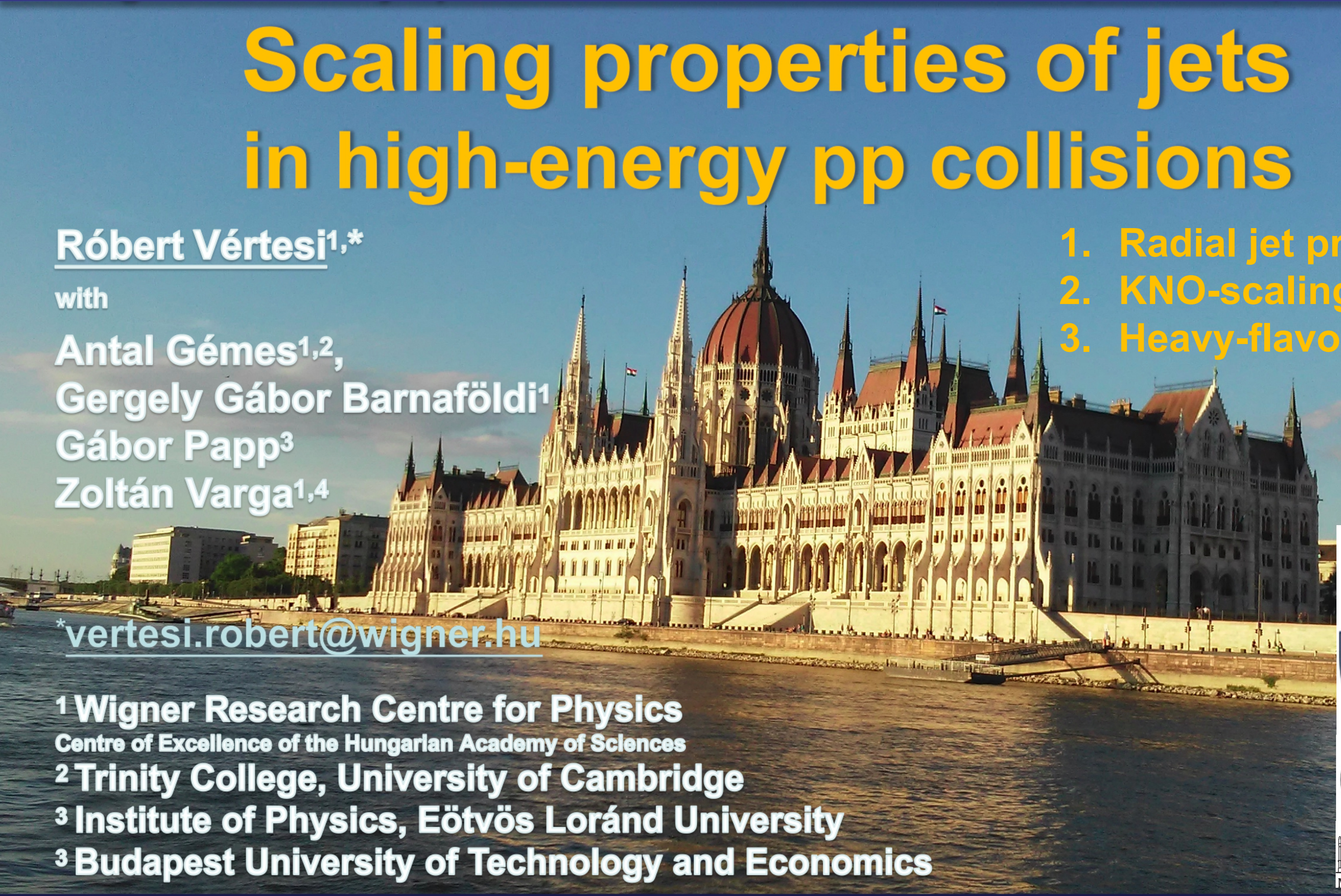
Margaret Island Symposium 2022 on Vacuum Structure, Particles, and Plasmas



Scaling properties of jets in high-energy pp collisions

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with
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1. Radial jet profiles
2. KNO-scaling within jets
3. Heavy-flavor jets

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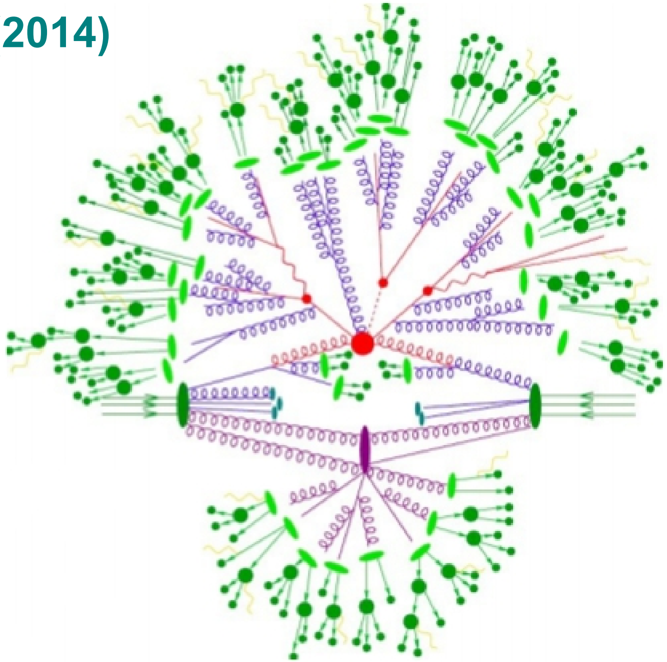
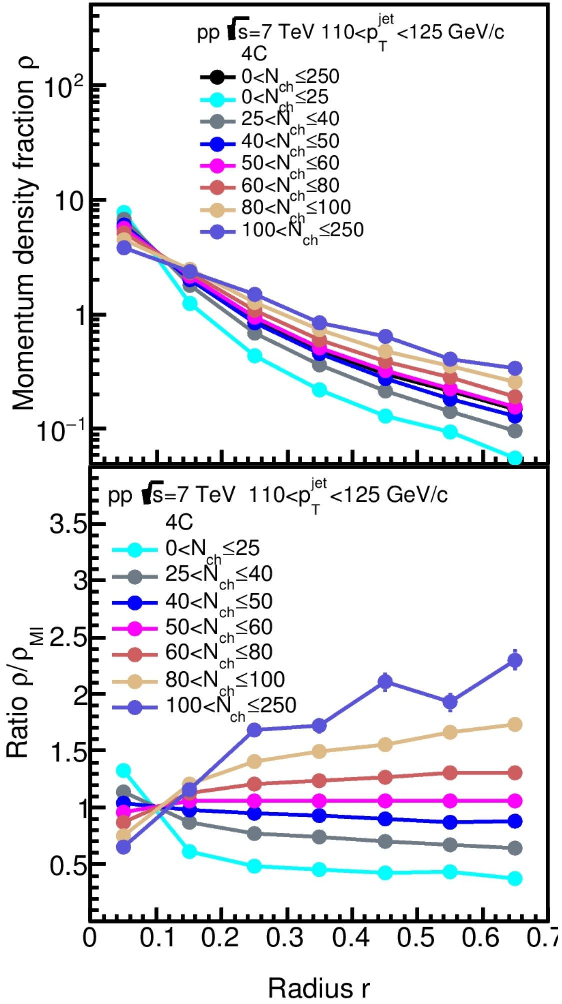
This work has been supported by the Hungarian NKFIH OTKA FK131979 and K135515 as well as the NKFIH 2019-2.1.11-TÉT-2019-00078, 2019-2.1.11-TÉT-2019-00050, 2019-2.1.6-NEMZKI-2019-00011, 2020-1.2.1-GYAK-2020-00013 grants

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 jet suppression expected;
    However: soft and hard processes are related by MPI
    => jets can serve to study this connection



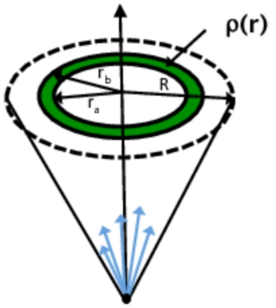
1) Radial jet profiles



- Radial jet profiles

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

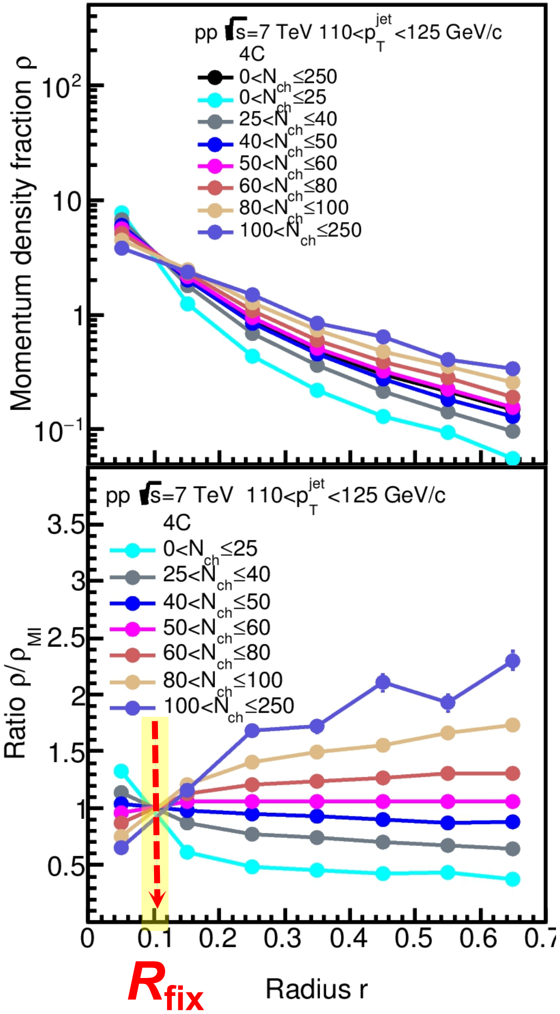
$$r_i = \sqrt{(\phi_i-\phi_{jet})^2+(\eta_i-\eta_{jet})^2}$$



- PYTHIA 8.2 simulations
  pp collisions at √s = 7 TeV, R=0.7, 50<p_T^{jet}<60 GeV/*c*, |*y*|<1
- **7 multiplicity classes**

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

1) Radial jet profiles



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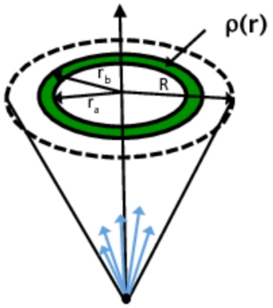


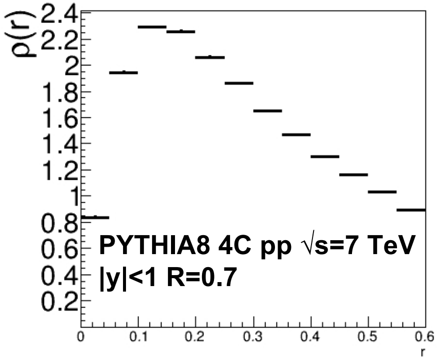
- PYTHIA 8.2 simulations
  pp collisions at √s = 7 TeV, R=0.7, 50<p_T^{jet}<60 GeV/*c*, |*y*|<1
- **7 multiplicity classes**
  jet profile curves intersect at R_{fix} in any p_T^{jet} window
- ***R_{fix}* independent of**
  - **generator**: Pythia, Hijing++
  - **tune**: 4C, Monash, Monash*
  - **nPDF**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

⇒ **Is it a scaling behavior?**

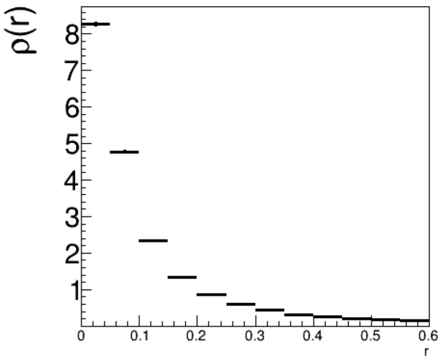
**Z. Varga, R.V, G.G.B,
Adv. HEP 2019, 6731362 (2019)**

Parametrizing the jet profiles

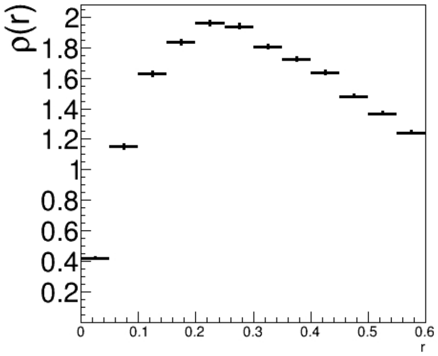
- Detailed PYTHIA 8 simulations (4C)
    - Jet radius: 12 bins up to *r*=0.6
    - Multiplicity 6 bins up to *N*=100
    - Momentum: 20 bins up to p_T^{jet}=400



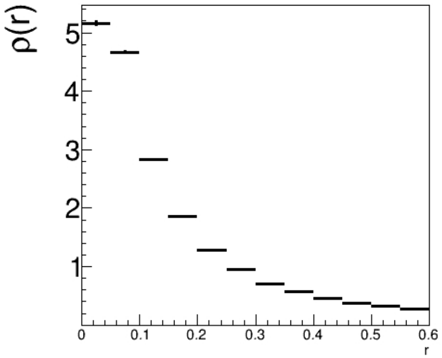
25<N<40, 15<p_T^{jet}<20 GeV/c



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:
    - **Gamma distribution**

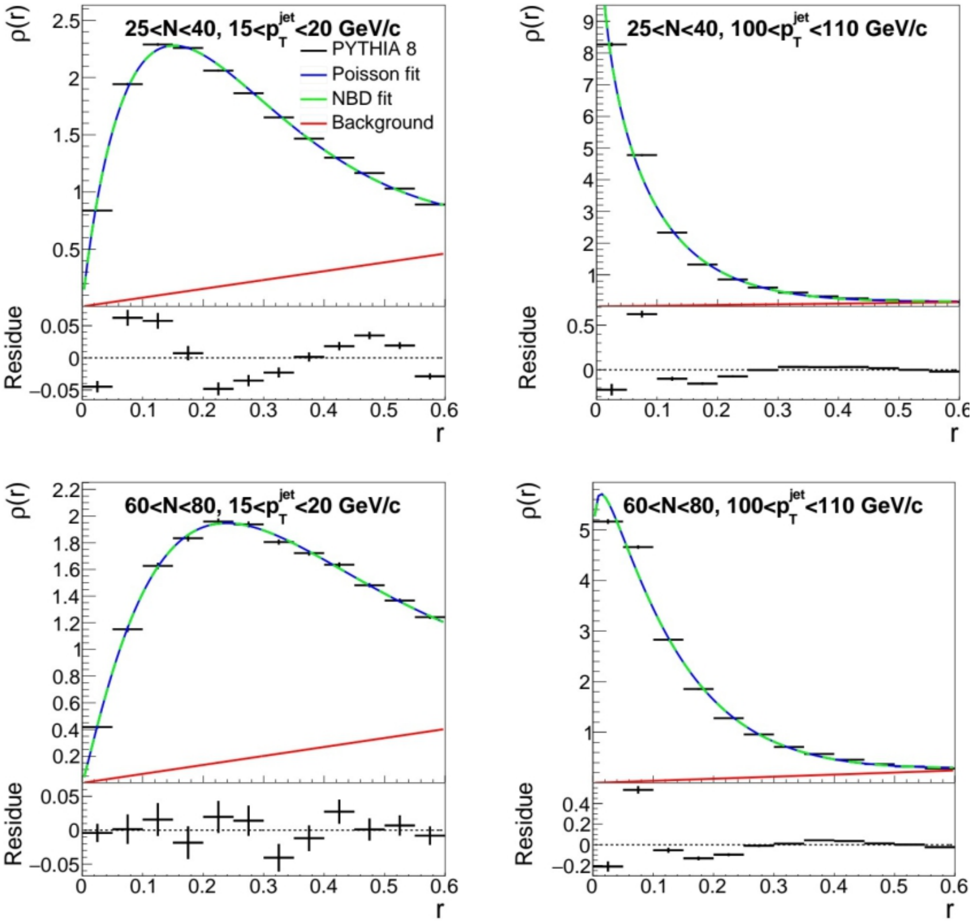
$$\rho(r)=Cr^{\gamma}e^{-\alpha r}$$

    - **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



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

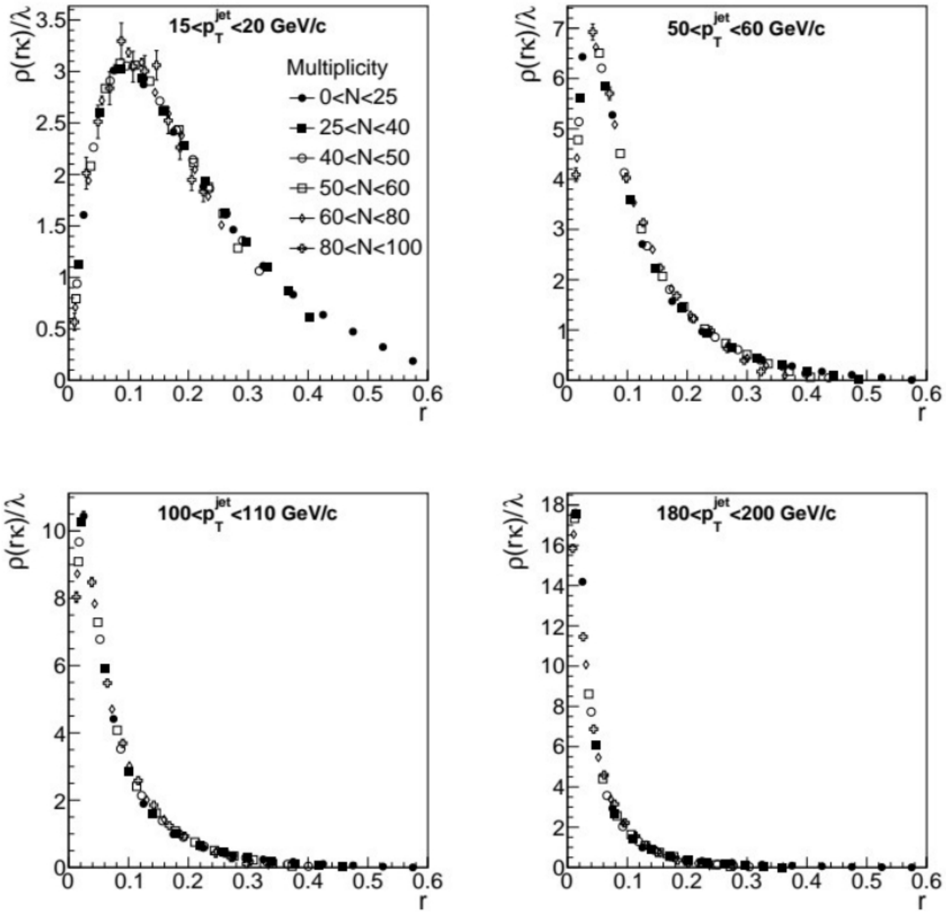
Scaling of the jet profiles

- 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**



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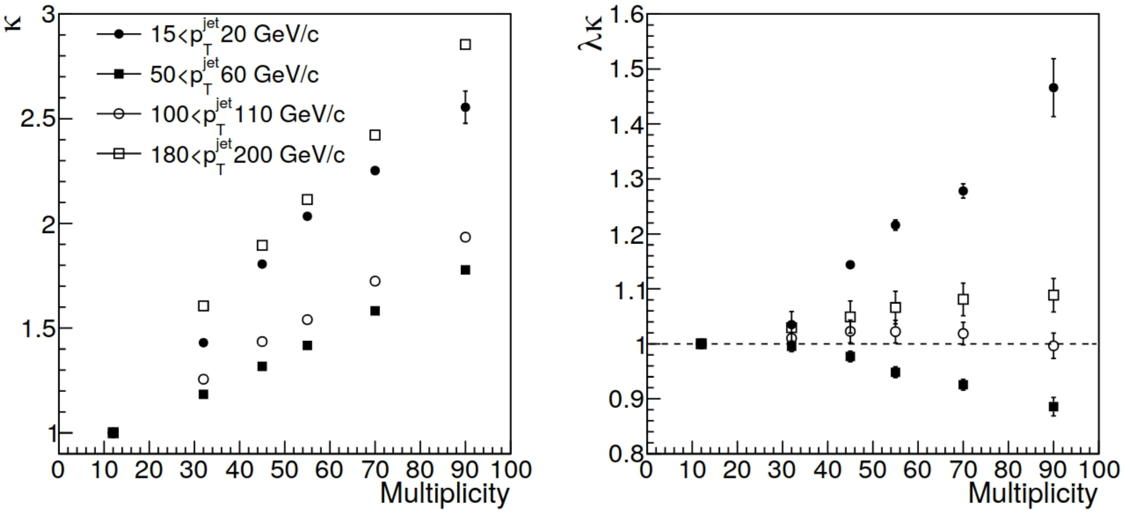
Scaling factors



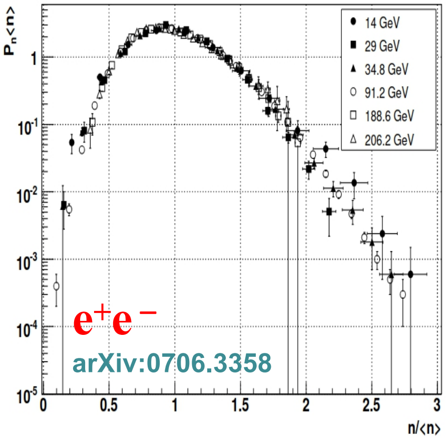
Gribov-90 Memorial Volume, 81 (2021) [arXiv:2008.08500]

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

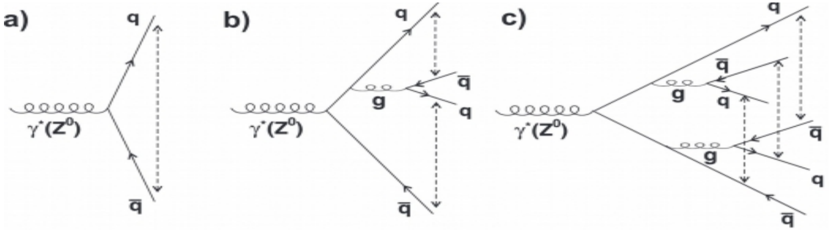
- The scaling parameter κ is approximately linear with multiplicity
- Ideally, $\lambda\kappa \sim 1$. This is fulfilled on the 10% level except for the lowest-p_T bin
    - Low-p_T increase is because leakage increases λ
    - Slight high-p_T decrease is because background determination

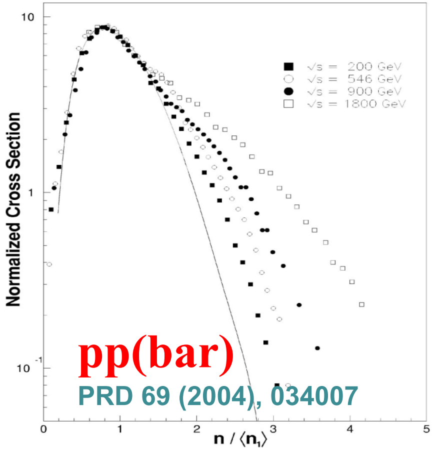
2) KNO-scaling within jets

- 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



e^+e^-
arXiv:0706.3358

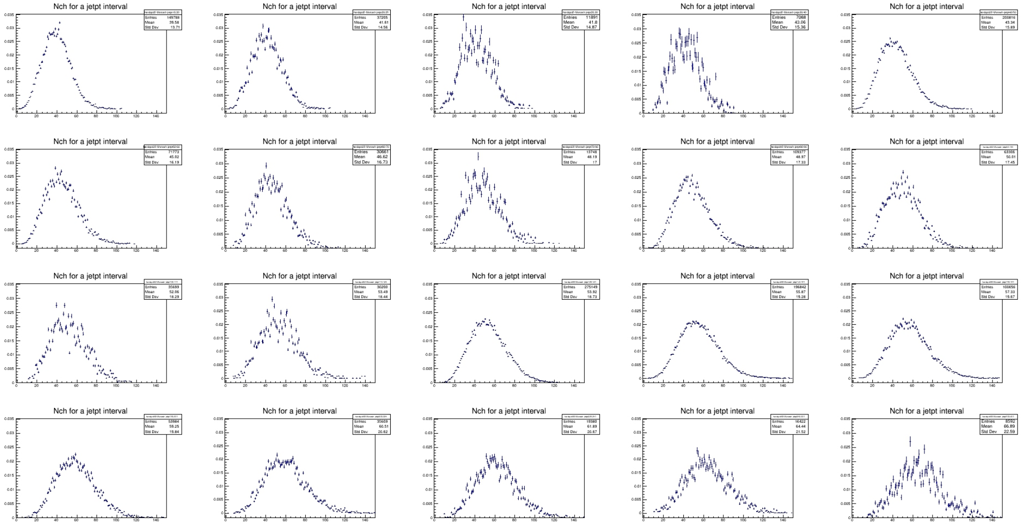




pp(bar)
PRD 69 (2004), 034007

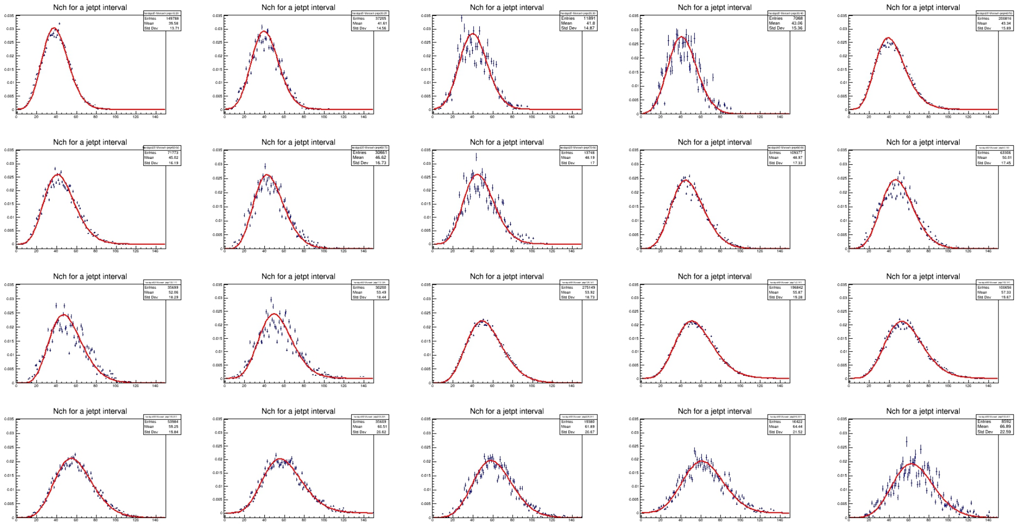
- **Is KNO-scaling valid within a single jet?**
- **How is affected by MPI and CR?**
- **Is there a connection of KNO to radial scaling?**

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



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

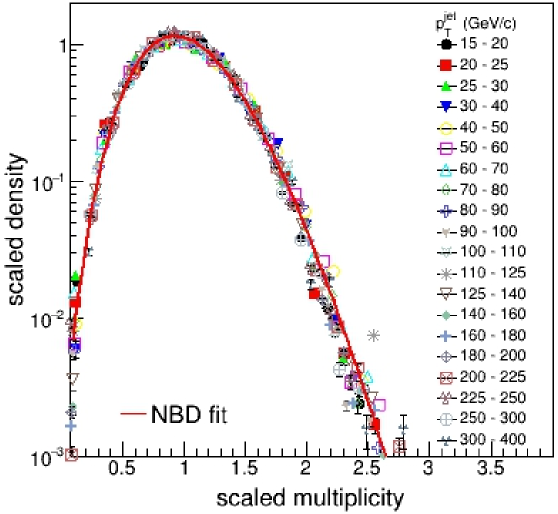
KNO within jet: multiplicity scaling with p_T^{jet}

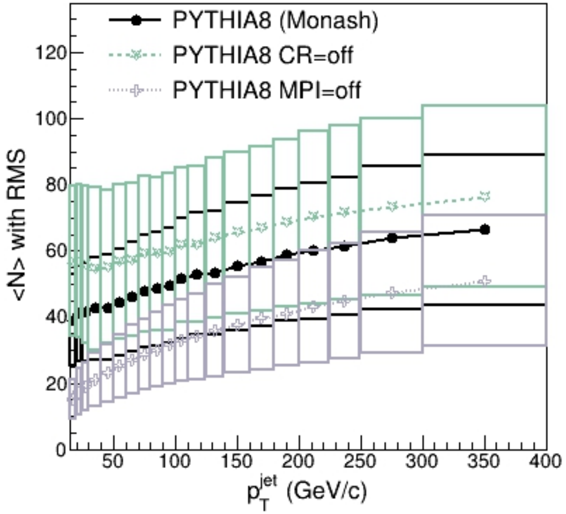


- Multiplicity (dominated by the jet multiplicity) vs. jet momentum p_T^{jet}
- Parametrized with a NBD

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

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





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

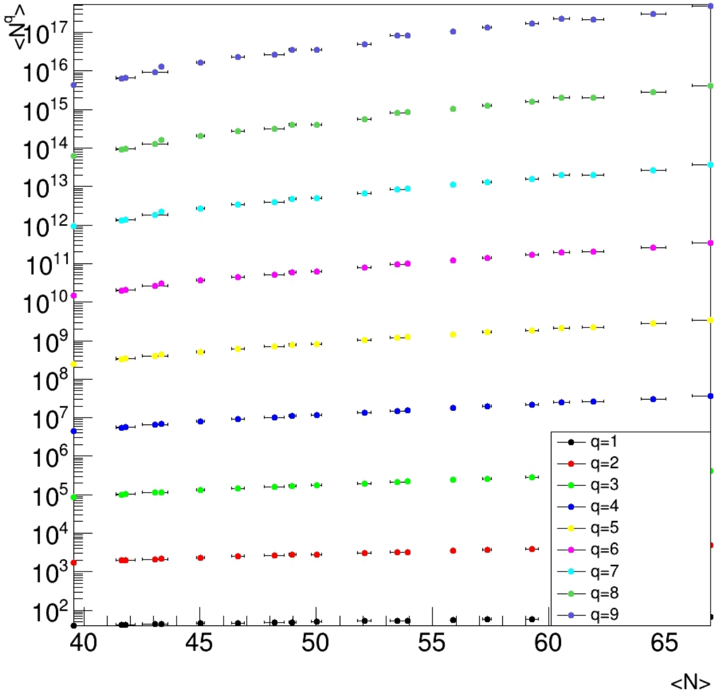
- Multiplicity (dominated by the jet multiplicity) vs. jet momentum p_T^{jet}
- Parametrized with a NBD $$P_N = \frac{\Gamma(Nk+a)}{\Gamma(a)\Gamma(Nk+1)} p^{Nk}(1-p)^a$$
- Distributions at all p_T^{jet} fit well on a single NBD curve
- **KNO-like scaling observed within a jet**
  - In the following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

$$\left\langle N^q(p_{\mathrm{T}}^{\mathrm{jet}}) \right\rangle = \lambda^q(p_{\mathrm{T}}^{\mathrm{jet}}) \left\langle N^q(p_0) \right\rangle \qquad \lambda(p_0) \;=\; 1$$

Multiplicity vs. p_T^{jet}: moments

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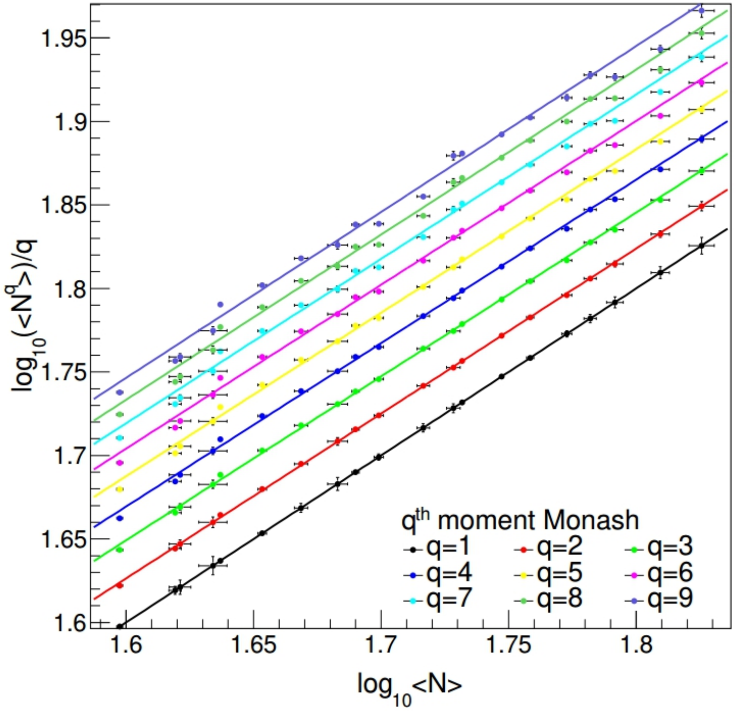


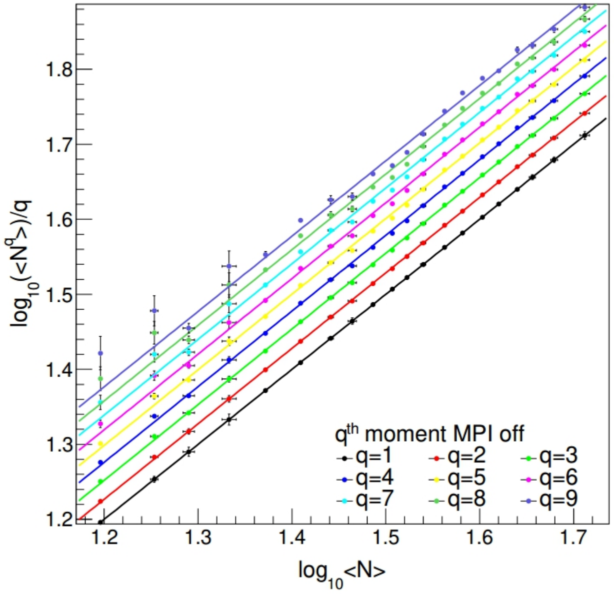
Phys.Rev.D 103 (2021) 5, L051503 [arXiv:2012.01132]

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

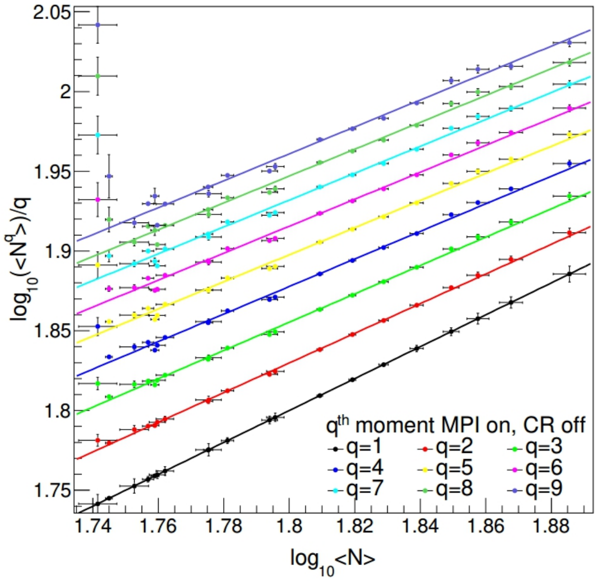
=> scaling is fulfilled in the whole p_T^{jet} range

Moments: Role of MPI and CR

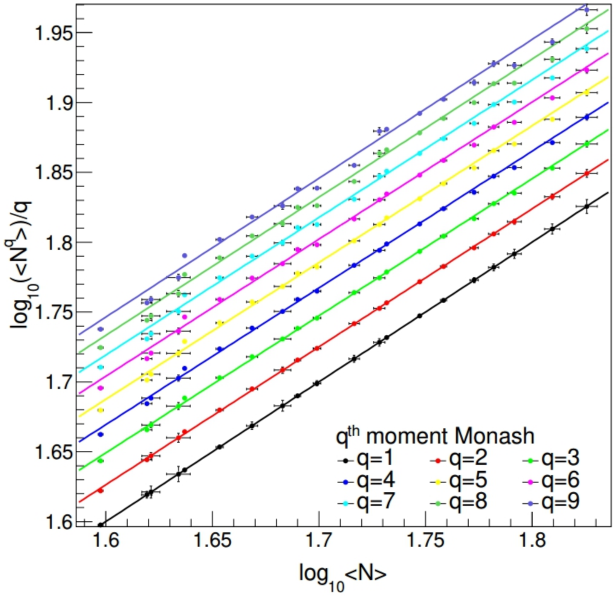
MPI off



CR off, MPI on



physical: CR on, MPI on



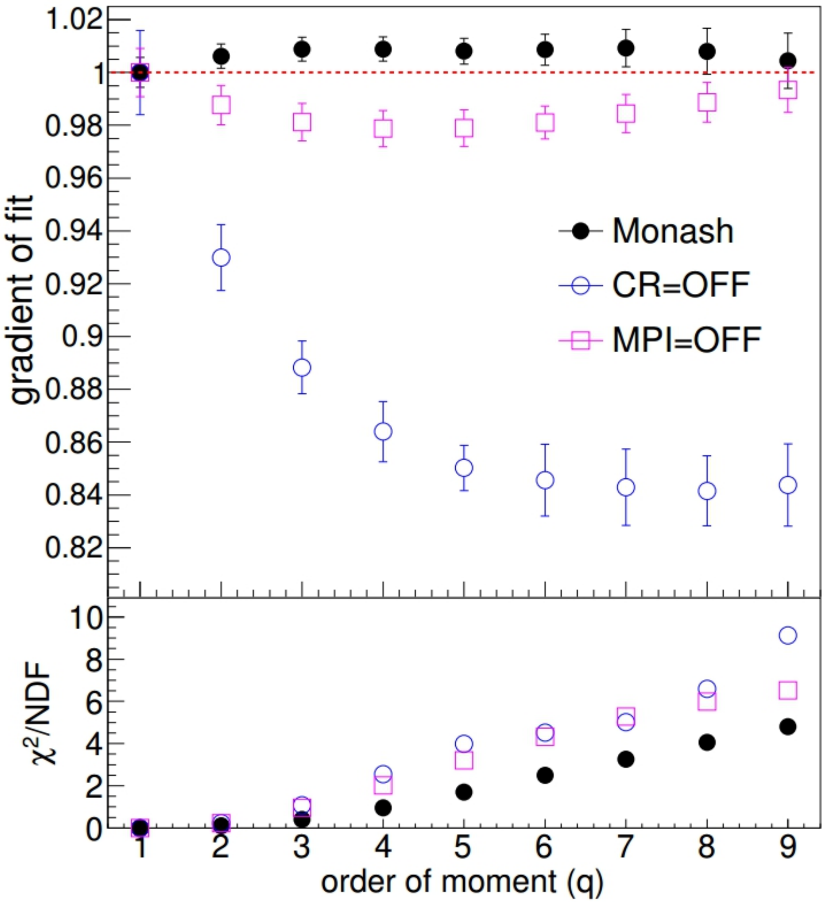
Phys.Rev.D 103 (2021) 5, L051503 [arXiv:2012.01132]

- **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 ~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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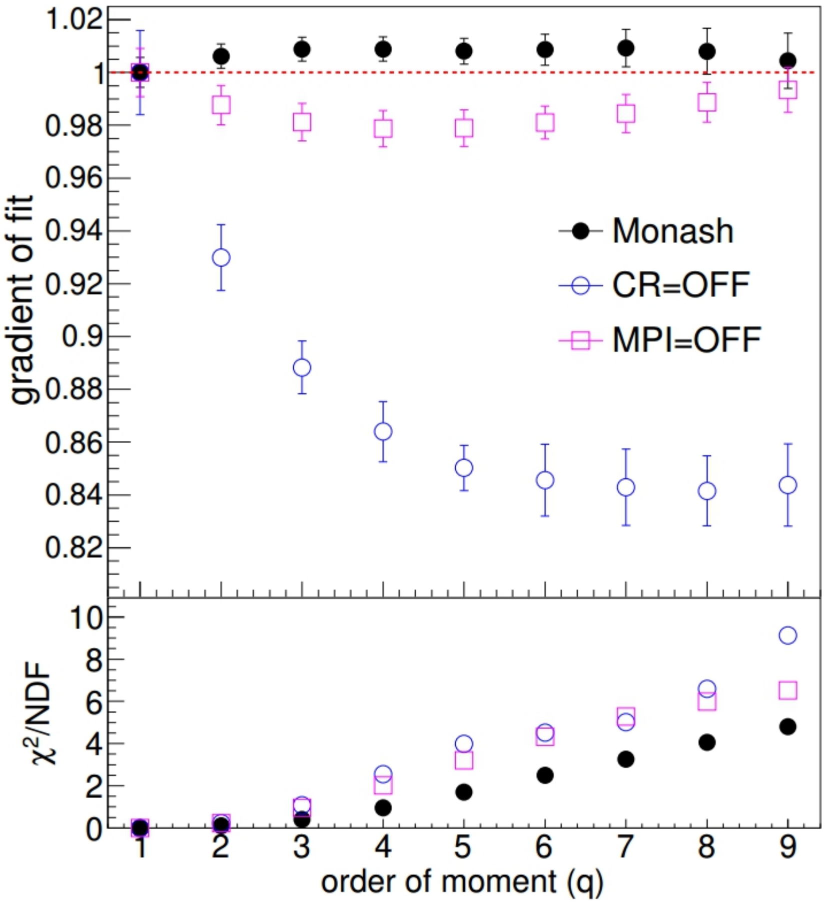
- **No CR**: Scaling is broken by ~15%
- **No MPI** (also no CR by construction): Scaling is fulfilled to ~2%.
- All fits are statistically good (χ^2/NDF<8, ~proportional to the order of moment)
- **The emerging picture is different from that of radial profile scaling, which holds for CR=off as well**



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

3) How do heavy-flavor jets scale?

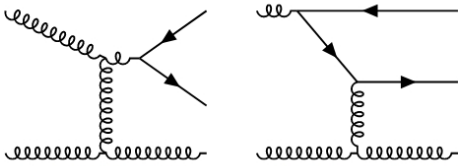
- HF created via...
  - **LO** Flavor Creation
  - **NLO** Gluon Splitting and Flavor Excitation
- These contributions are of similar magnitudes

  Cao et al., Phys.Rev.C 93 (2016) 2, 024912

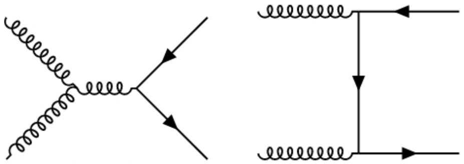
- Heavy-flavor jet production affected by:
  - Mass dependent effects: harder fragmentation, dead-cone effect
  - Color-dependent effects: HF initiated by quark jets only

  => HF jets are different than LF jets

- Comparison of scaling LO and NLO: sensitivity to its origin (hard QCD process vs. jet development)

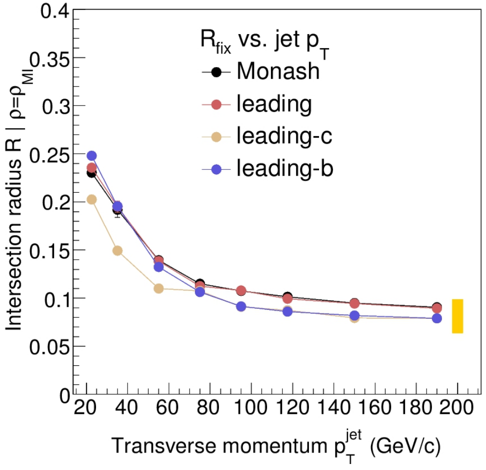


(a) Gluon Splitting (b) Flavor Excitation



(c) *s*-channel Flavor Creation (d) *t*-channel Flavor Creation

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



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

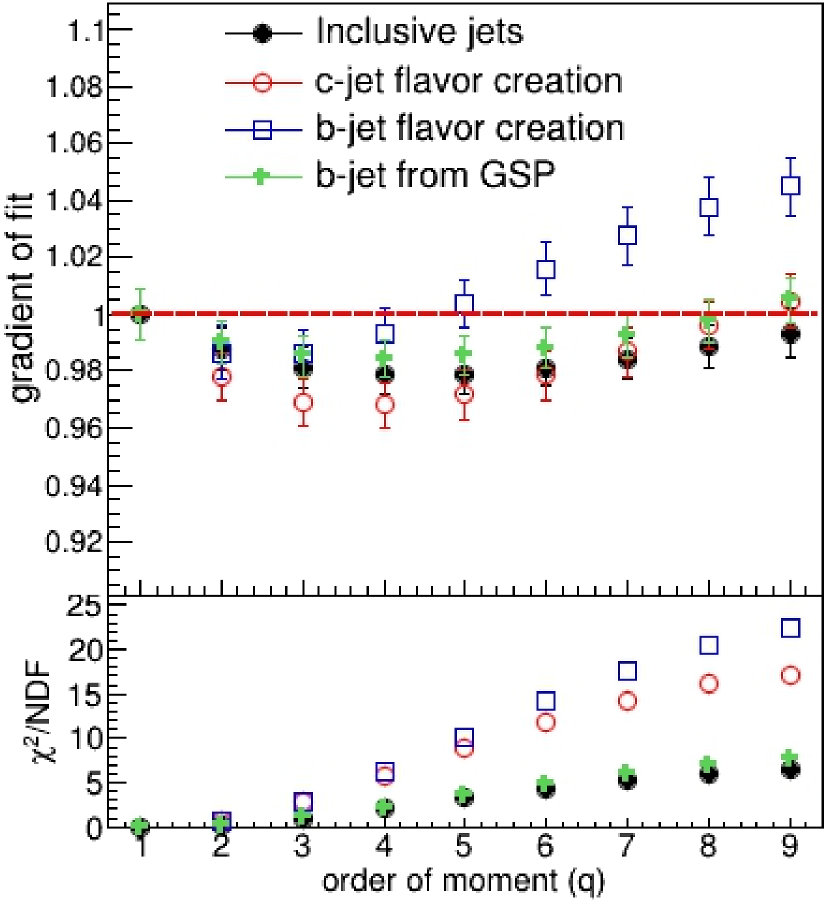
HF jets - production vs. fragmentation

- 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



manuscript under preparation

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 => **fundamental statistical origin?**
- 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

- LO flavor creation: quark-mass dependent, imperfect scaling
- NLO gluon splitting: follows (gluon-dominated) light-jet pattern
- **Jet scaling driven by the initial hard parton-production process**

Thank you!

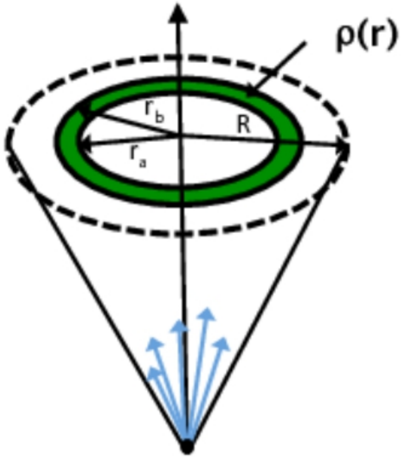
Special thanks to Sándor Hegyi
for fruitful discussions and guidance

This work has been supported by the Hungarian NKFIH OTKA FK131979 and K135515 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

1) Radial jet profiles

- Differential jet shape

CMS, JHEP 06, 160 (2012)



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

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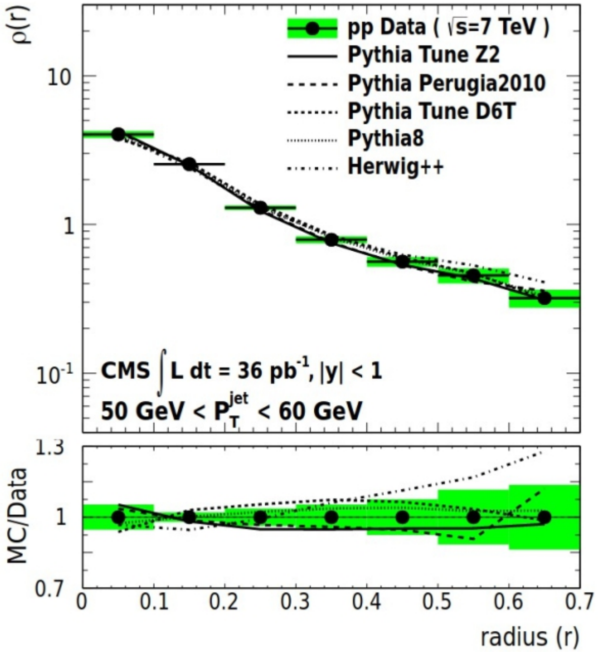


- CMS@LHC pp collisions, $\sqrt{s}$ = 7 TeV
- R=0.7 jets, 50<$p_T^{\rm jet}$<60 GeV/c, $|y|$<1

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

Scaling of the jet profiles - log scale

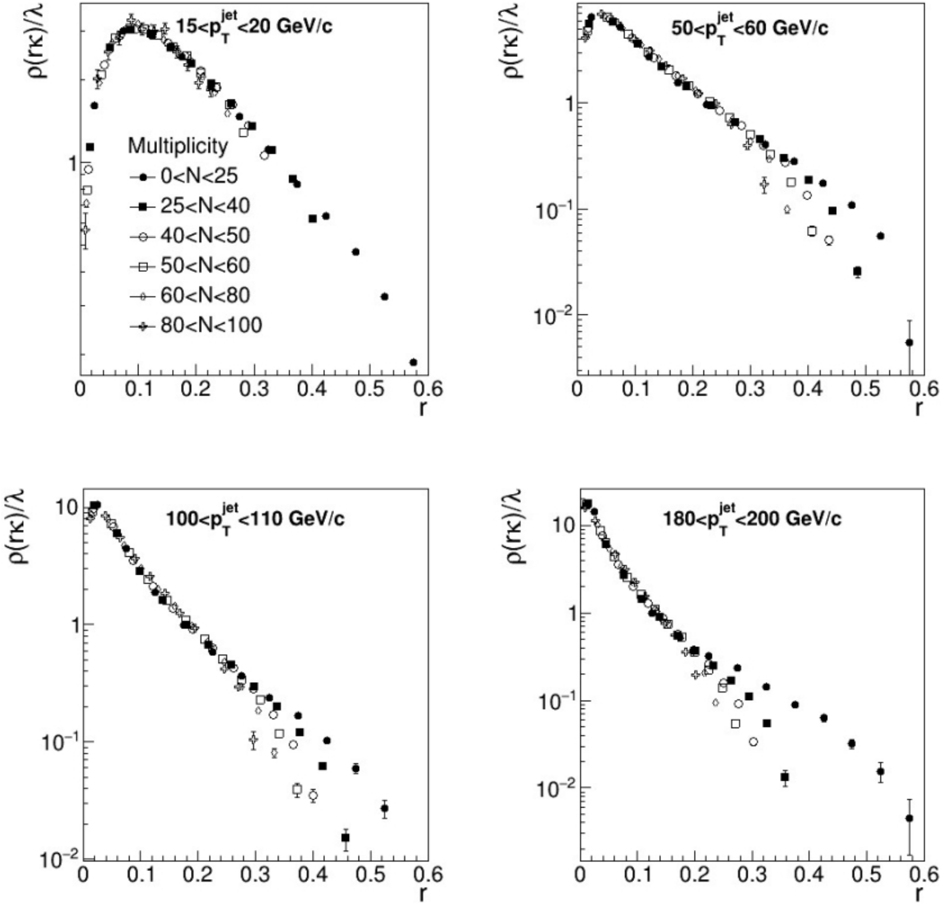
- Scaling assumption: profiles at all multiplicities collapse into a single distribution,

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

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**



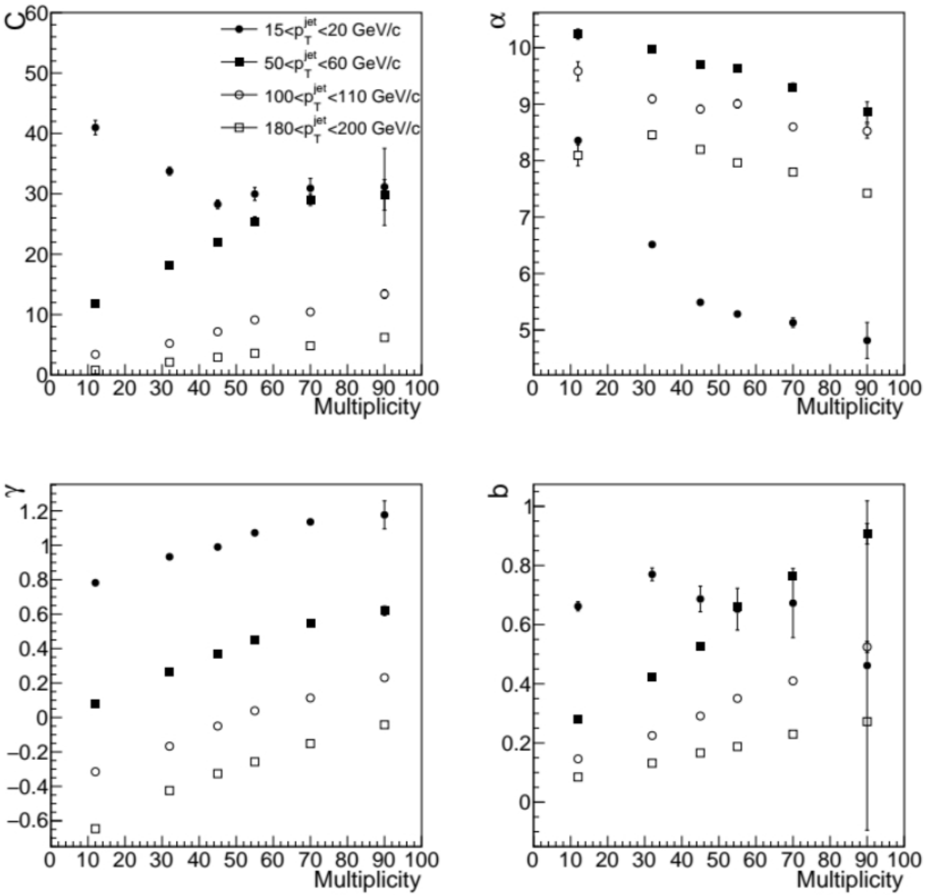
Parameters of the fits

- 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]

How good are the fits?

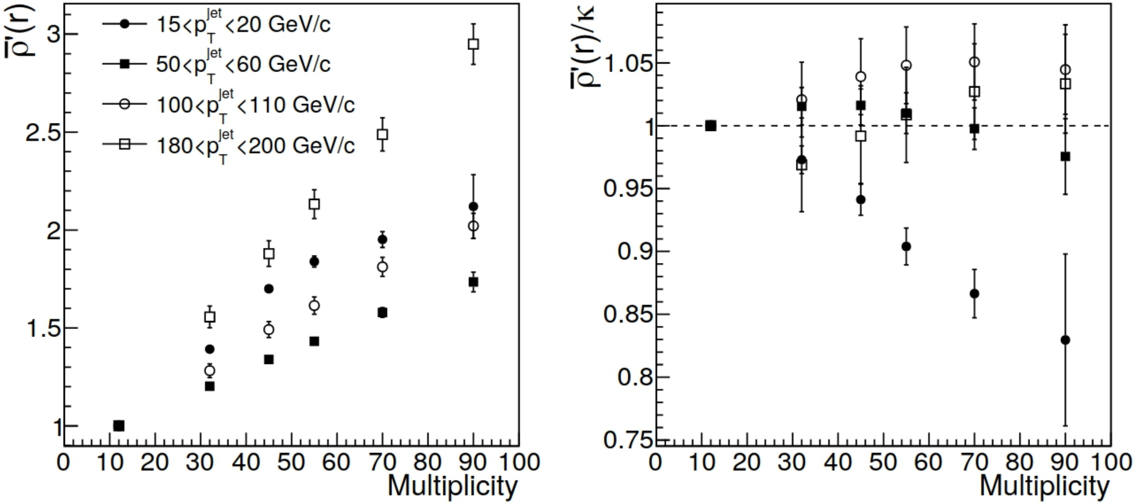
- Fitted distribution mean:

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

- Ideally, it shoud scale:

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

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



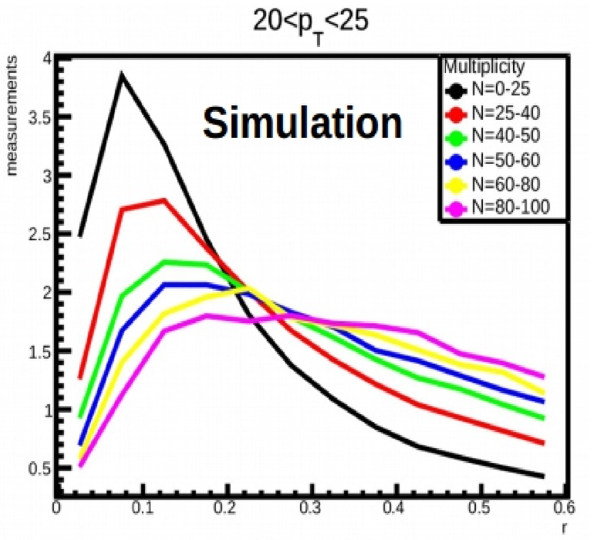
- The mean approximately scales linearly with multiplicity
- Except for the lowest p_T bin, $\kappa/\bar{\varrho}' \sim 1$ within 5%
- Hence,

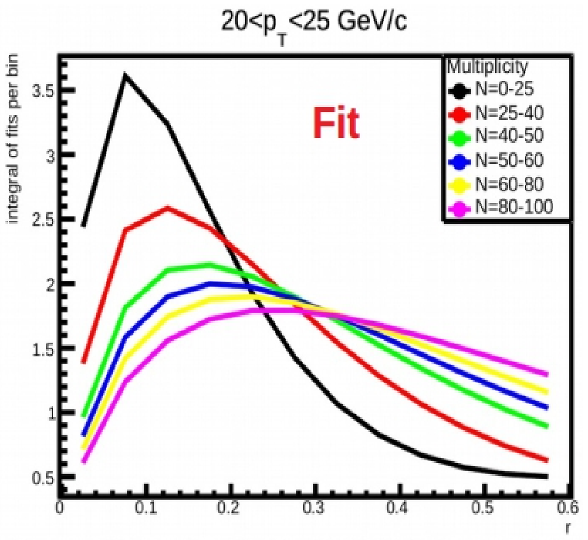
» **Radial profiles scale with multiplicity**

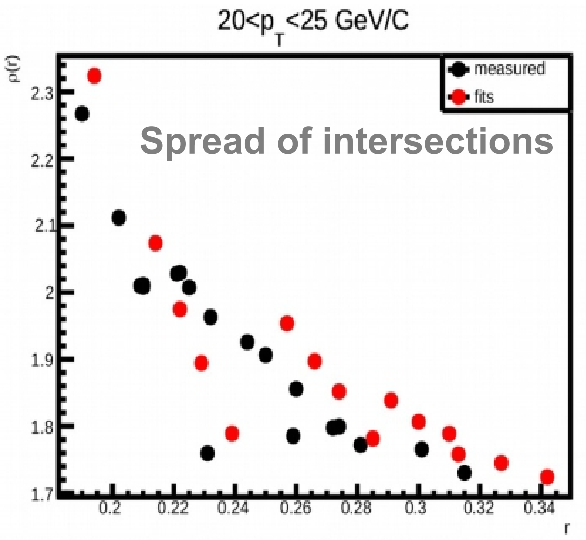
» **The gamma distribution is an adequate description**

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

Is there really an R_{fix}?

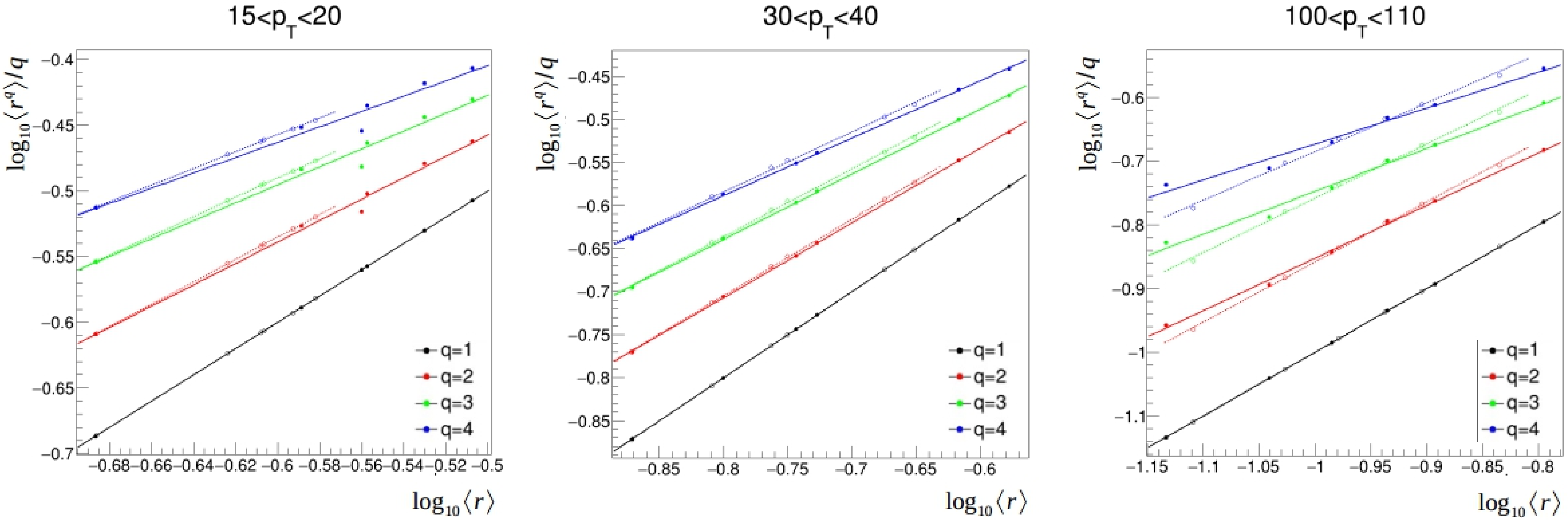






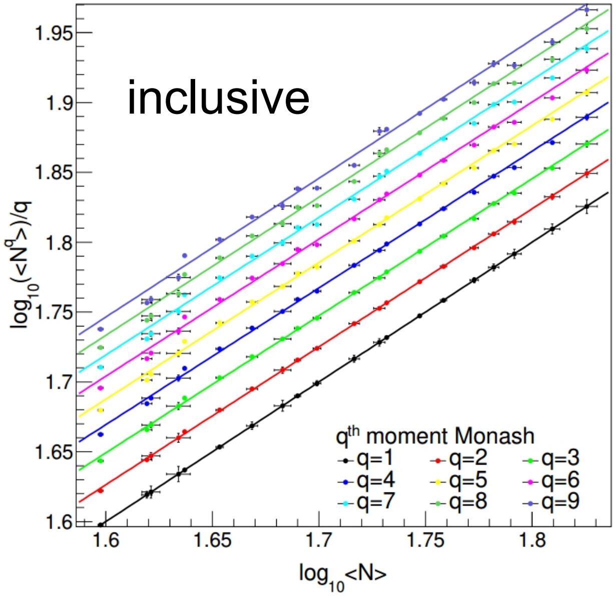
- Based on the parametrization of the Gamma distribution, **R_{fix} is an approximate consequence of the scaling**
- *Note: R_{fix} would be exact if $\rho(r)$ fell linearly in the given region*

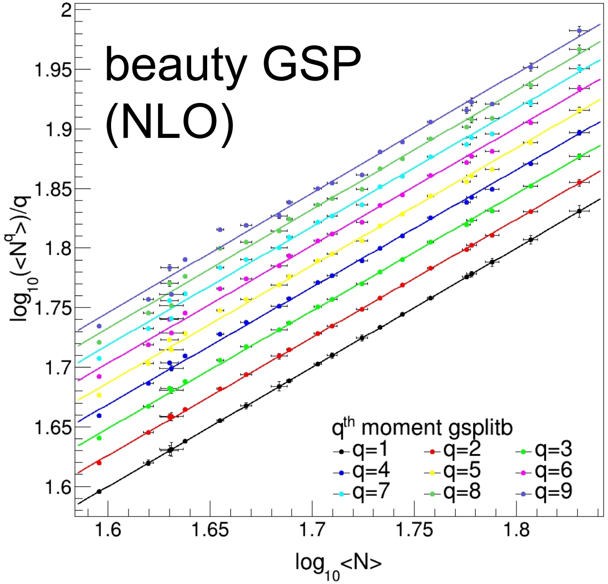
Effects of finite-size bins (jet profiles)

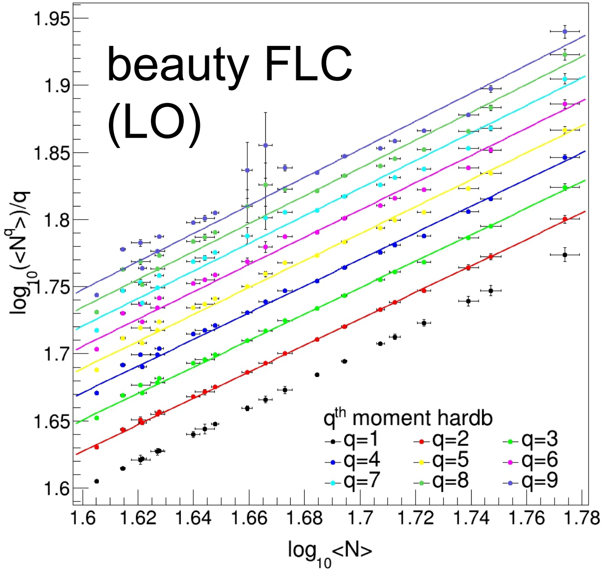


Dotted lines: effect of binning on analytical curves. Qualitatively explains the behavior seen in the simulations.

3) KNO-like scaling: Heavy Flavor







- Beauty-jets