Recent multiplicity-based measurements in jet physics

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Is there QGP creation in small systems?

Experimental observation 1:
There is QGP formation in A-A collisions (large systems).

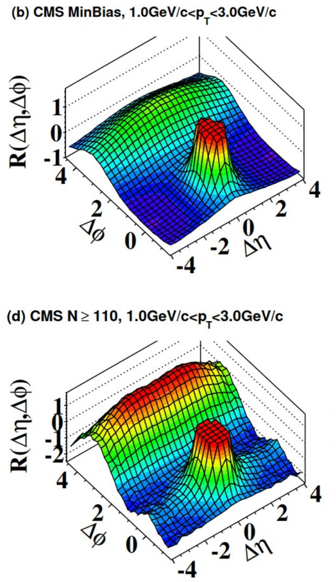
Experimental observation 2:
Collective phenomena in **high-multiplicity pp** collisions:
- significant elliptic flow (v_n),
- increased production of rare hadrons,
- ridge structure.

Question: How do QGP signatures change with system size?
- Is there evidence for jet modification in small systems?

QGP is not required to explain collective phenomena:

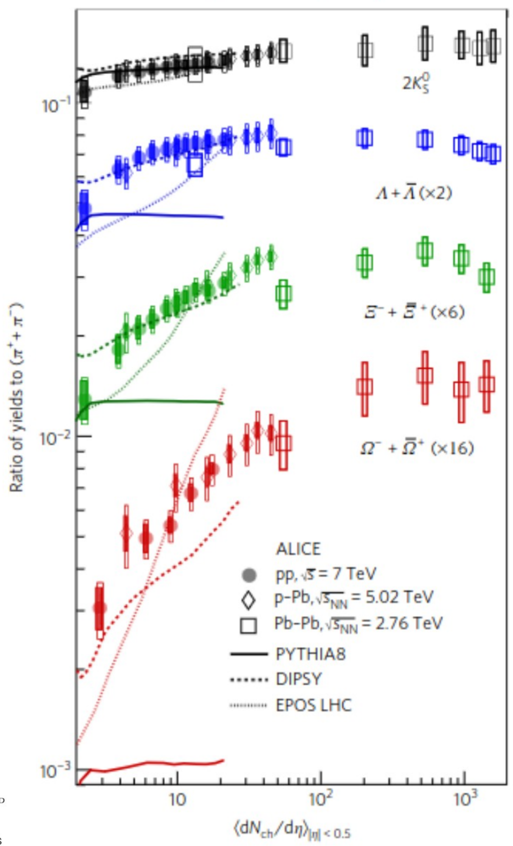
- These can be understood through **vacuum QCD processes** occurring at the boundary between the soft and hard regimes. e.g. **multiple-parton interactions** and **color reconnection**.

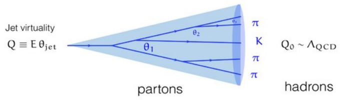
- We do not expect suppression, but the **shape** of the jets could be modified as a function of **multiplicity**.



CMS, JHEP 09 (2010) 091

Nature Physics 13 (2017) 535-539

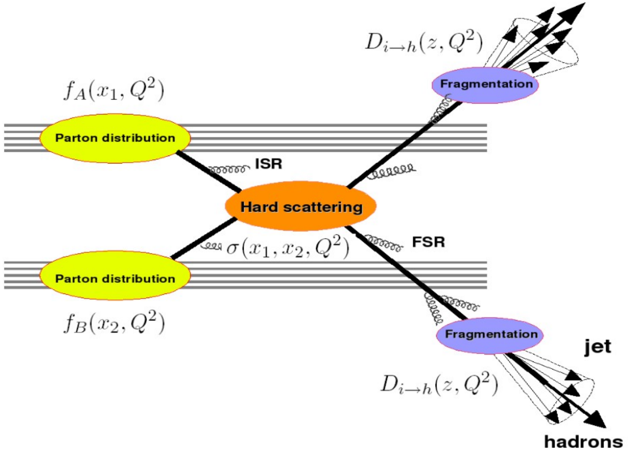


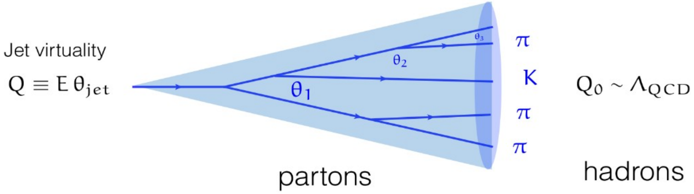


Background

- **Jets:** collimated showers of particles produced by fragmentation and hadronization of hard-scattered partons.
- **Experimentally:** defined by a jet reconstruction algorithm and a jet resolution parameter R.
- An experimentally accessible **observable** to "capture" the directly unmeasurable **parton shower**.
- **Jet multiplicity** is the number of charged final-state particles within the jet cone.
- Important information to probe particle production models.

D. d'Enterria arXiv:0902.2011

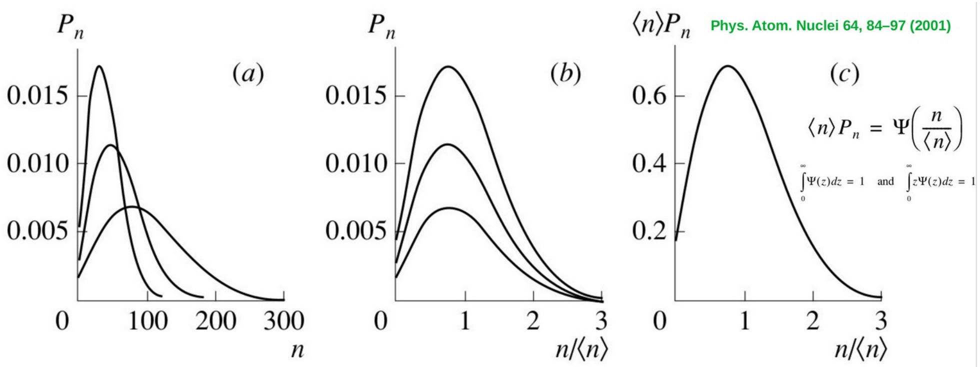


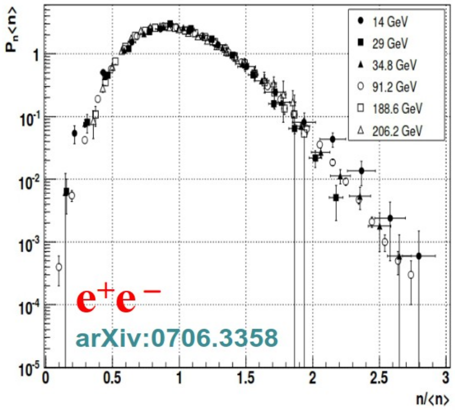


Koba-Nielsen-Olesen (KNO) scaling

Koba-Nielsen-Olesen (KNO) scaling hypothesis:

- Influential contribution to the analysis of event multiplicities in high-energy particle collisions.

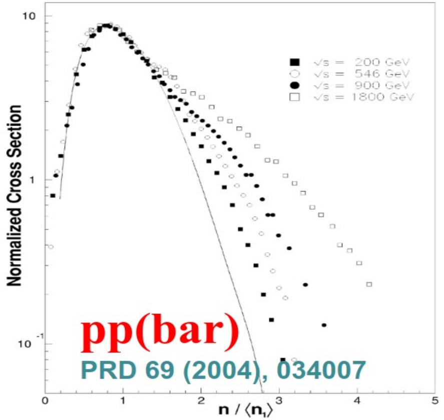




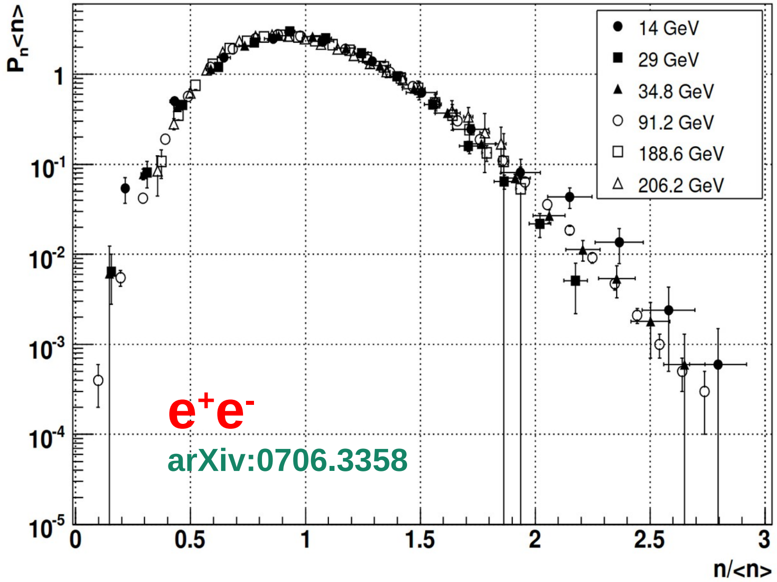
(a): many possible function shapes for given energy.
(b): Contract linearly along horizontal axis in proportion to <n>.
(c): Extend along vertical axis in proportion to <n>.

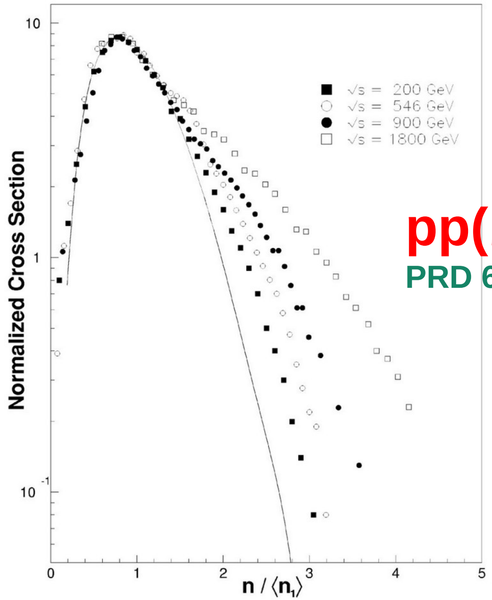
KNO-scaling: these curves (multiplicity distributions) will coincide at each point.

Recent phenomenological studies: a similar scaling may hold within single jets for **jet multiplicity as a function of jet p_T.**



Koba-Nielsen-Olesen (KNO) scaling





pp(bar)

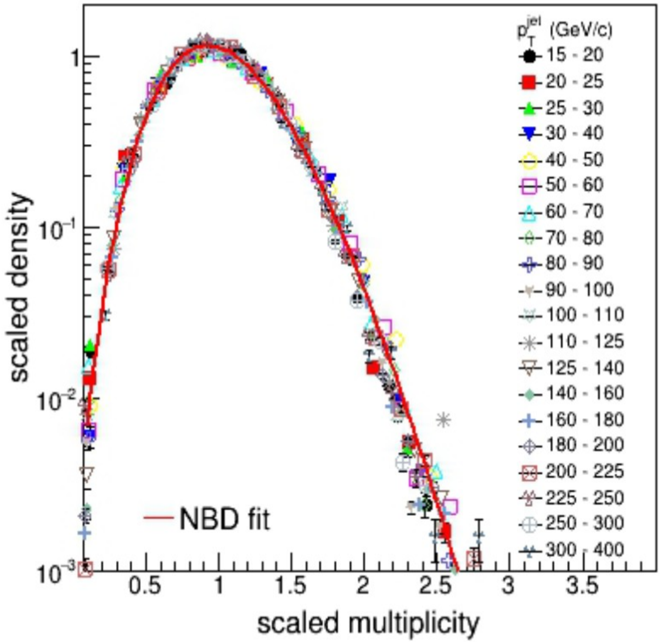
PRD 69 (2004), 034007

- **KNO scaling**: observed in **e^+e^- collisions**, and in **p-pbar** collisions.
- The scaling is violated toward higher energies and larger rapidity windows.
- Reason not fully understood, it might be violated by **MPI** and **overlapping color strings**.

Walker PRD 69, 034007 (2004); Abramovsky et al., arXiv:0706.3358

- **Is KNO scaling valid in jets? Origin of the scaling? How is it affected by MPI and CR?**
- **Flavor dependence: initial pQCD process or parton shower?**

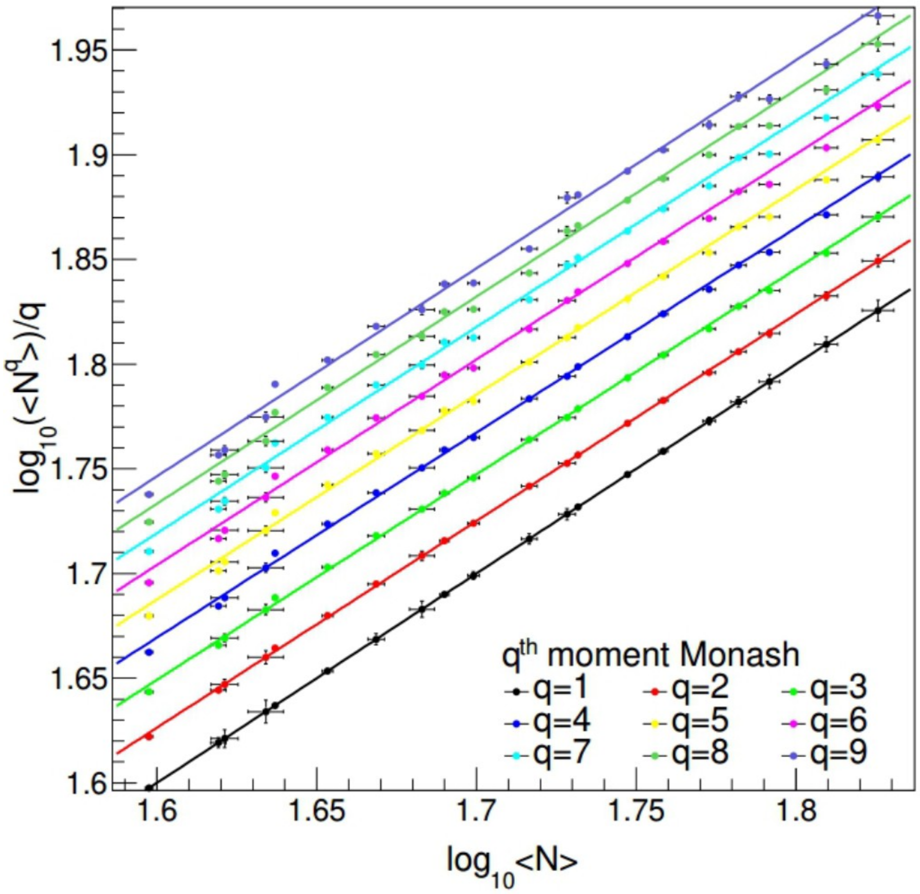
Simulated pp collisions – a KNO-like scaling



Pythia 8 standalone simulations:
A KNO-like scaling is observed within single jets for a wide range of jet p_T values!

- 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

Simulated pp collisions – statistical moments



Quantifying how well the scaling is fulfilled:

- 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

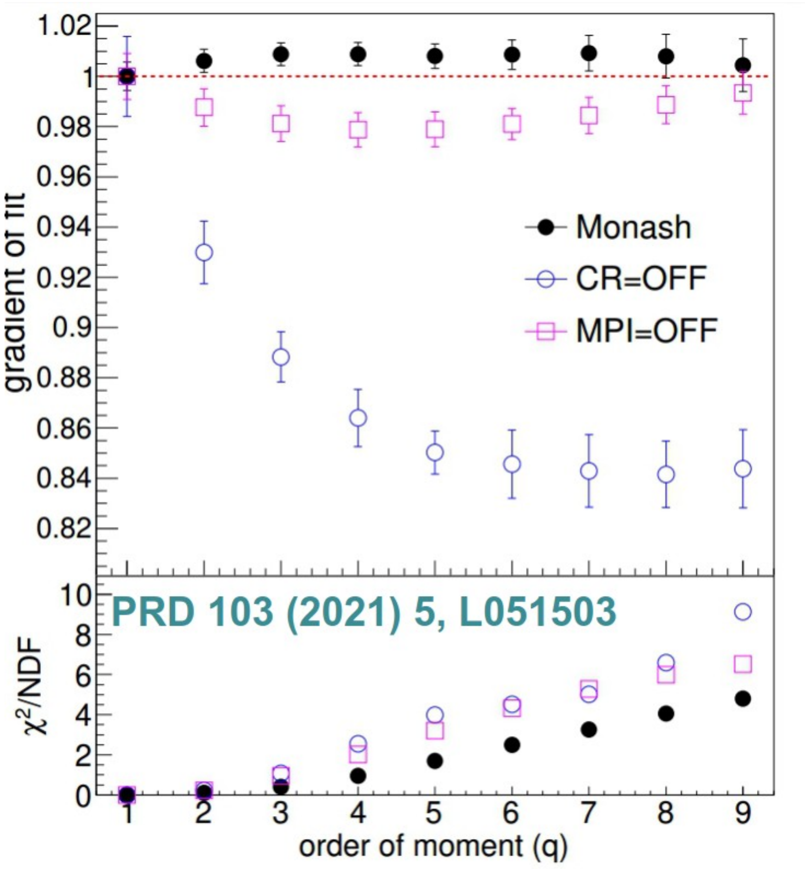
- Scaling:

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

$$\log\langle N^q\rangle/q \approx \log\langle N\rangle$$

Scaling is fulfilled in the whole jet p_T range!

Multiplicity vs p_T^{jet}: moments



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

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- Origin of scaling (PYTHIA)
  - Physical case (Monash): All 9 moments are consistent with unity, slope within ~1%
  - No CR: Scaling is broken by ~15%
  - No MPI (also no CR): Scaling fulfilled to ~2%

Heavy-flavor jets

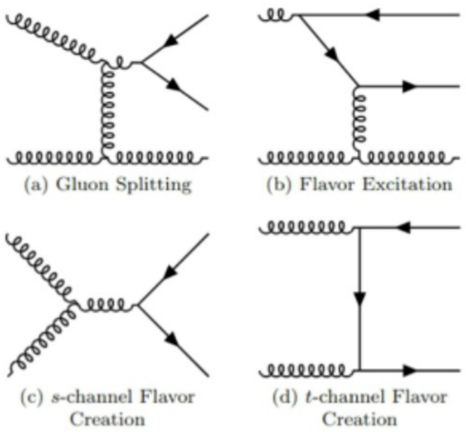
Heavy-flavor (HF) jets: created via hard pQCD processes
- LO flavor creation
- NLO gluon splitting + flavor excitation

} contributions are of similar magnitude

S. Cao, G.Y. Qin, X.N. Wang, Phys.Rev.C 93 (2016) 2, 024912

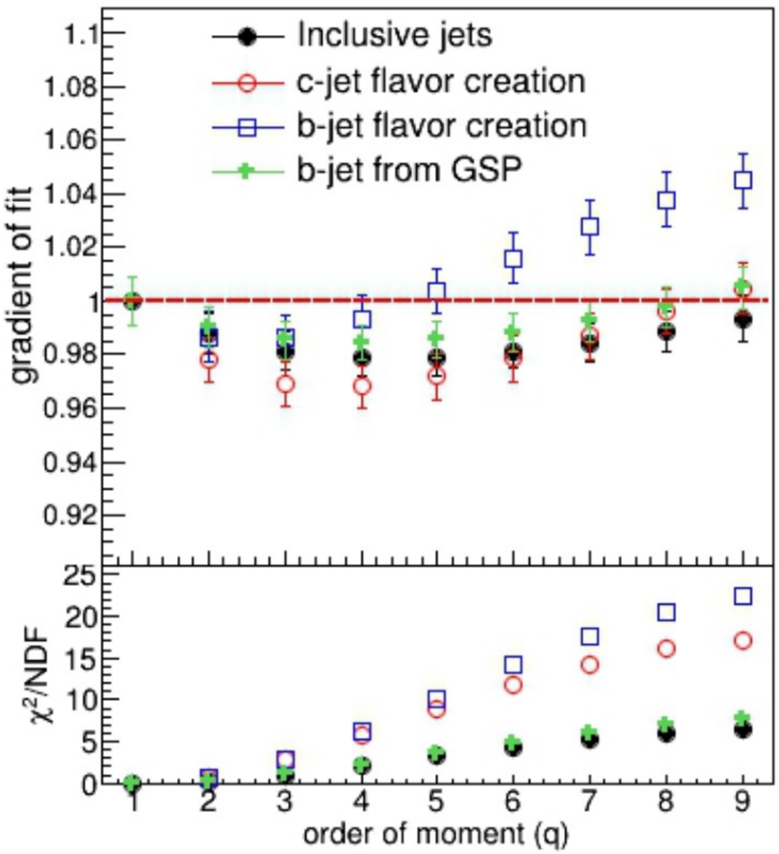
Jet production depends on quark flavor:
- mass dependence: harder fragmentation (dead-cone)
- color-dependence: HF initiated by quark jets only

Comparing the scaling for LO vs. NLO:
- sensitivity to its origin (i. e. hard QCD vs. jet development)



KNO-like scaling in HF jets may provide information on the origin of KNO scaling!

Heavy-flavor jet scaling



Z. Varga, R. Vértesi, Symmetry 14 (2022) 1379

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

All slopes are around unity within 5%
- Flavor creation (LO): mass-dependent deviation from inclusive jets
- Gluon splitting (NLO): Follows inclusive (mostly gluon) jets

Scaling is driven by initial hard processes!

What do we see in DATA?

- Analysis on published ATLAS data has similar conclusions.
G. R. Germano, F. S. Navarra, G. Wilk, Z. Wlodarczyk Phys.Rev.D 110 (2024) 3, 034026
- Analysis in ALICE is underway!

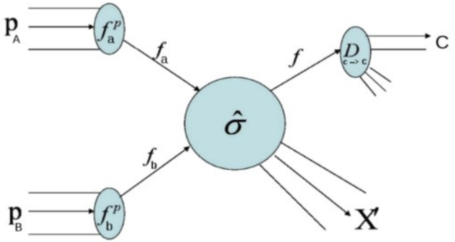
Charm baryon enhancement

Perturbative quantum chromodynamics (pQCD) calculations have been successful in describing the production of heavy-flavor mesons for several collision energies at the LHC.

$$d\sigma^{hard}_{AB\to C} = \sum_{a,b} f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes d\sigma^{hard}_{ab\to c}(x_a, x_b, q^2) \otimes D_{c\to C}(z, Q^2)$$

Parton Distribution Function (PDF) **Partonic hard scattering cross-section** **Fragmentation function**

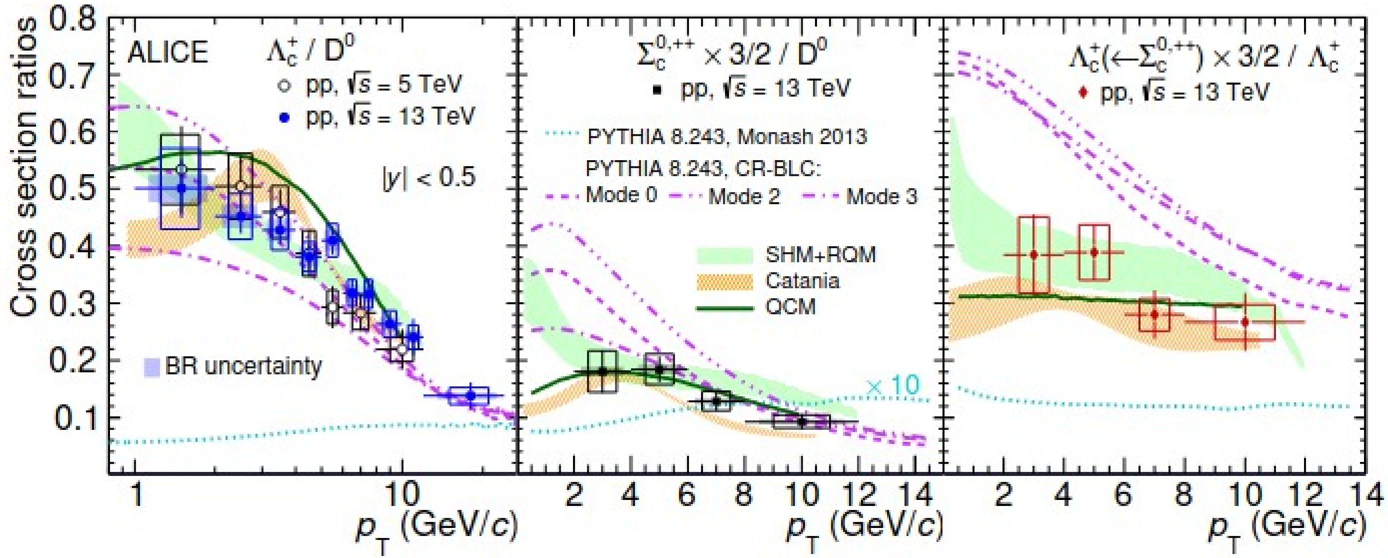
The usual description relies on the **factorization approach:** production cross section of heavy-flavor hadrons is calculated as a convolution of

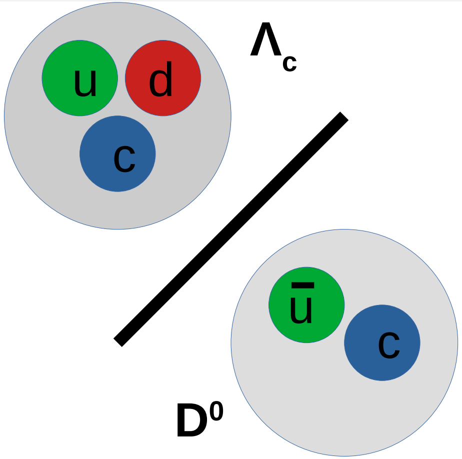


- **parton density functions (PDFs)** of the colliding hadrons,
- **cross section of the hard-scattering process** and
- **heavy-quark fragmentation function**.

Fragmentation function: usually taken from e^-e^+ collisions on the assumption of universality, e.g. Monash tune in PYTHIA 8. → **Experimental evidence suggest this is not true!**

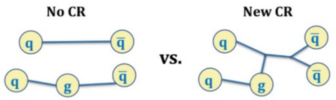
Charm baryon enhancement





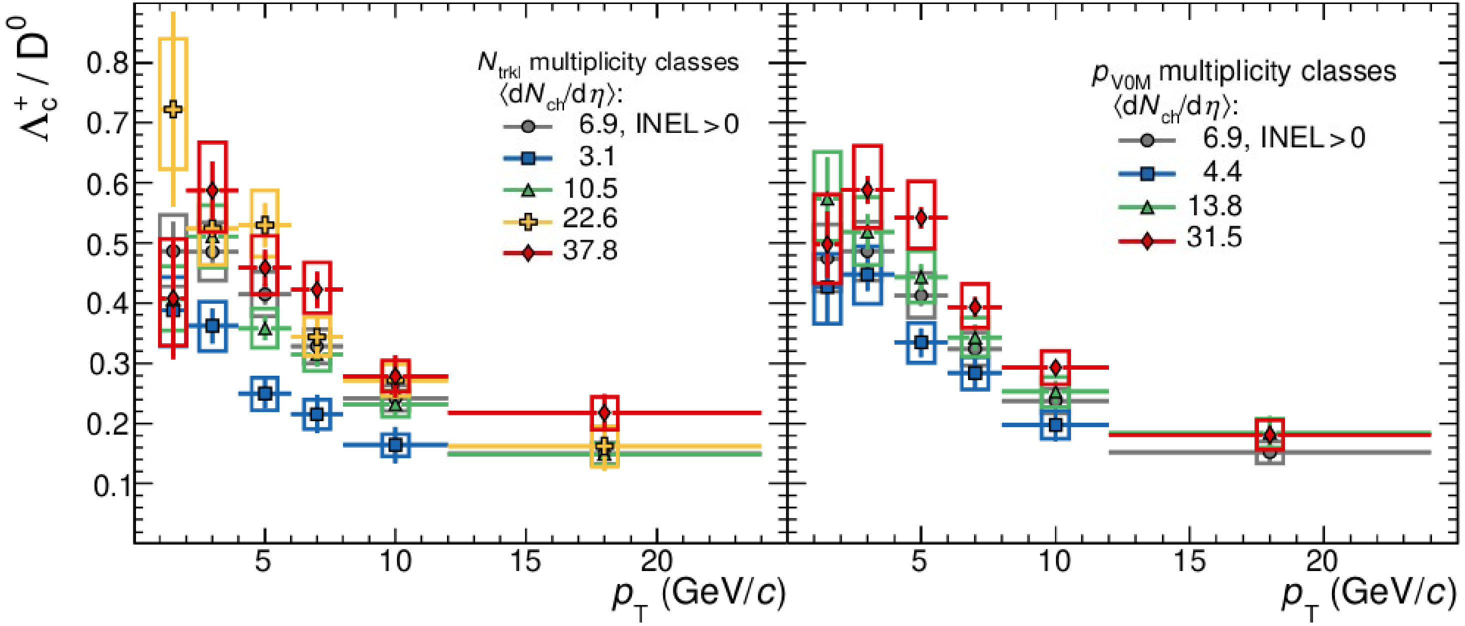
- **Charm baryon-to-meson ratios:** **sensitive probes of fragmentation!**
- Λ_c/D^0 and Σ_c/D^0 underestimated by models: **HF fragmentation universality broken!**

- **PYTHIA 8 CR-BLC**: string formation beyond leading color approximation,
- **SH model + RQM:** feed-down from augmented set of charm-baryon states,
- **Catania**: fragmentation + coalescence of charm and light quarks,
- **QCM:** coalescence model based on statistical weights + equal quark-velocity.



Multiplicity dependence of Λ_c/D^0

ALICE Coll. Phys.Lett.B 829 (2022) 137065



- The enhancement in Λ_c/D^0 depends on the final state multiplicity at mid- and forward rapidity.
- **Goal: Understand the origin of the enhancement with detailed event activity studies.**
- **Does it originate in jet processes or the underlying event? How to measure it?**
- Using standalone PYTHIA 8 to test the observable effects of the **CR-BLC model**.

Event classifiers

The collisions can be categorized with different **event characteristics**, which help distinguish how much the **jets** or the **background** event dominate in a given event.

- N_{CH} **: charged-hadron multiplicity** at central rapidity ($|\eta| < 1$):
  - number of final-state charged particles,
  - global parameter that does not take leading process into account.

- N_{fw} **: forward multiplicity** ($2 < \eta < 5$).

- R_T **: relative transverse multiplicity (UE activity)**
  - exclude jets from leading process,
  - high-p_T trigger hadron required.

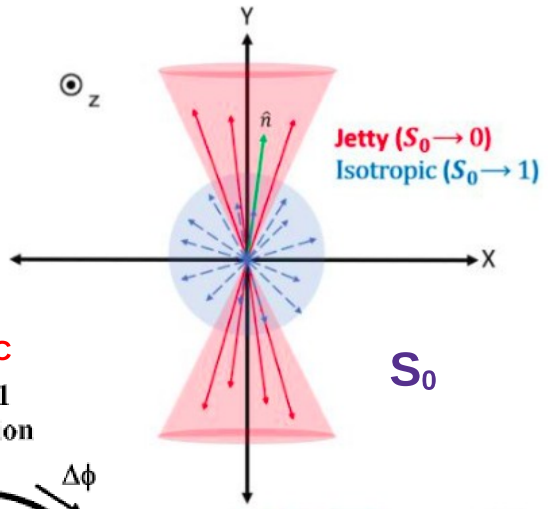
$$R_T = \frac{N_{CH}^{transverse}}{\langle N_{CH}^{transverse} \rangle} \qquad \frac{\pi}{3} < |\Delta\phi| < \frac{2\pi}{3}$$

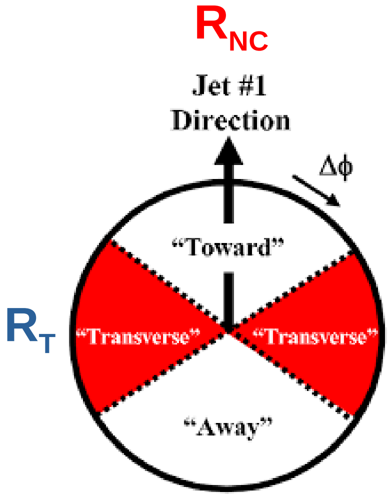
- R_{NC} **: relative near-cone multiplicity (jet region activity)**
  - includes leading process,
  - high-pT trigger required.

$$R_{NC} = \frac{N_{CH}^{near-side\ cone}}{\langle N_{CH}^{near-side\ cone} \rangle} \qquad \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.5$$

- S_0 **: spherocity**
  - jetty or isotropic event,
  - no need for trigger hadron.
  - only mid-rapidity.

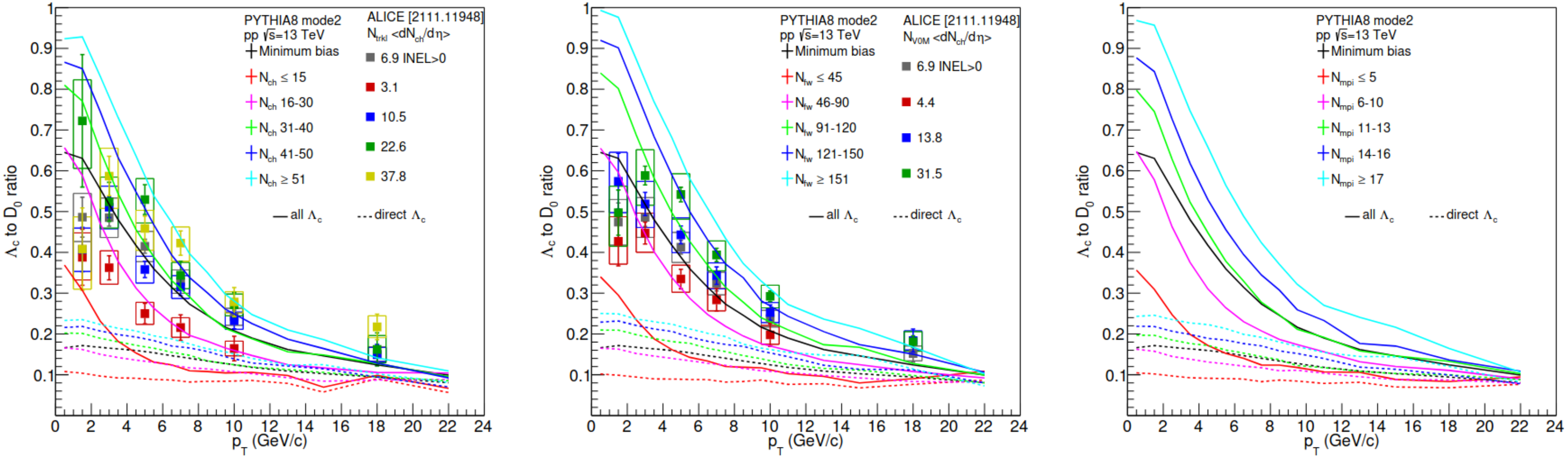
$$S_0 = \frac{\pi^2}{4} \times \min_{\hat{n}=(n_x,n_y,0)} \left(\frac{\Sigma_i |\vec{p}_{T_i} \times \hat{n}|}{\Sigma_i \vec{p}_{T_i}} \right)^2$$





Multiplicity dependence of Λ_c/D^0

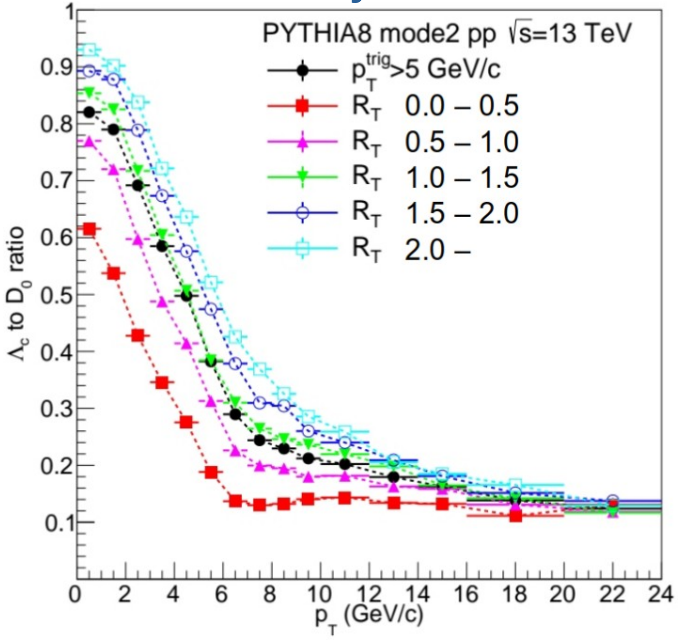
Z. Varga, R. Vértesi, A. Misák, J. Phys. G: Nucl. Part. Phys. 50 (2023) 075002



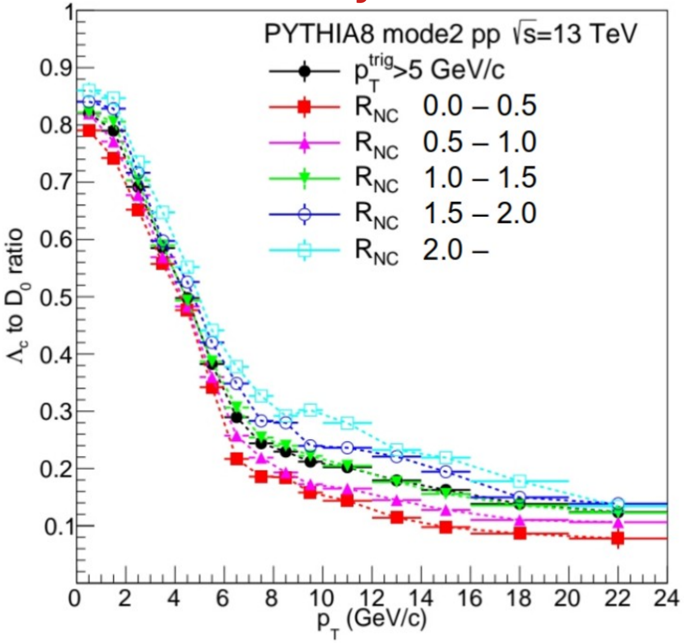
- **Simulations are in agreement with ALICE experiment** (minbias + miltiplicity-differential).
- Rapidity gap: reduces correlation between leading hard processes and the multiplicity.
- **Multiplicity dependence not driven by charm production inside jets.**

Λ_c/D^0 yield for triggered events

UE activity classifier



Jet activity classifier

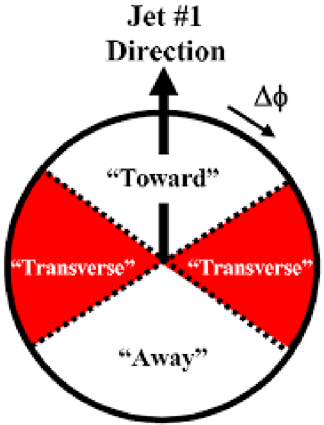


Z. Varga, R. Vértesi, J. Phys. G: Nucl. Part. Phys. 49 (2022) 075005

$\Lambda_c(qqc)$, I = 0

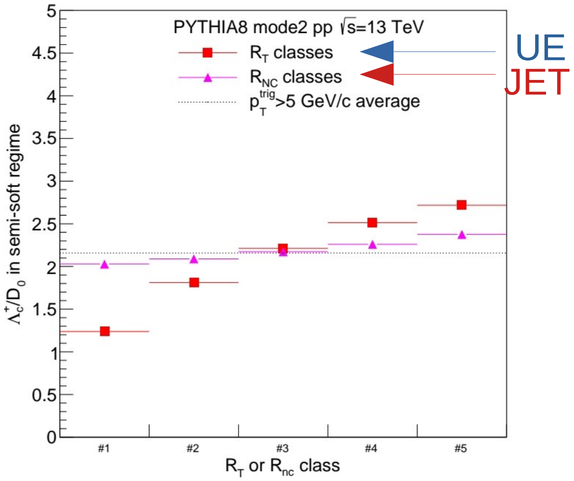
R_{NC}

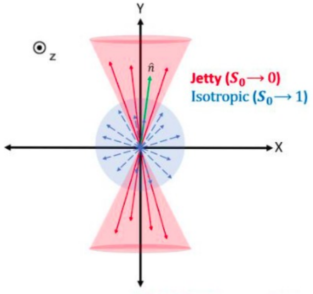
R_T

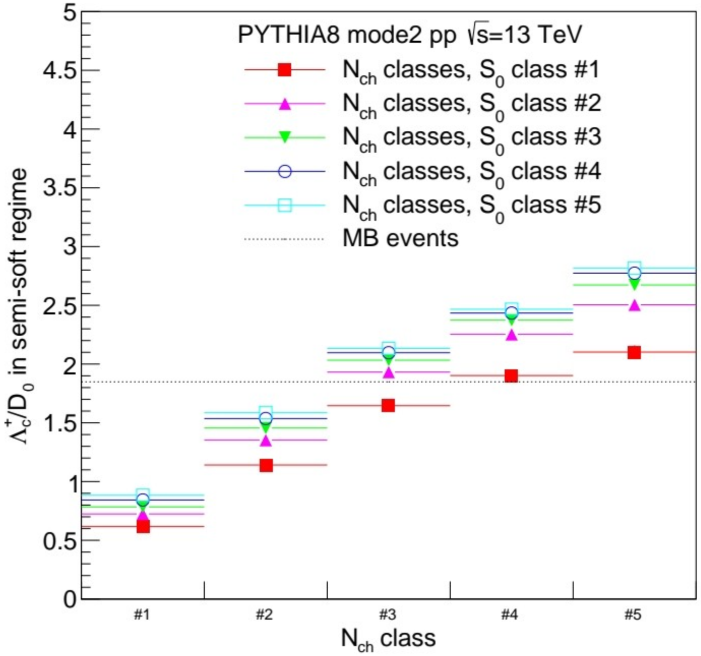


- Events require p_T>5 GeV/c **hadron trigger**.
- Significant difference is observable in case of R_T (**UE activity**).
- No significant difference when classified by R_{NC} classes (**jet activity**).

Λ_c/D^0 yield ratios – trigger vs. minbias

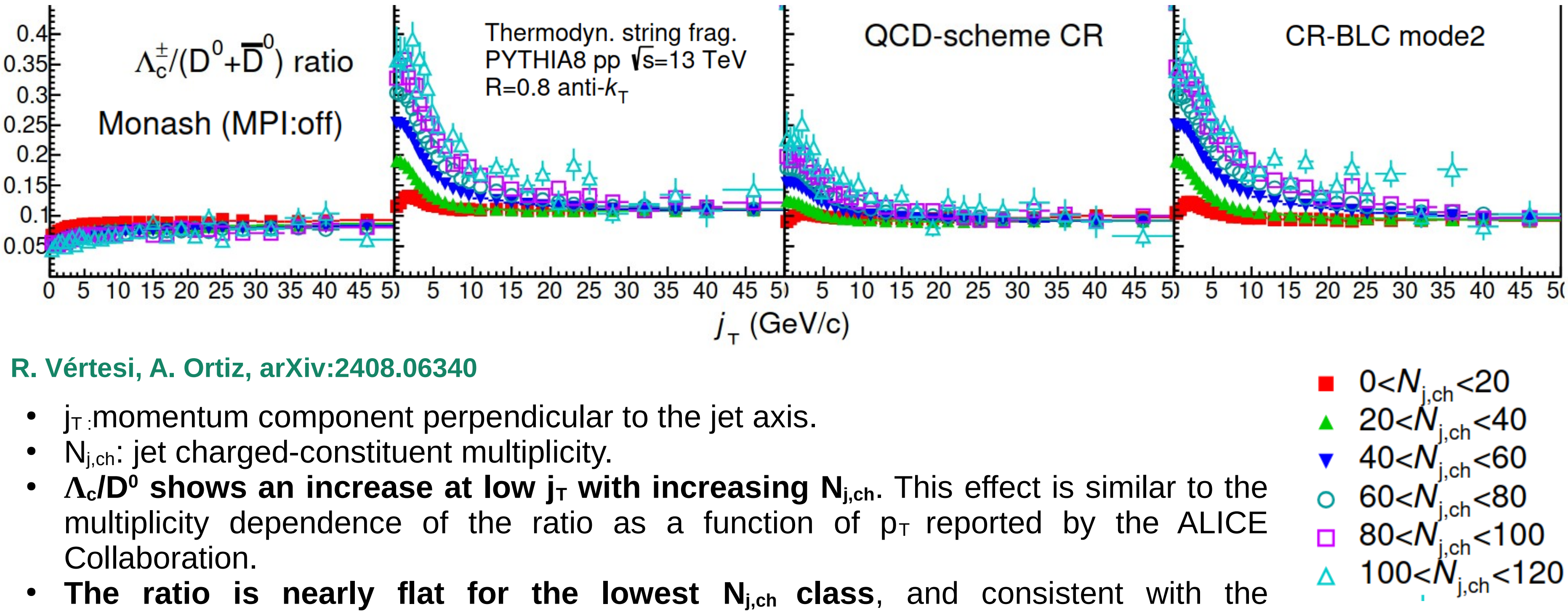






- In case we require a hard process ($P_T^{trigger}$ > 5 GeV/c):
  - **Strong dependence** of ratios on the **UE activity**,
  - **No pronounced dependence** on the **jet multiplicity**.
- In minimum-bias events
  - In case of high final-state multiplicity, ratio depends on jettiness,
  - Dependence is minute for low final-state multiplicity.
- For spherocity S_0, dependence on jettiness observable in minimum-bias events. No need to use a trigger that biases the sample and decreases available statistics.

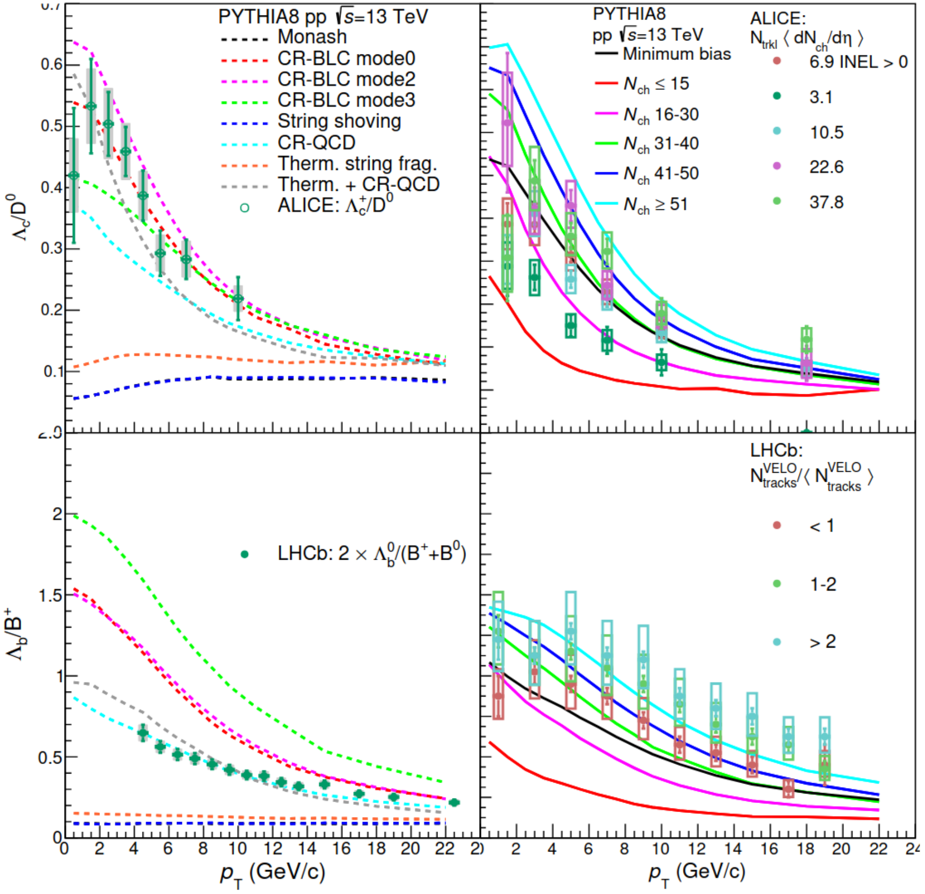
String fragmentation in jets



R. Vértesi, A. Ortiz, arXiv:2408.06340

- j_T : momentum component perpendicular to the jet axis.
- $N_{j,ch}$: jet charged-constituent multiplicity.
- **Λ_c/D^0 shows an increase at low j_T with increasing $N_{j,ch}$**. This effect is similar to the multiplicity dependence of the ratio as a function of p_T reported by the ALICE Collaboration.
- **The ratio is nearly flat for the lowest $N_{j,ch}$ class**, and consistent with the corresponding ratios measured in e^-e^+ collisions at LEP.
- Utilizing jet substructure measurements provide more information on the fragmentation of heavy flavor.

Λ_b/B^+ yield for triggered events



L. V. Földvári, Z. Varga, R. Vértesi, arXiv:2408.16447

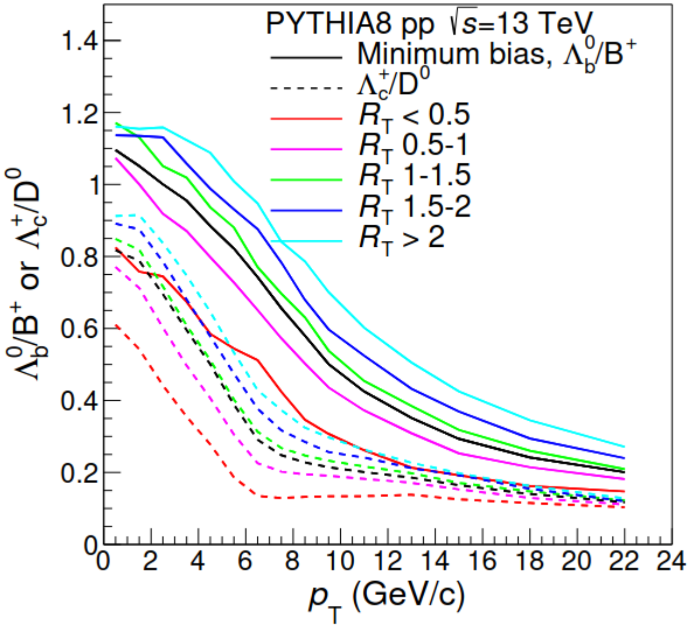
- Performance of multiple models compared for Λ_c/D^0,
- and also to recent Λ_b/B^+ measurements by LHCb.

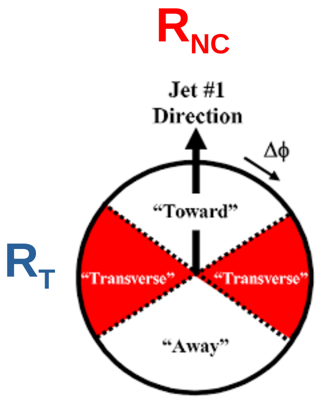
LHCb Collab. Phys. Rev. Lett. 132, 081901 (2024)

- **CR-BLC** overall **outperform other models for charm**, however **overestimates beauty production**.
- New high-luminosity data from LHC Run 3 data can further constrain heavy-flavor fragmentation mechanisms.

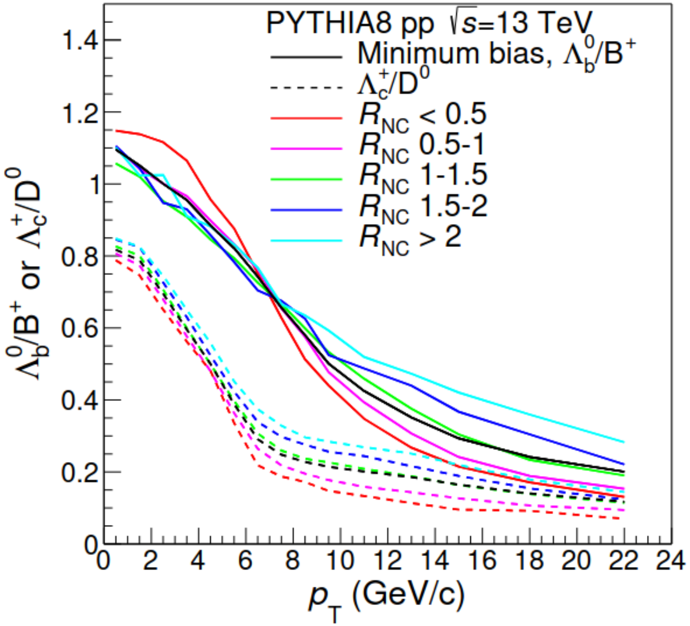
Λ_b/B^+ yield for triggered events

UE activity classifier





Jet activity classifier



- Similar conclusions for beauty baryon enhancement as for charm.
- Significant difference is observable in case of R_T (**UE activity**).
- No significant difference when classified by R_{NC} classes (**jet activity**).

Production of Excited Charm and Charm-strange Baryon States

Previous studies extended for several excited charm baryon states:

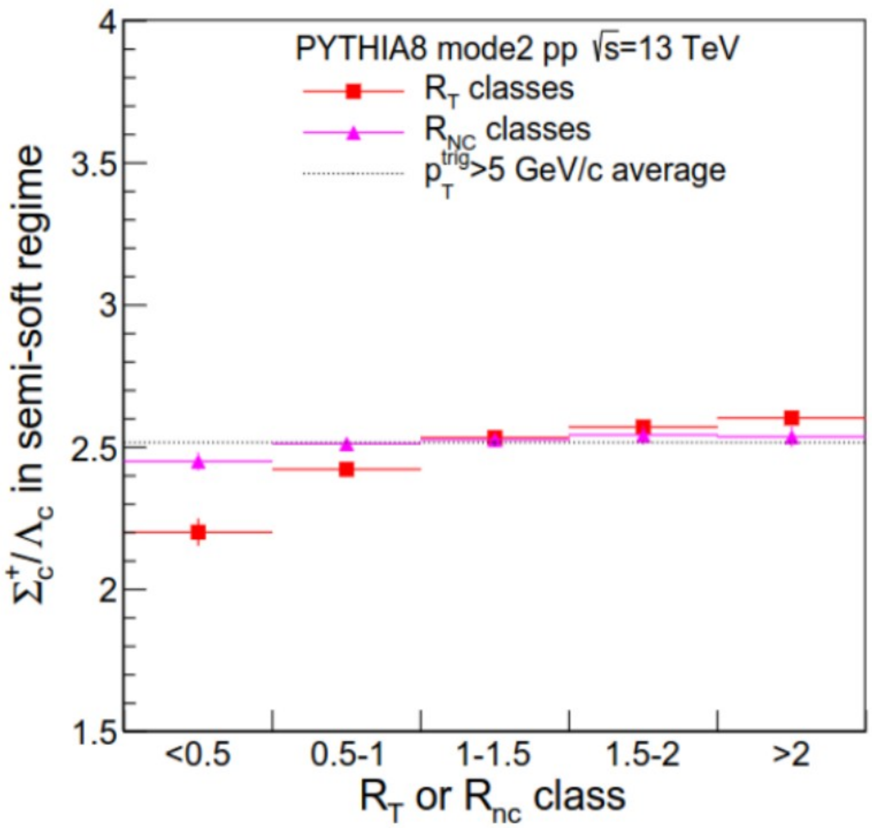
- investigating the production of charmed baryons with different **isospin** and **strangeness** content,

- comparison to both charmed D^0 mesons and Λ_c^+ baryons in pp collisions at LHC energies.

- Conclusion 1: **Strangeness content has no further sensitivity to event-property descriptors**.

- Conclusion 2: **Charm enhancement driven by different mechanism than strange enhancement**.

- Conclusion 3: The **isospin** of the charmed-baryon state has a strong **impact on the enhancement**.



Z. Varga, R. Vértesi, A. Misák, J. Phys. G: Nucl. Part. Phys. 50 (2023) 075002

Summary

- **KNO scaling:** Event multiplicity distributions scale with center-of-mass energy.
  - Violated at higher energies, and not fully understood.

- Recent phenomenological studies: **a KNO-like scaling may be present within jets**.
  - Jet multiplicity distributions are NBD and can be collapsed onto a universal distribution.
  - KNO scaling is likely violated by complex QCD processes outside the jet development, such as single and double-parton scatterings or softer MPI.

- Testing for this scaling behavior can be an important element in model development.

- In CR-BLC model the charm baryon enhancement originates in the underlying event → the processes inside the jets do not play a significant role.

- Good quantitative description of both charm and beauty baryon enhancement with the same model settings is still missing, but **demonstrated a good sensitivity to certain event-activity observables**.

- Utilizing jet substructure measurements may provide more information on the hadronization.

LHC Run 3 data with increased statistics will be essential.

Thank you!