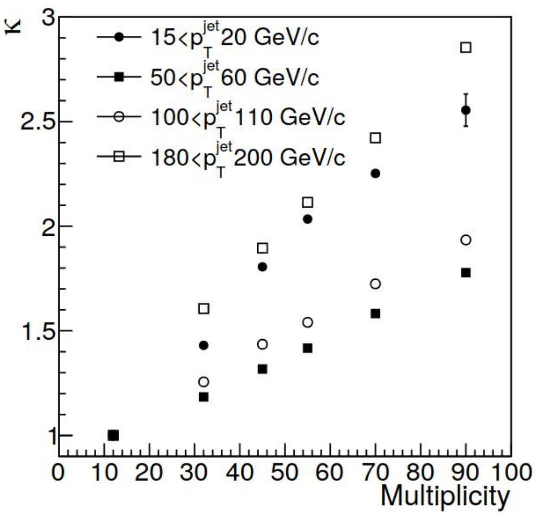

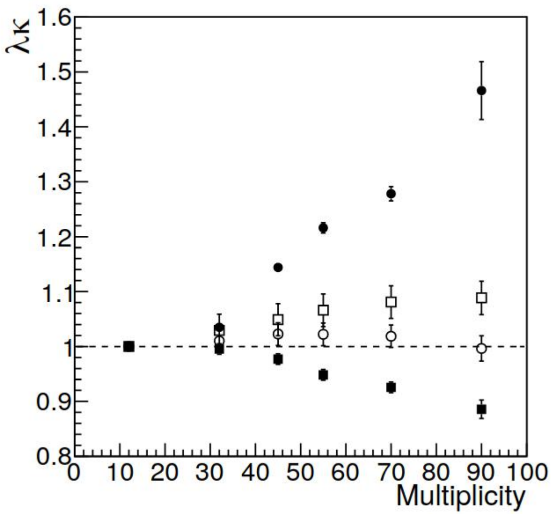

$$\rho_N(r) = \lambda(N) f\left(\frac{r}{\kappa(N)}\right)$$

- 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 Poisson fits?

- Poissonian mean:

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

- Ideally, it should scale:

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

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

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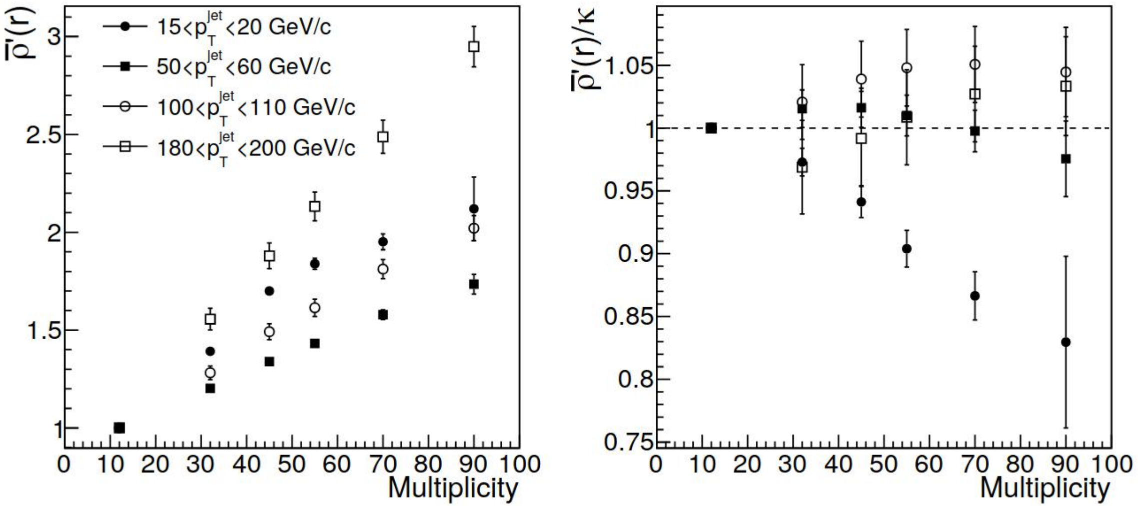

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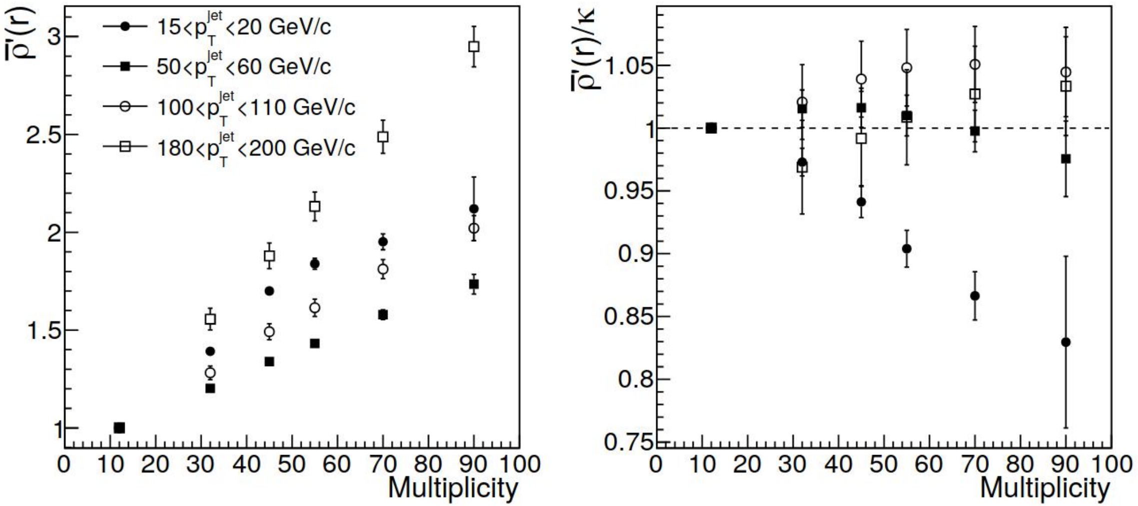
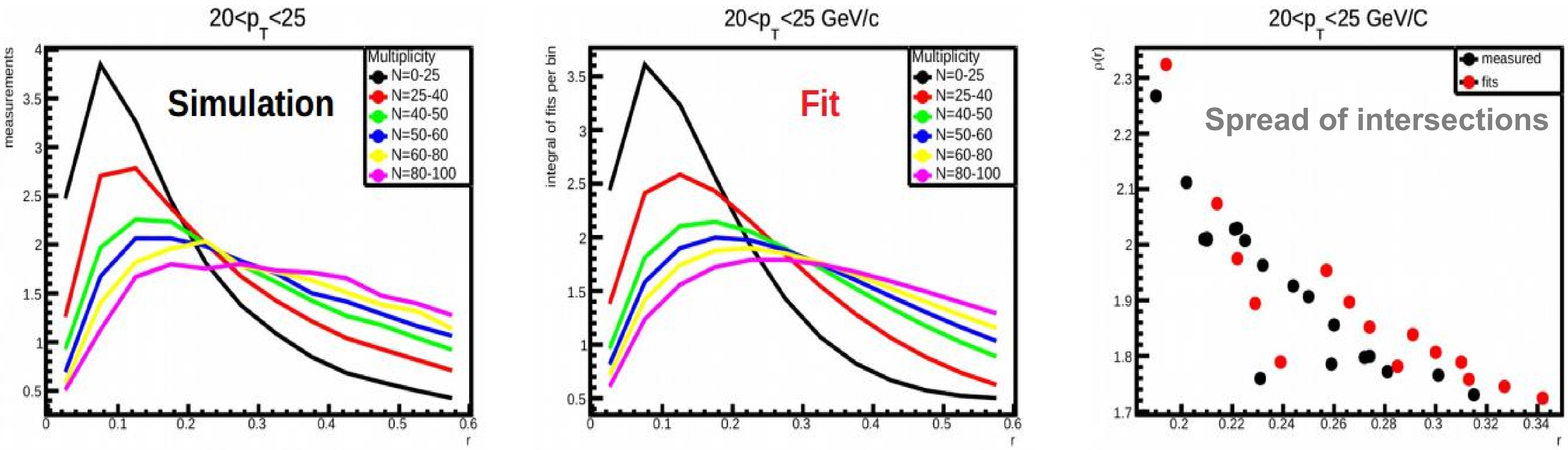


- The mean scales approximately linearly with multiplicity
- Except for the lowest p_T bin, $\kappa / \overline{\varrho}' \sim 1$ within 5%
- Hence,

⇨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**
- *<u>Note</u>: R_{fix} would be exact if $\rho(r)$ fell linearly in the given region*

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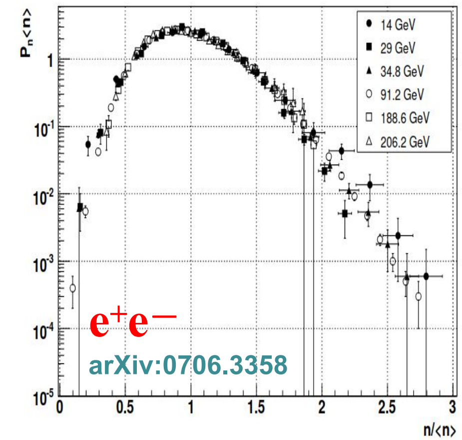
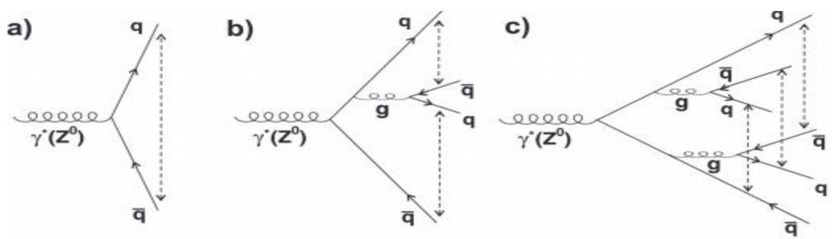
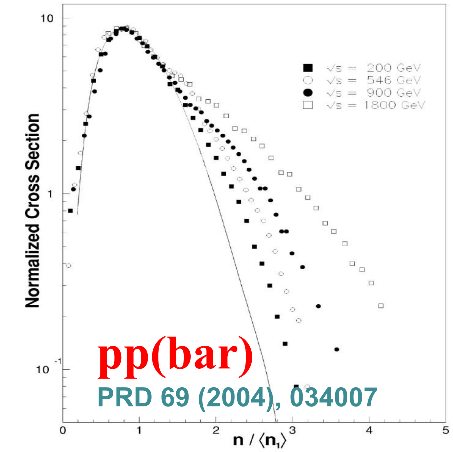
KNO-scaling and its violation

- KNO scaling: the multiplicity distribution scales with $\sqrt{s}$
  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







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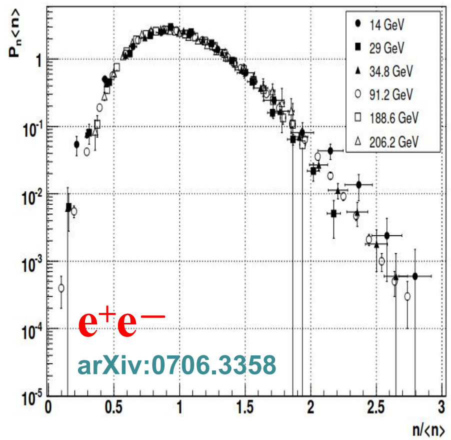
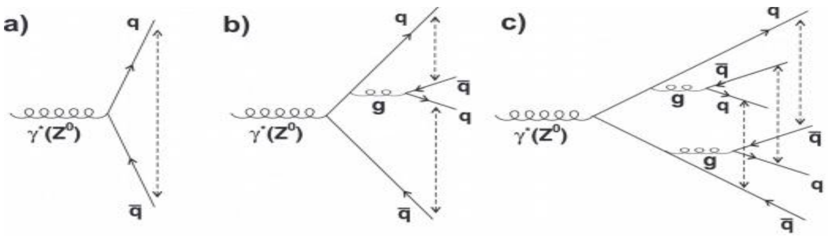
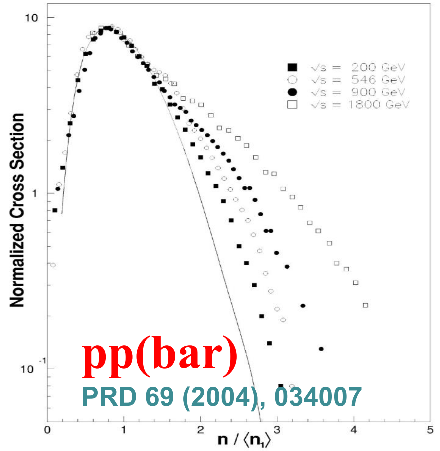
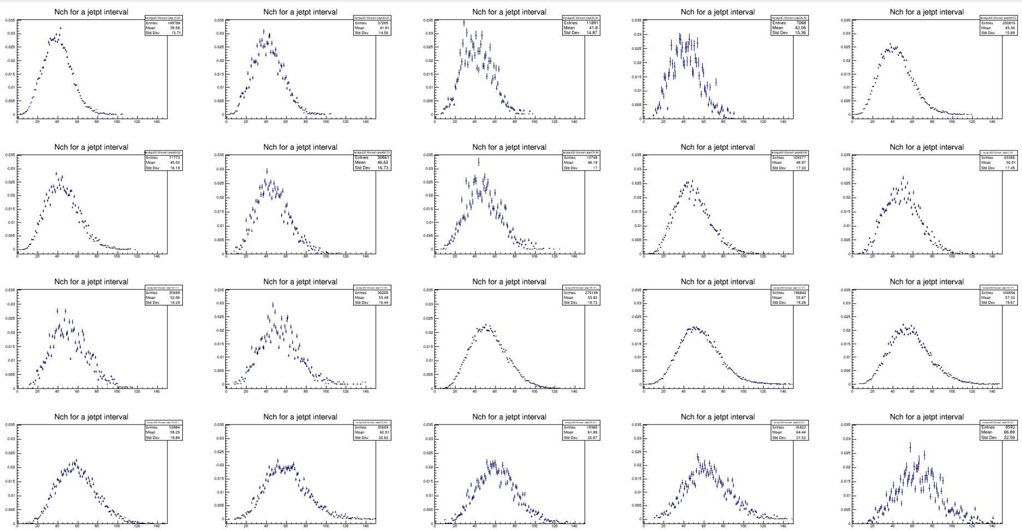


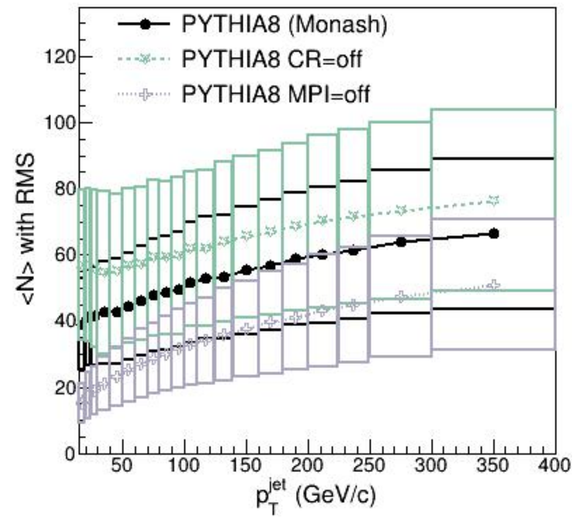




- **Is KNO-scaling valid within a single jet?**
- **How is affected by MPI and CR?**
- **Is there a connection of KNO to radial scaling?**

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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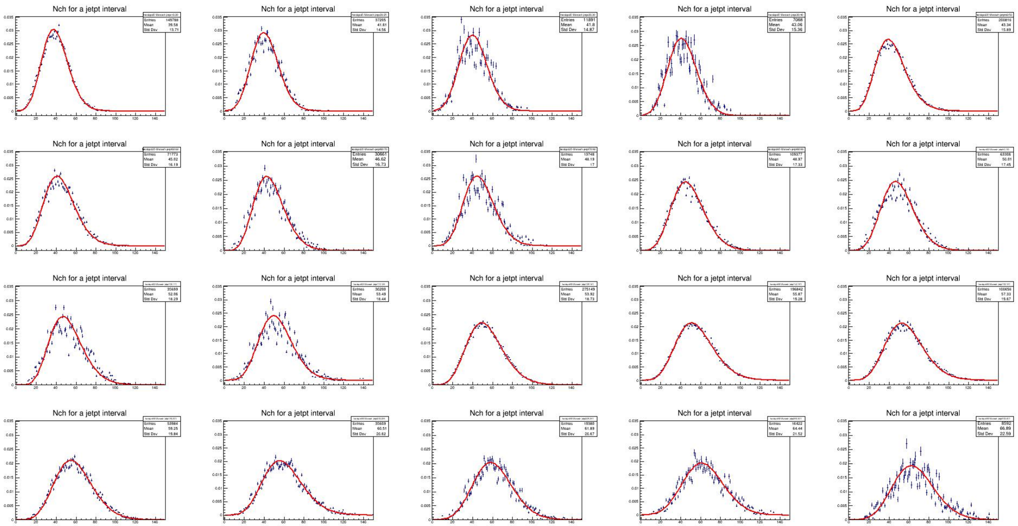

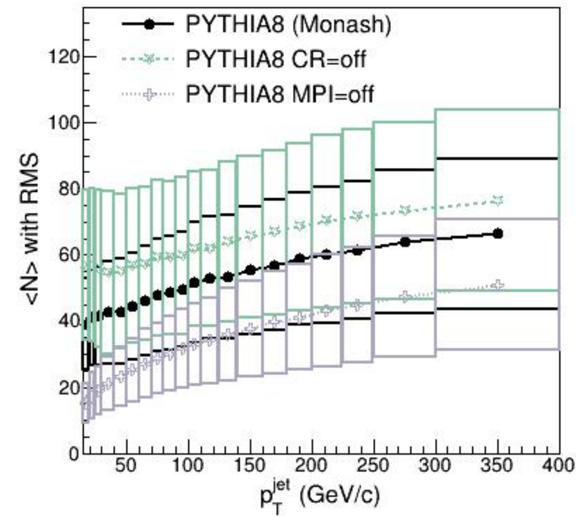

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- Parametrized with a NBD

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

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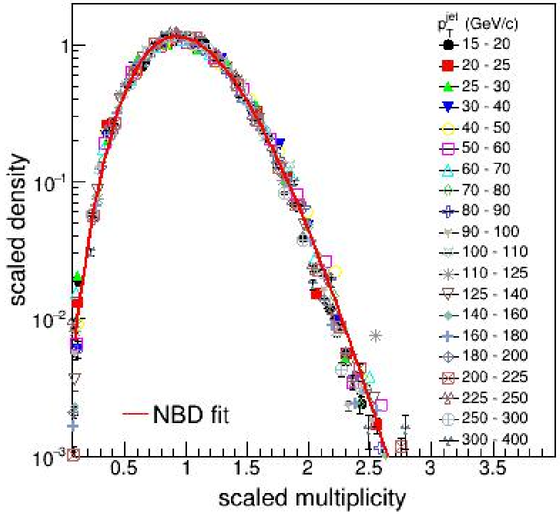
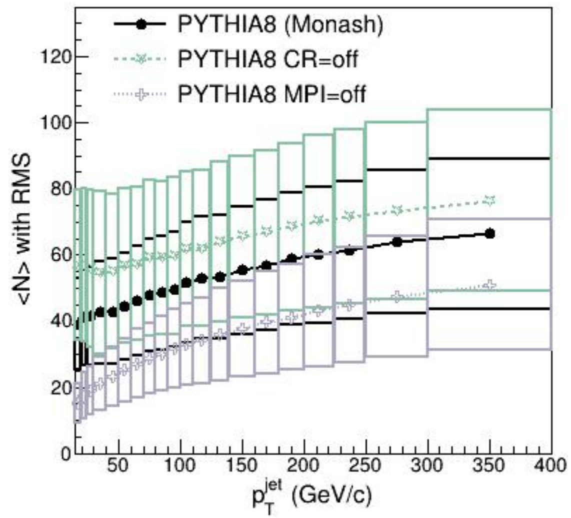




- Multiplicity (dominated by the jet multiplicity) vs. jet momentum p_T^{jet}
- Parametrized with a NBD $$P_N = \frac{\Gamma(Nk+a)}{\Gamma(a)\Gamma(Nk+1)} p^{Nk}(1-p)^a$$
- Distributions at all p_T^{jet} fit well on a single NBD curve
- **KNO-like scaling observed within a jet**
  - In the following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

Multiplicity vs. p_T^{jet}: moments

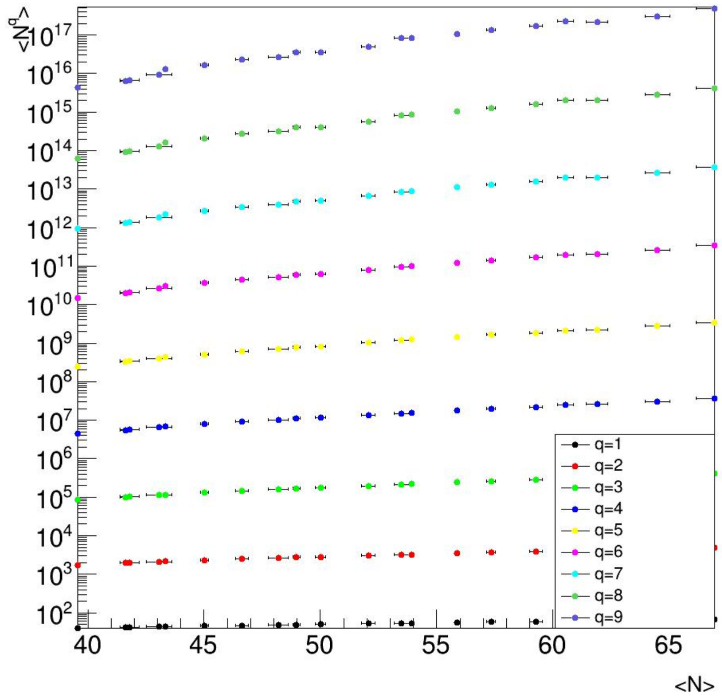
- q^{th} statistical moment

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

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

- Scaling:

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



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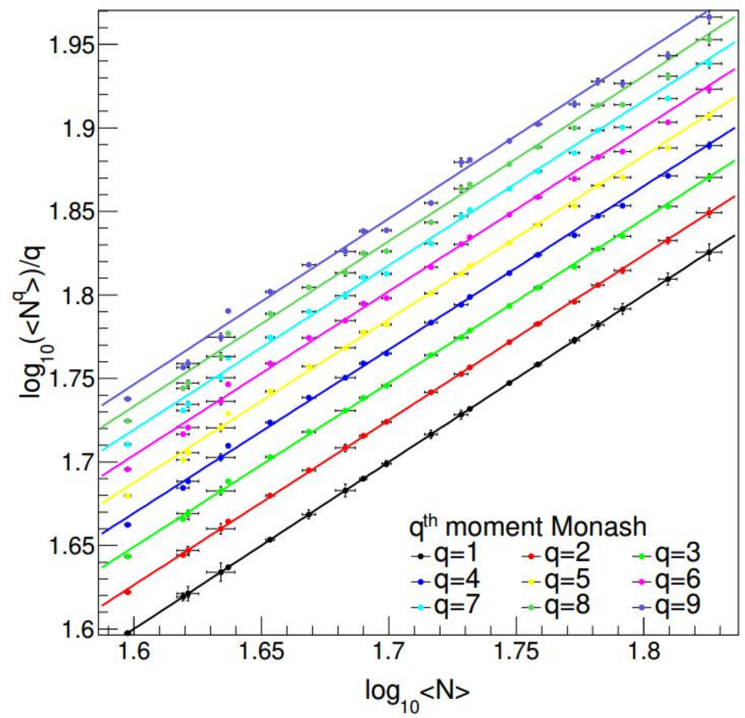
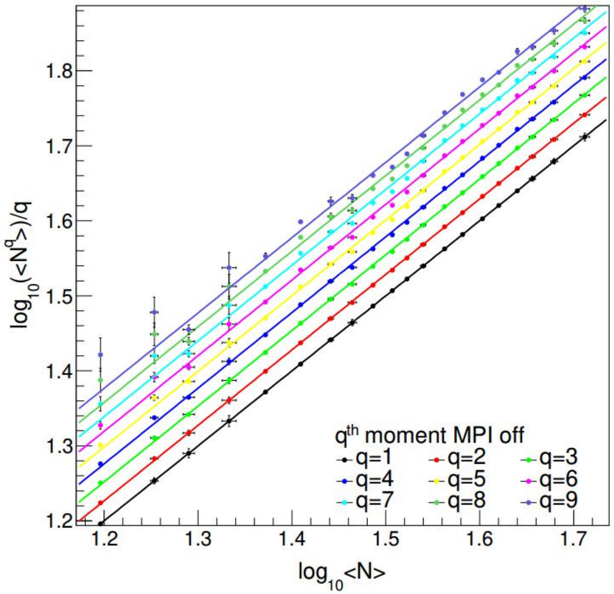


- $\log\langle N^q\rangle/q$ vs. $\log\langle N\rangle$ is a straight line with ~unity slope
  - up to the 9^{th} moment

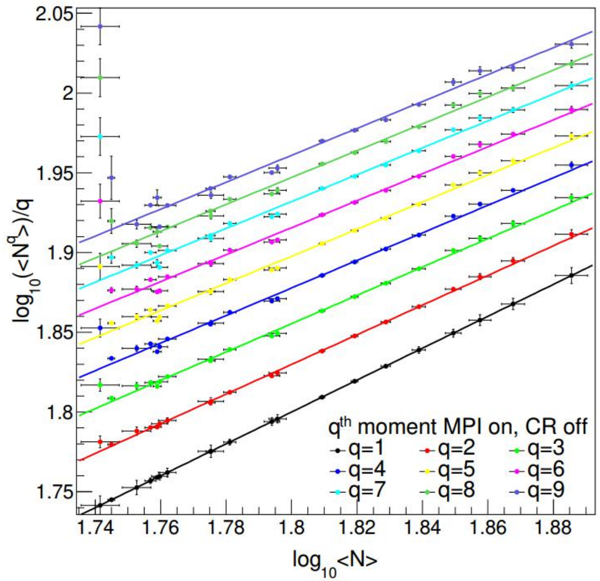
=> scaling is fulfilled in the whole p_T^{jet} range

Moments: Role of MPI and CR

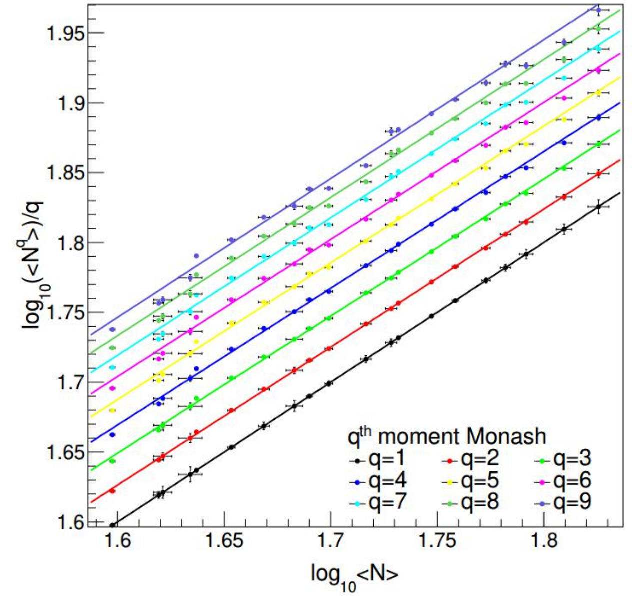
MPI off



CR off, MPI on



physical: CR on, MPI on

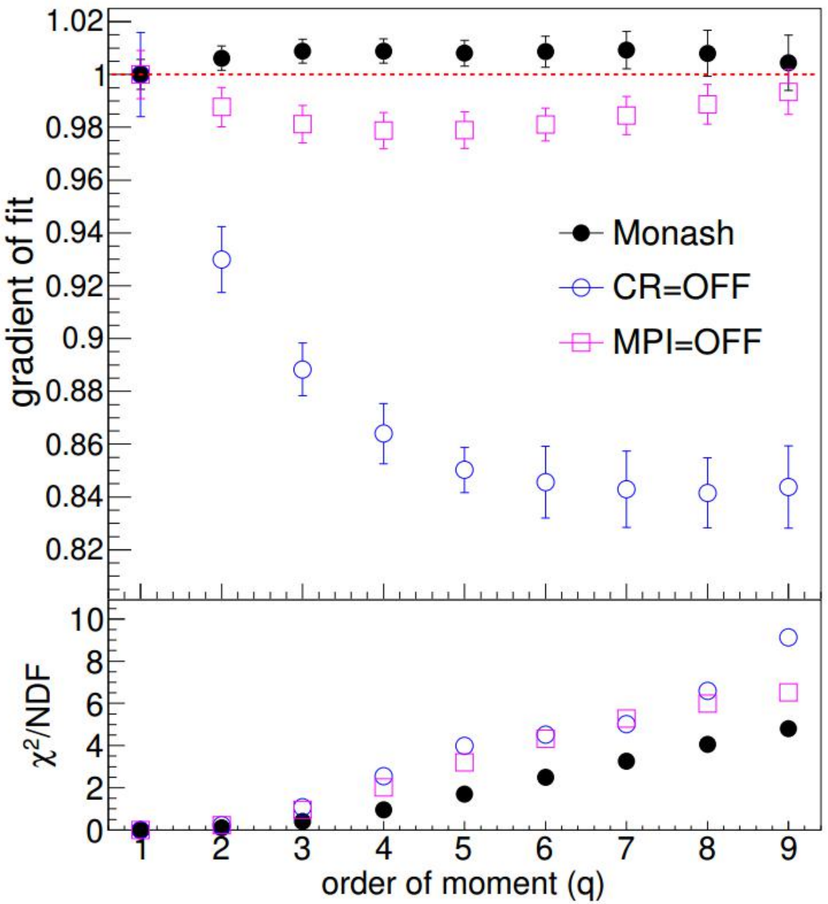


- **No multiple-parton interactions: scaling is present**
  - "possible physical" scenario producing low-activity events
- **No color reconnection: no scaling**
  - color-flow not handled, non-physical scenario

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)



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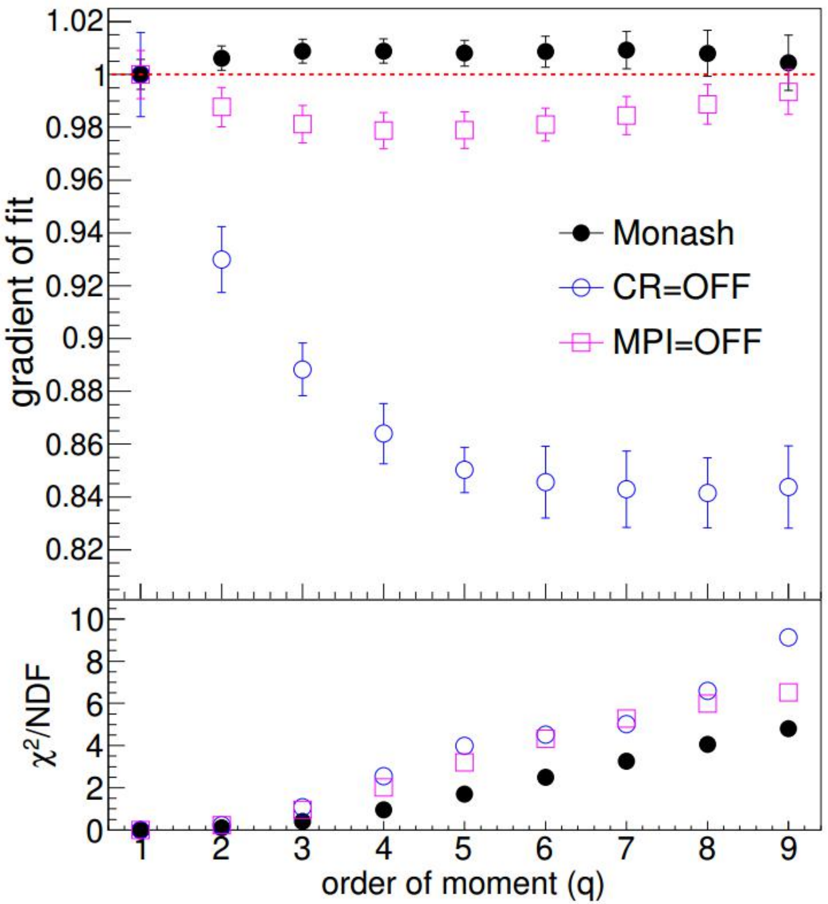

Summary

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- **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)
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Thank you!

Special thanks to Sándor Hegyi
for fruitful discussions and guidance

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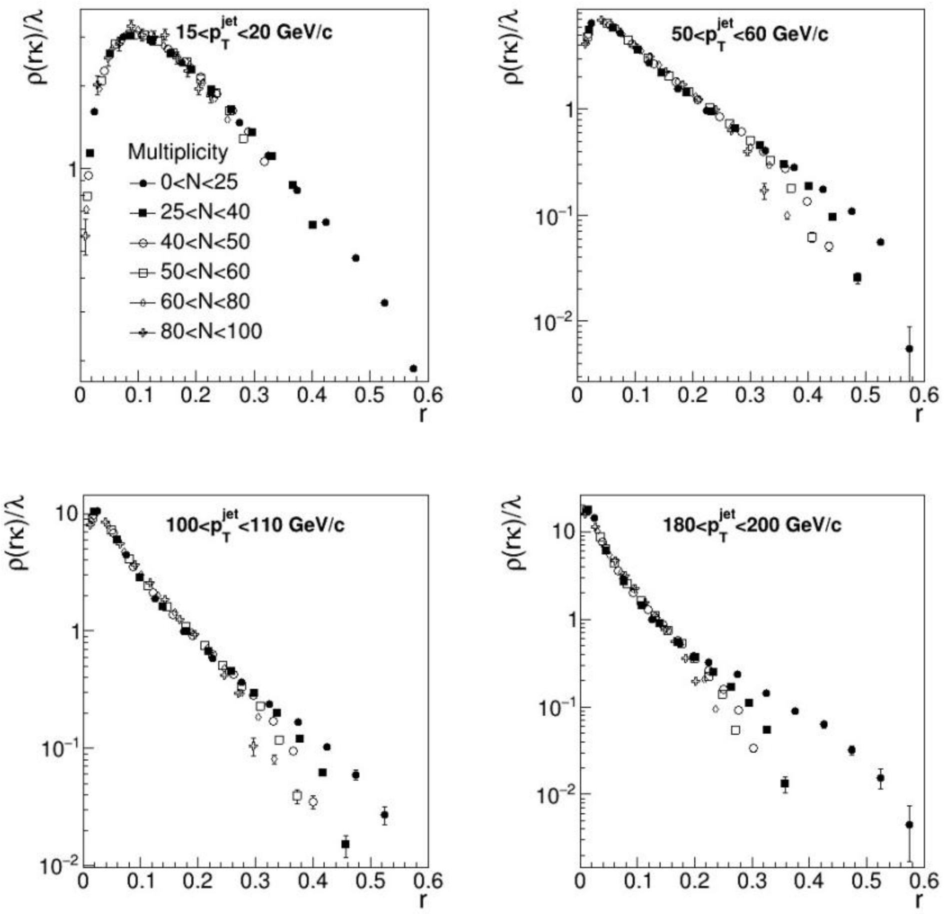
Scaling of the jet profiles - log scale

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

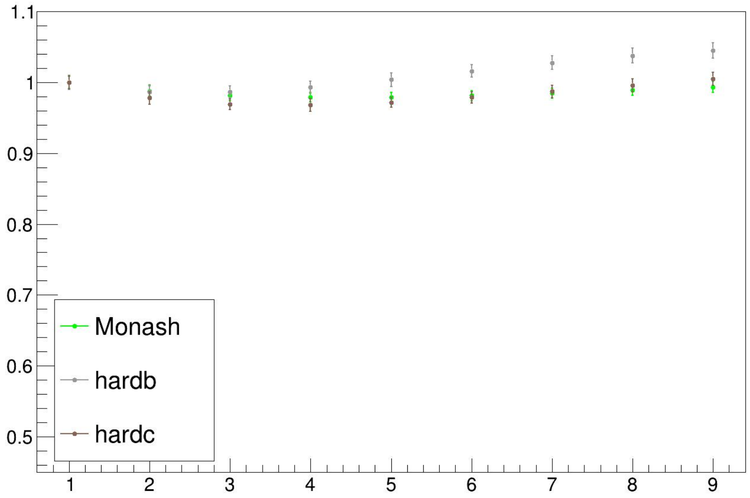
$$\rho_N(r) = \lambda(N) f\left(\frac{r}{\kappa(N)}\right)$$

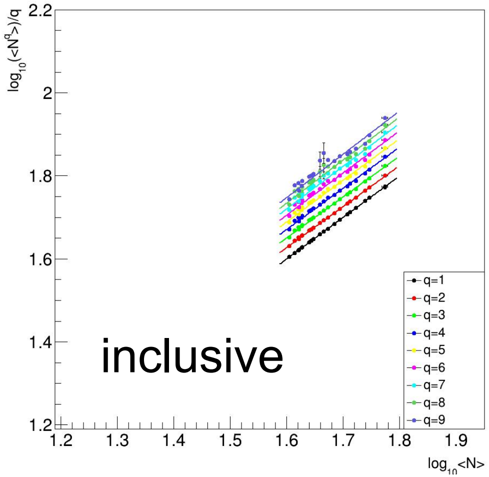
Note: Ideally, $\lambda = 1/\kappa$, however... "leakage" (distribution is cut-off at high *r* before normalization)

- Scaling is determined based on 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**

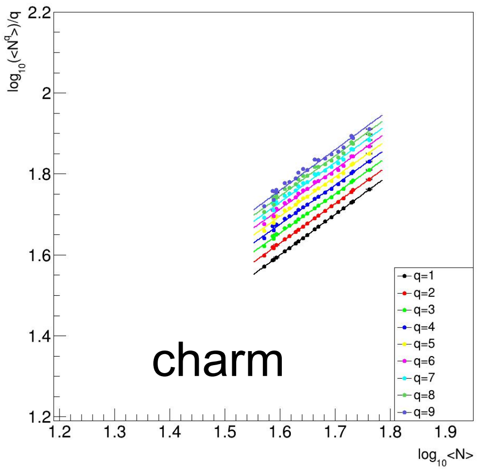


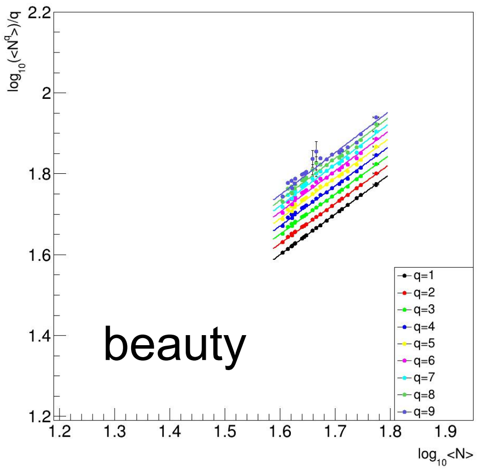
KNO-like scaling: Heavy Flavor



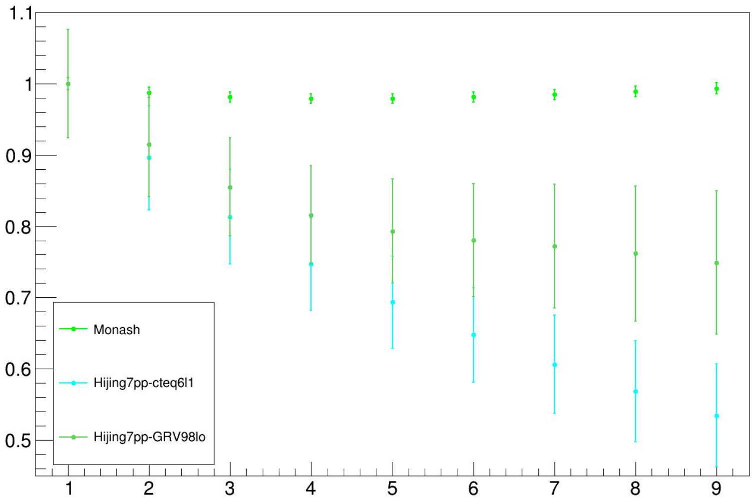


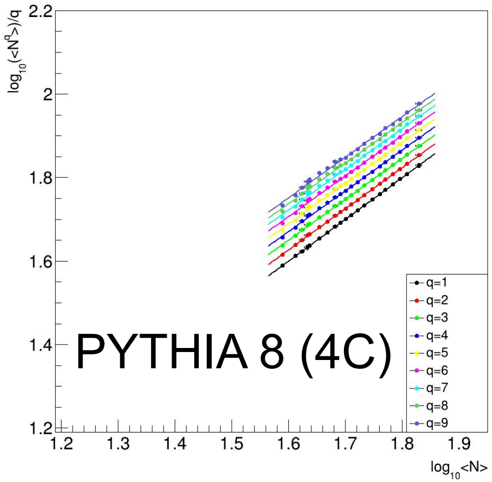
- Heavy-flavor jets also show KNO-like scaling



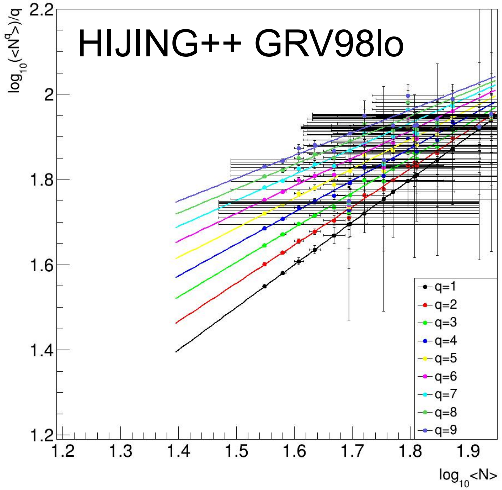


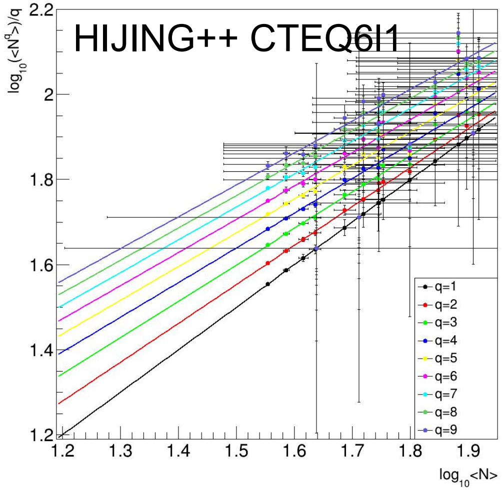
KNO-like scaling: Hijing++



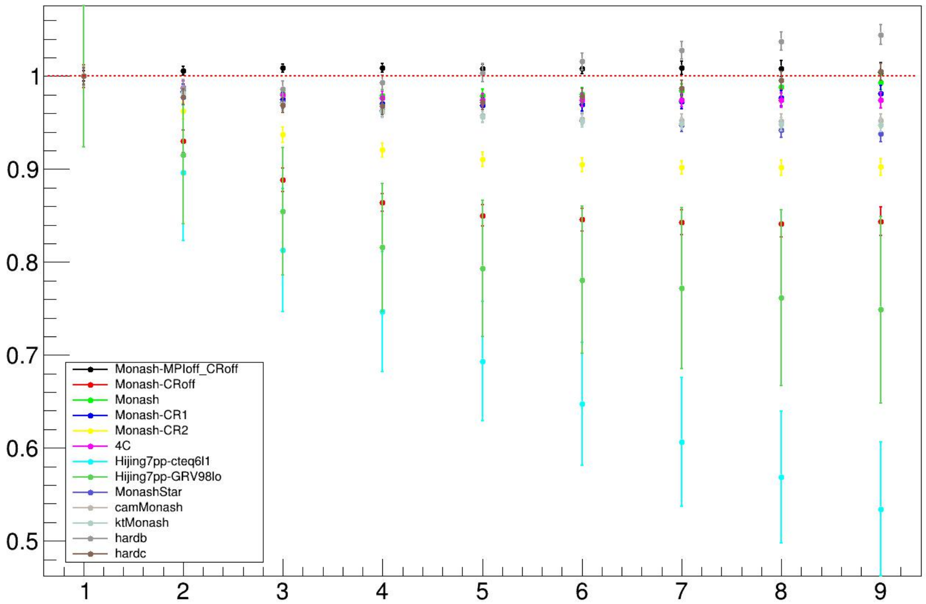


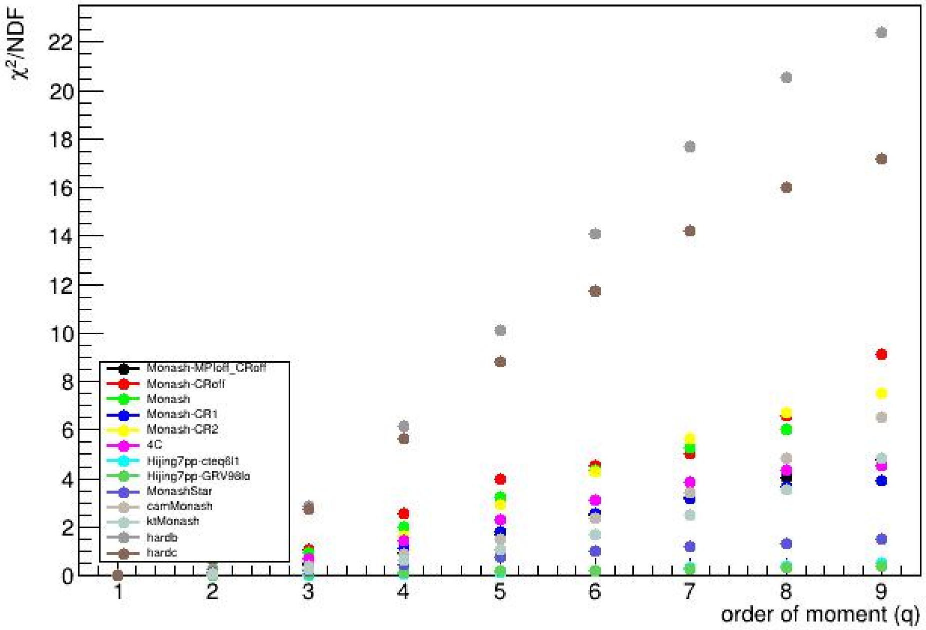
- Hijing++ does not exhibit the scaling



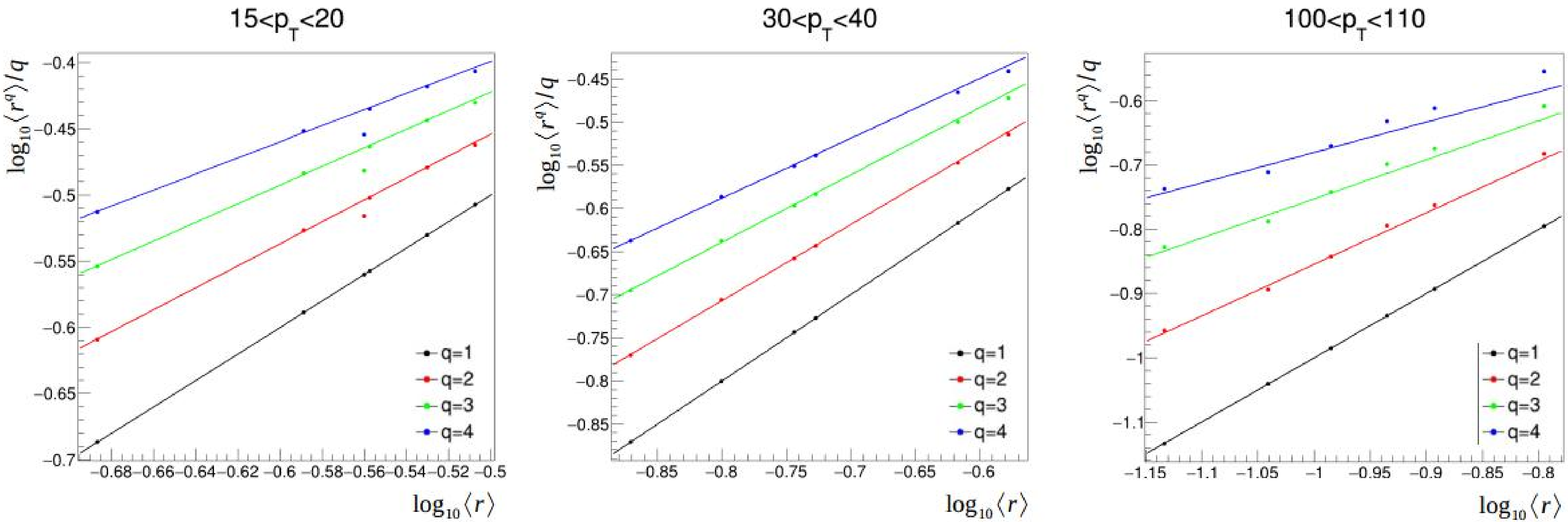


KNO-like scaling: summary



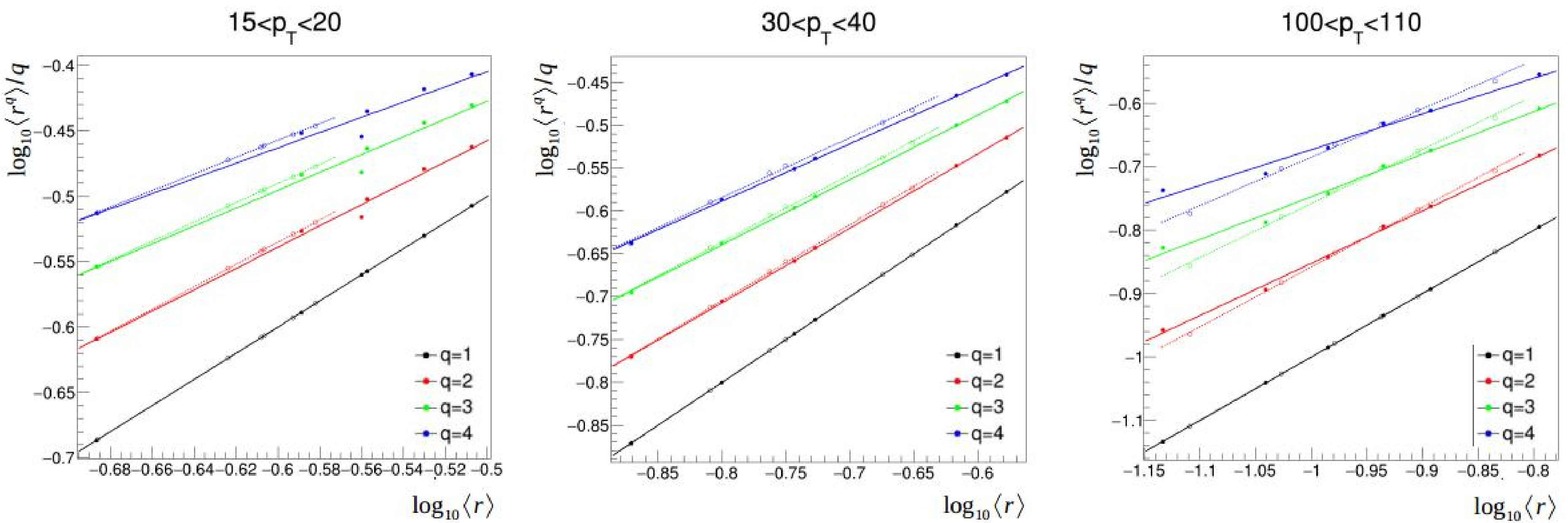


Statistical moments of jet profiles (Monash with MPI and CR)



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.