Wigner Theory Seminar 2023

Exploring the underlying event through heavy-flavor production

Zoltán Varga[1,2]

in collaboration with Róbert Vértesi[1]

1. Wigner Research Centre for Physics

2. Budapest University of Technology and Economics

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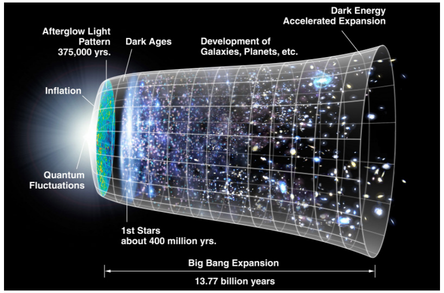
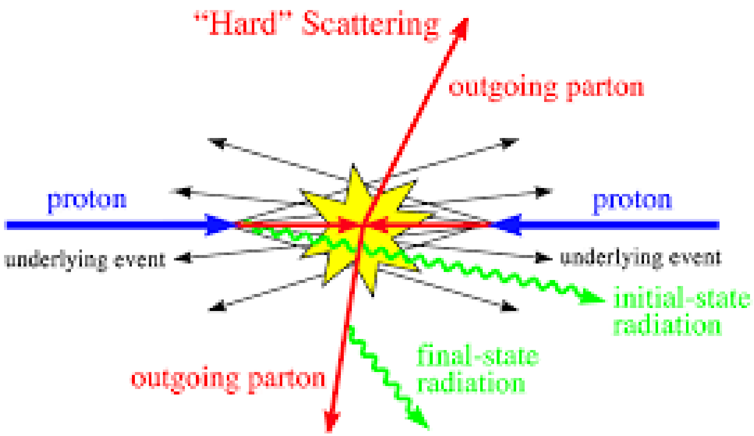
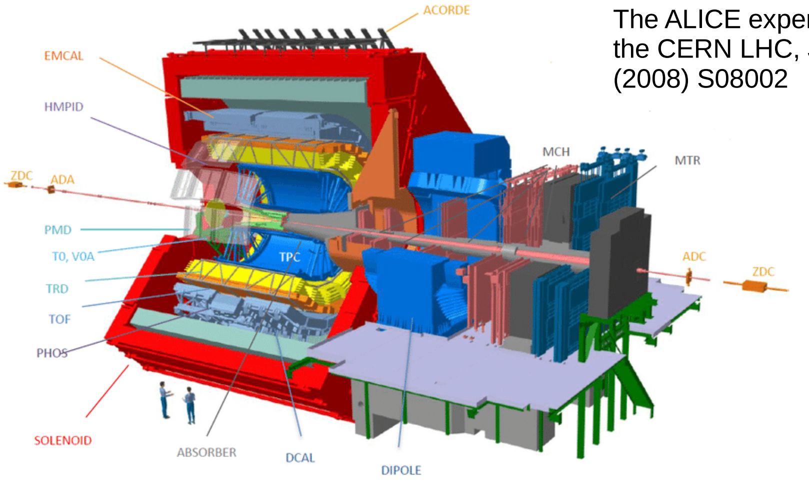
Heavy-ion collisions



- **Cosmological models:**
  - Our universe was born from the Big Bang ~13.8 billion years ago (+/- 20 million years).
- **Quark-gluon plasma (QGP):**
  - The matter which existed a few microseconds after the Big Bang.
  - It forms at high T and densities, which makes the calculations extremely challenging.
  - Important testing ground for finite temperature field theory and needed to understand the early evolution of our universe.
- **T. D. Lee**: “In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. But, in order to study the question of ‘vacuum’, we must turn to a different direction; we should investigate bulk phenomena by distributing high energy over a relatively large volume.”
- **Multiple experiments:** e.g. ALICE at the LHC.

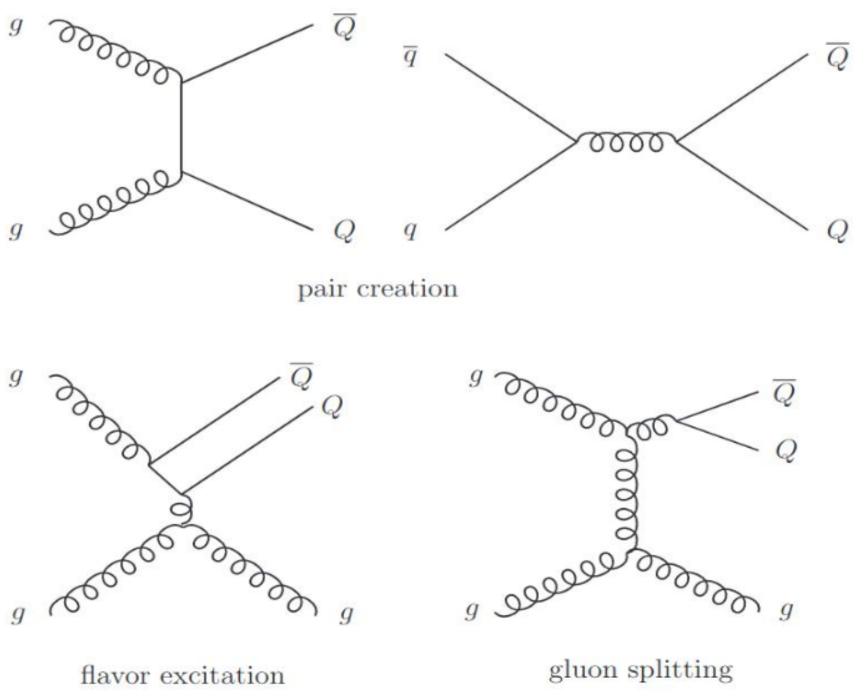




The ALICE experiment at the CERN LHC, JINST 3 (2008) S08002

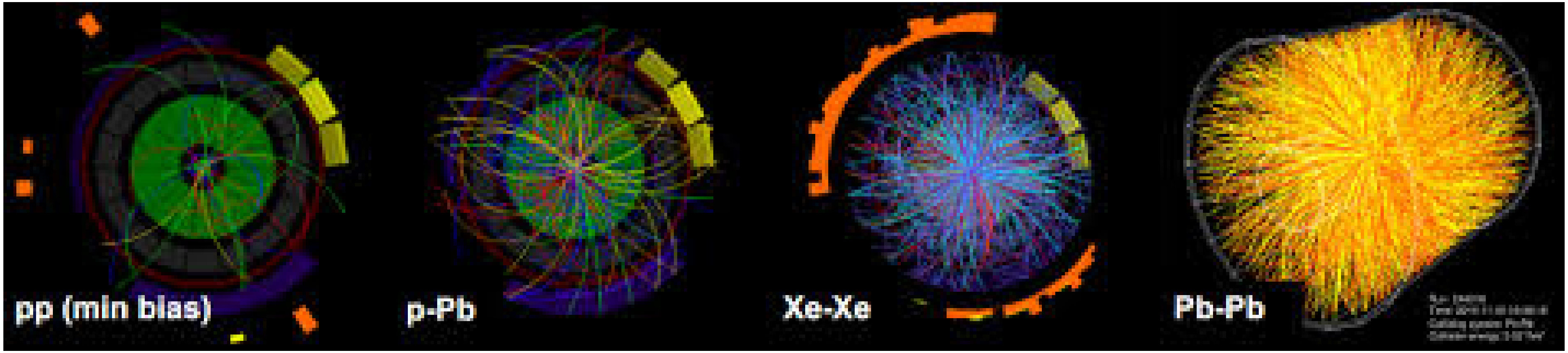
Heavy-flavor quarks

- Production of heavy-flavor quarks (charm, beauty) occurs in initial hard scatterings of quarks and gluons,
- while the production of light quarks (in the underlying event) is dominated by soft processes.
- Heavy-flavor quarks are mostly produced in the initial processes with large momentum transfer.
- Main processes:
  - Pair creation: $gg \to Q\overline{Q}; \quad q\overline{q} \to Q\overline{Q}$
  - Flavor excitation: $Qg \to Qg; \quad Qq \to Qq$
  - Gluon splitting: $g \to Q\overline{Q}$



Heavy-flavor quarks

- In **pp** collisions:
  - Test **pQCD predictions** (cross sections).
  - Gaining information about **parton shower**: dead-cone effect (mass-ordering) and Casimir color factor (color charge effect).
  - Test of different **fragmentation models**: meson vs. baryon, jet substructure.
  - Provide a **baseline for p-Pb and Pb-Pb** collisions.
- In **p-Pb** collisions:
  - Help isolating **initial state** and **cold nuclear matter effects**.
  - Used in studying possible **collective effects**.
- In **Pb-Pb** collisions:
  - Produced before the QGP ($m \gg T_{QGP}$), therefore **experience the full evolution of the medium** → probing the **transport properties of the medium**.
  - Measuring the **energy loss via gluon radiation** and **collisional energy loss**.

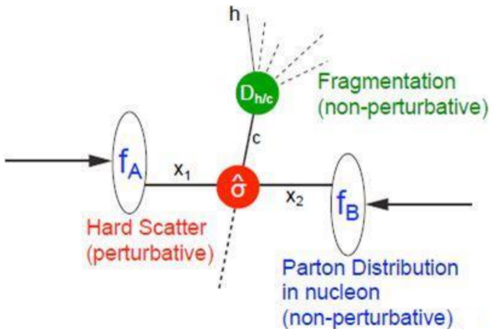


Production of heavy-flavor baryons

- Heavy-flavor production is usually described with the factorization approach, in which incoming <u>**hadron PDFs**</u>, hard <u>**parton-parton scattering**</u> and <u>**fragmentation**</u> are independent:

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

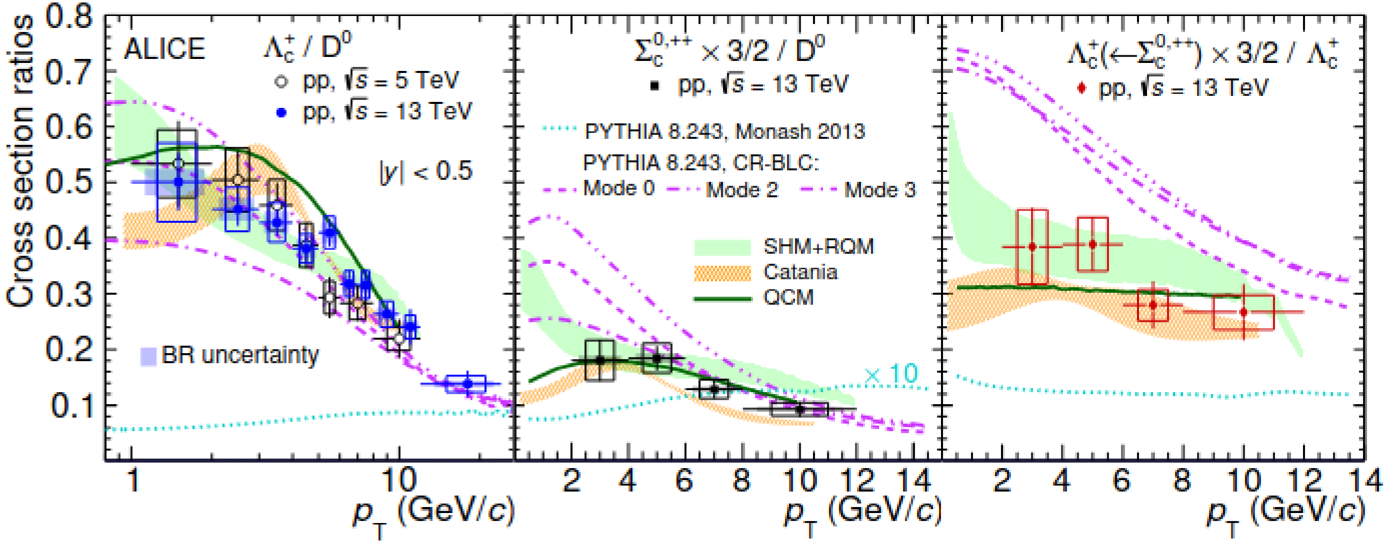
Parton Distribution Function (PDF) — Partonic hard scattering cross-section — Fragmentation Function (FF)



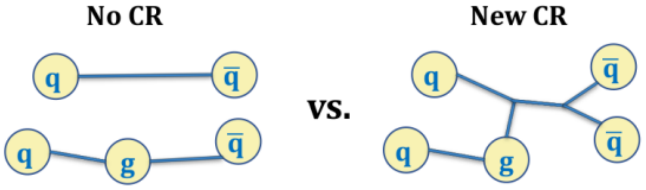
- <u>Traditional assumption</u>: fragmentation functions are **universal** for different collision systems
  - **Frag. functions** are often determined from **e^-e^+** (or **e^-p**) collisions, where **PDF** plays no (or less important) role
- Recent experimental results (ALICE, CMS, LHCb) on charmed baryon production **do not support** this assumption!

Charm baryon enhancement

ALICE Coll., “Measurement of prompt D0, Lambda_c+, and Sigma_c{0,++}(2455) production in pp collisions at sqrt(s) = 13$ TeV” (arXiv:2106.08278)

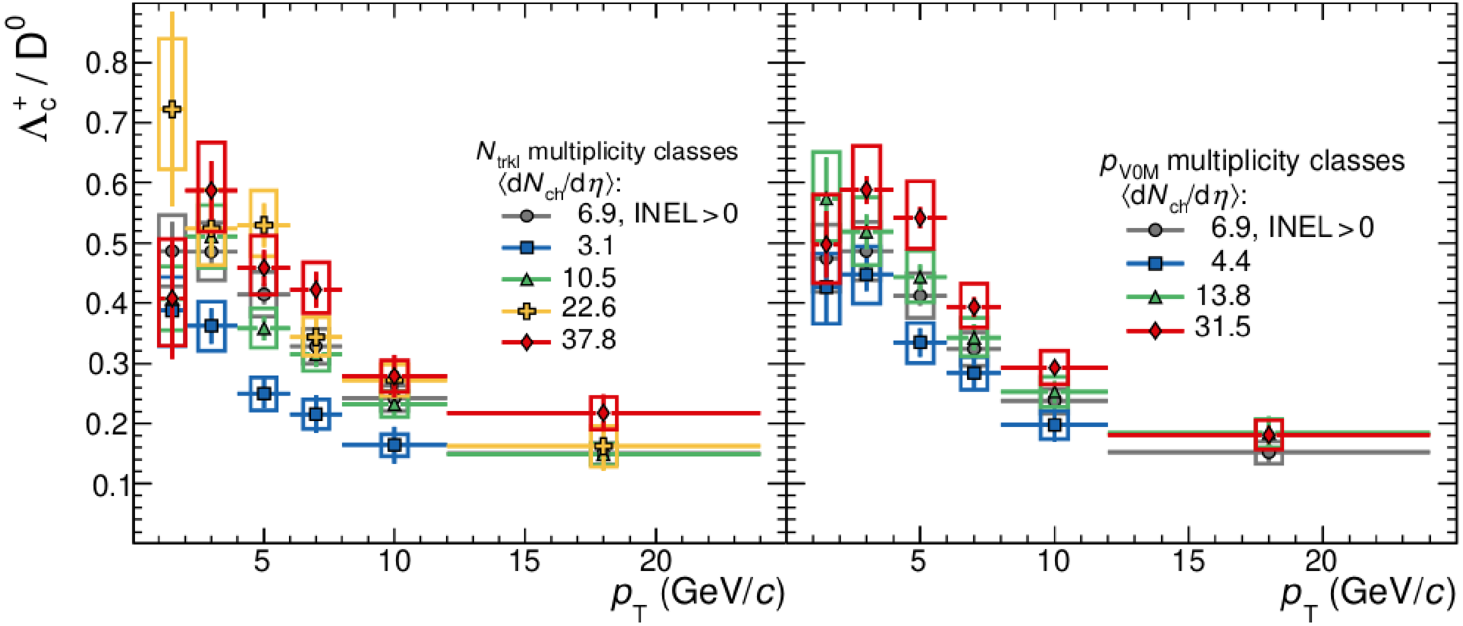


- **Ratios of charm-baryon to charm-meson yields show a p_T dependent enhancement compared to e^-e^+ results**
- **Several scenarios are proposed to explain this observation:**
  - **String formation beyond leading color (CR-BLC)** (arXiv:1505.01681 [hep-ph]),
  - Augmented set of charm baryon states (SHM + RQM) (arXiv:1902.08889 [nucl-th]),
  - Coalescence models: Catania (arXiv:1712.00730 [hep-ph]) and Quark Comb. Mech. (QCM) (arXiv:1801.09402 [hep-ph]).



The enhancement depends on the multiplicity

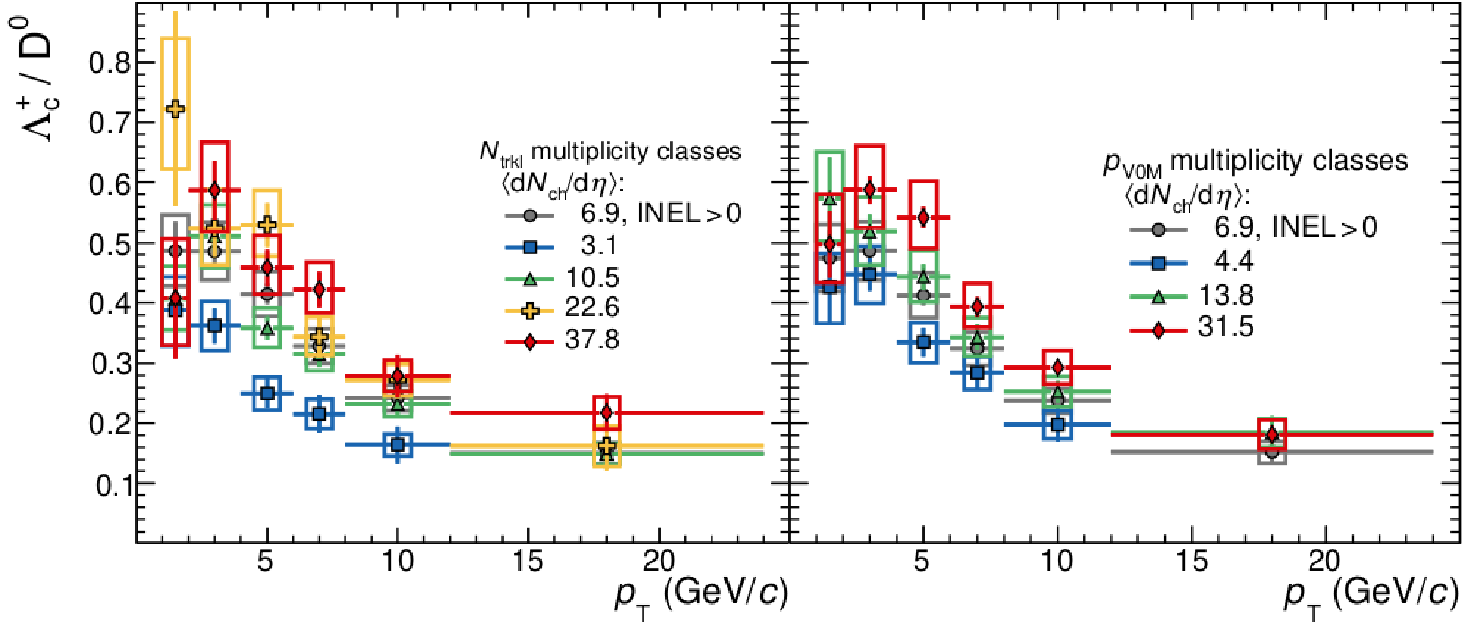
ALICE Coll. Observation of a multiplicity dependence in the pT-differential charm baryon-to-meson ratios in proton-proton collisions at s√=13 TeV (Phys.Lett.B 829 (2022) 137065)



- The enhancement in **Λ_c/D^0** also depends on the final state multiplicity at mid-/forward rapidity.
- The **Λ_c/D^0** enhancement with respect to event-activity qualifiers provides a sensitive probe to access the source of the enhancement and to differentiate between the different proposed mechanisms.
- **Multiplicity**: **provides insights into** the interplay between **soft and hard mechanisms** of the particle production!

The enhancement depends on the multiplicity

ALICE Coll. Observation of a multiplicity dependence in the pT-differential charm baryon-to-meson ratios in proton-proton collisions at s√=13 TeV (Phys.Lett.B 829 (2022) 137065)

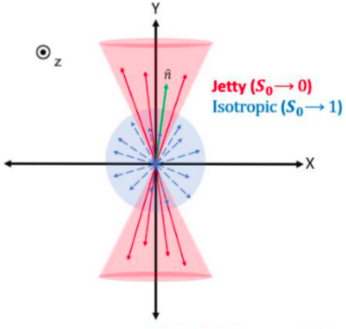


- The enhancement in Λ_c/D^0 also depends on the final state multiplicity at mid-/forward rapidity.
- The Λ_c/D^0 enhancement with respect to event-activity qualifiers provides a sensitive probe to access the source of the enhancement and to differentiate between the different proposed mechanisms.
- **Goal: Understand the origin of the enhancement with detailed event activity studies!**
- Using standalone PYTHIA 8 to test the observable effects of the **CR-BLC model**.

Event activity classifiers

- **N_{CH}** – multiplicity at mid-rapidity ($|\eta| < 1$): number of final state charged particles, describing the activity of the whole event.
- **N_{fw}** - forward multiplicity at forward rapidity ($2 < \eta < 5$),
- **R_T** = $N_{CH}^{transverse}$ / $<N_{CH}^{transverse}>$: **underlying event** activity, region excluding jets from the leading process. ($\pi/3<|\Delta\phi|<2\pi/3$)
- **R_{NC}** = $N_{CH}^{near\text{-}side\ cone}$ / $<N_{CH}^{near\text{-}side\ cone}>$: activity connected to the **jet region**, containing the leading process. $\sqrt{(\Delta\phi^2+\Delta\eta^2)}<0.5$
- **S_0**: **spherocity**, measures how spherical or jet-like the event is.

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



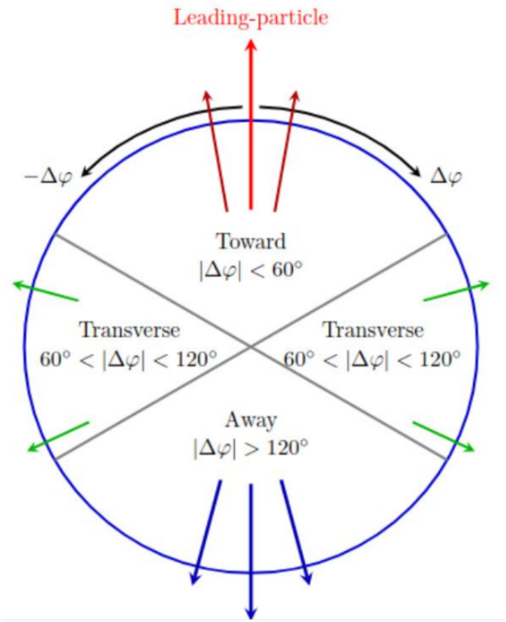
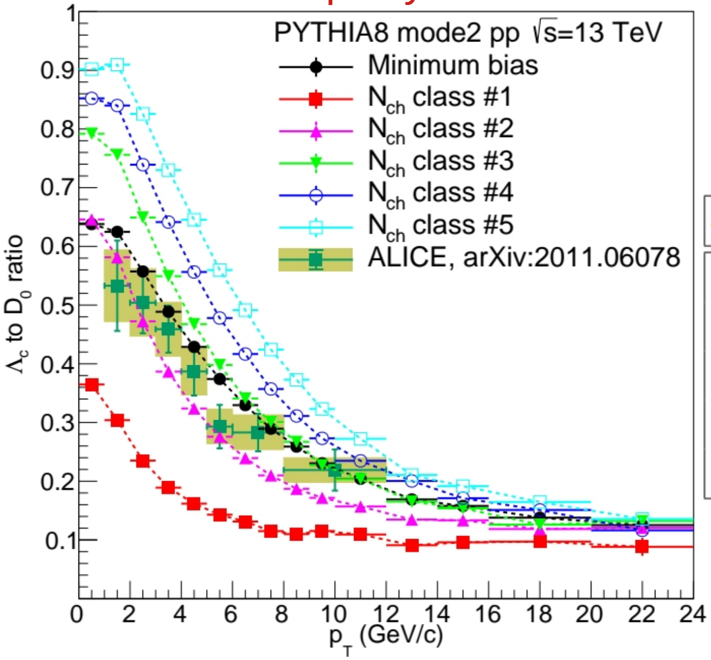


*Fig. taken from ALICE, arXiv:2204.10157 [nucl-ex]

Λ_c/D^0 yield ratios for central and forward rapidity

Central rapidity classifier

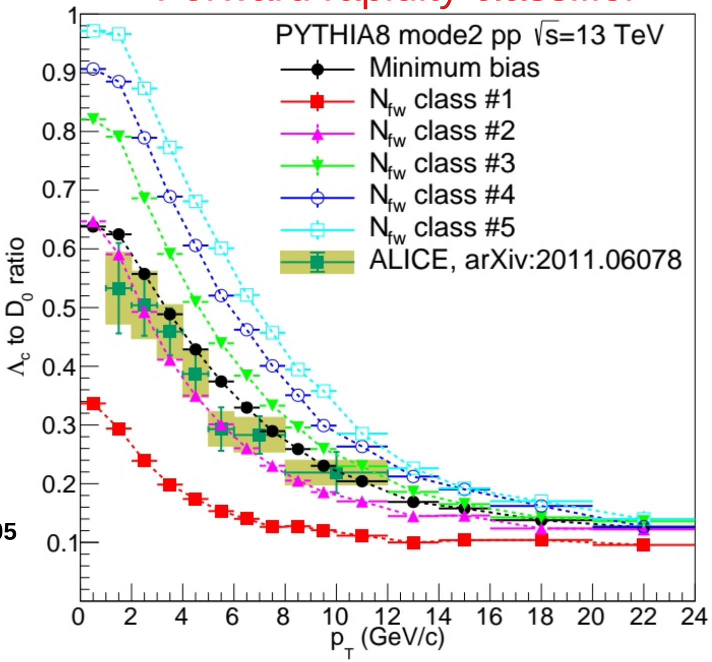


Λ_c(qqc), I = 0

class	#1	#2	#3	#4	#5
N_{ch}	≤15	16–30	31–40	41–50	≥51
N_{fw}	≤45	46–90	91–120	121–150	≥151
R_T	<0.5	0.5–1	1–1.5	1.5–2	>2
R_{NC}	<0.5	0.5–1	1–1.5	1.5–2	>2
S_0	0–0.25	0.25–0.45	0.45–0.55	0.55–0.75	0.75–1

Z.V., R.V., J. Phys. G: Nucl. Part. Phys. 49 (2022) 075005 (arXiv:2111.00060)

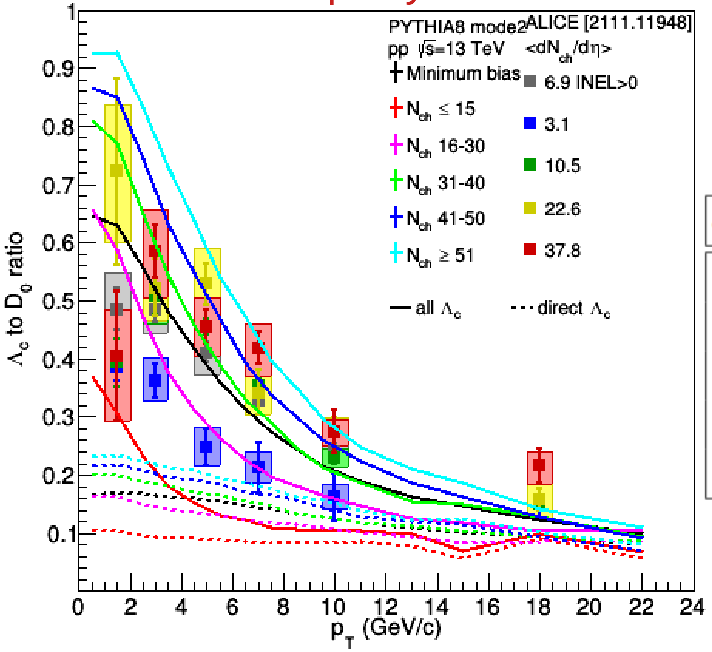
Forward rapidity classifier



- Simulation results are **in agreement with the ALICE** experimental data.
- For N_{fw}: a **rapidity gap** is present, which **reduces the correlation** between leading hard processes and the multiplicity.
- **Multiplicity dependence not driven by charm production in jets!**

Λ_c/D^0 yield ratios for central and forward rapidity

Central rapidity classifier



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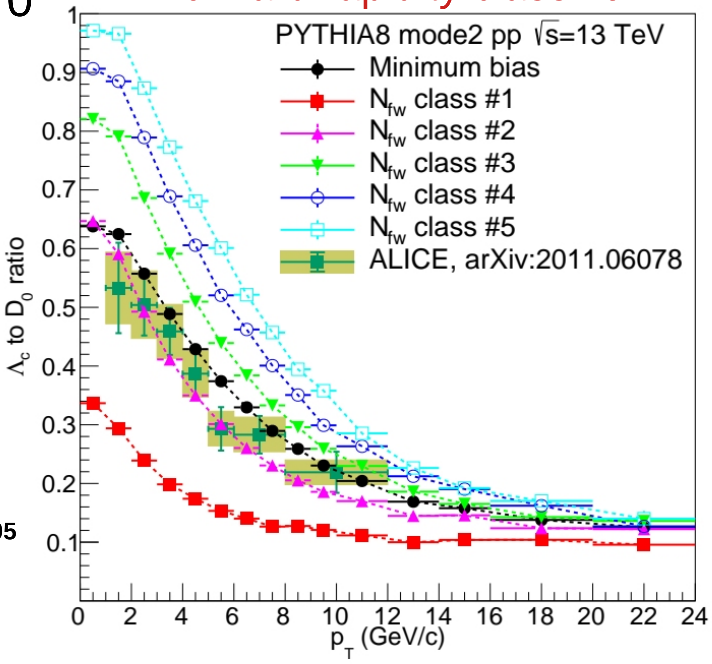
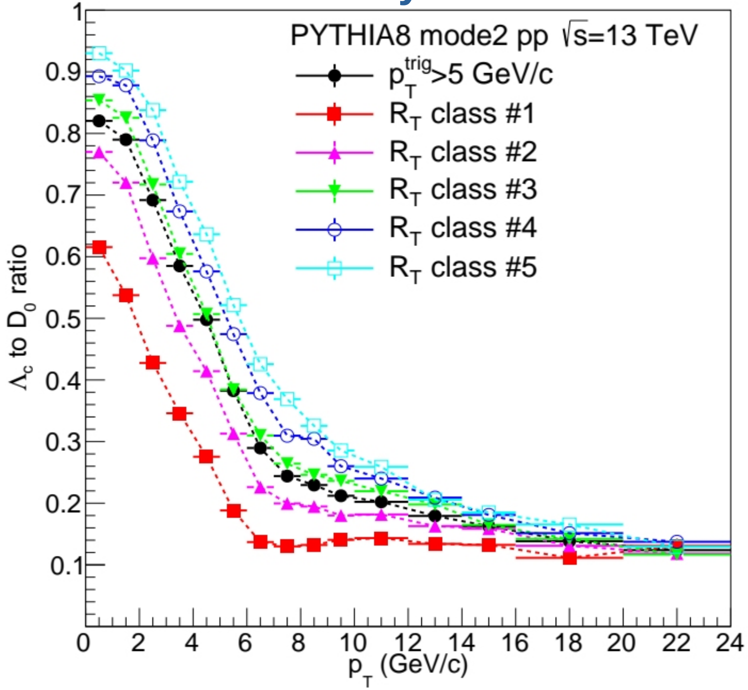
Forward rapidity classifier

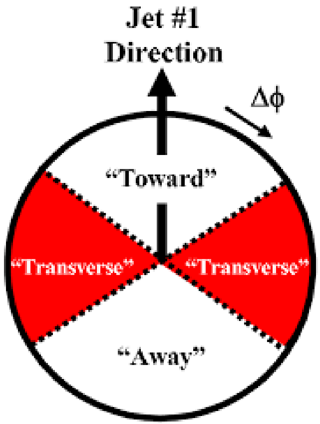


- Simulation results are **in agreement with the ALICE** experimental data.
- For N_{fw}: a rapidity gap is present, which reduces the correlation between leading hard processes and the multiplicity.
- Multiplicity dependence not driven by charm production in jets.
- Recently observed **multiplicity trends** also **reproduced**.
- p_T dependence may be sensitive to the baryon type.

Λ_c/D^0 yield for triggered events

UE activity classifier





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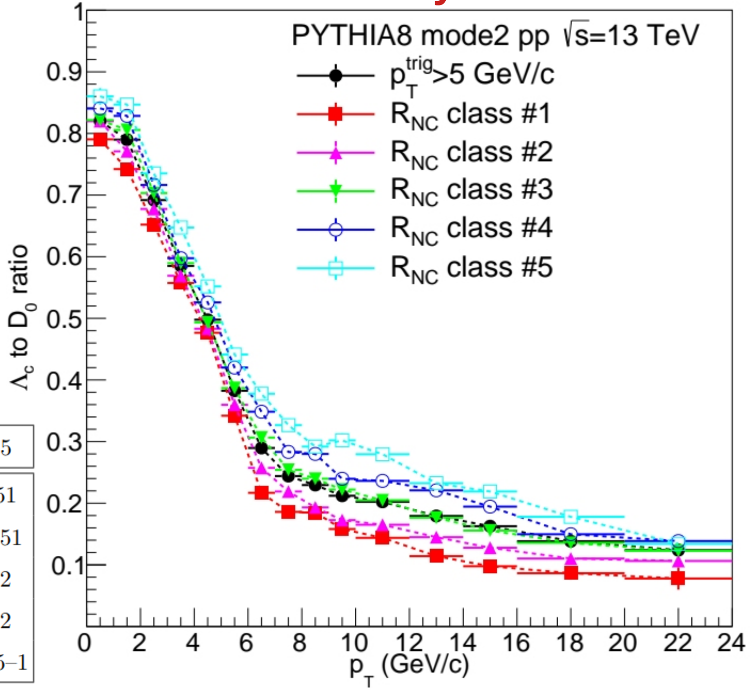
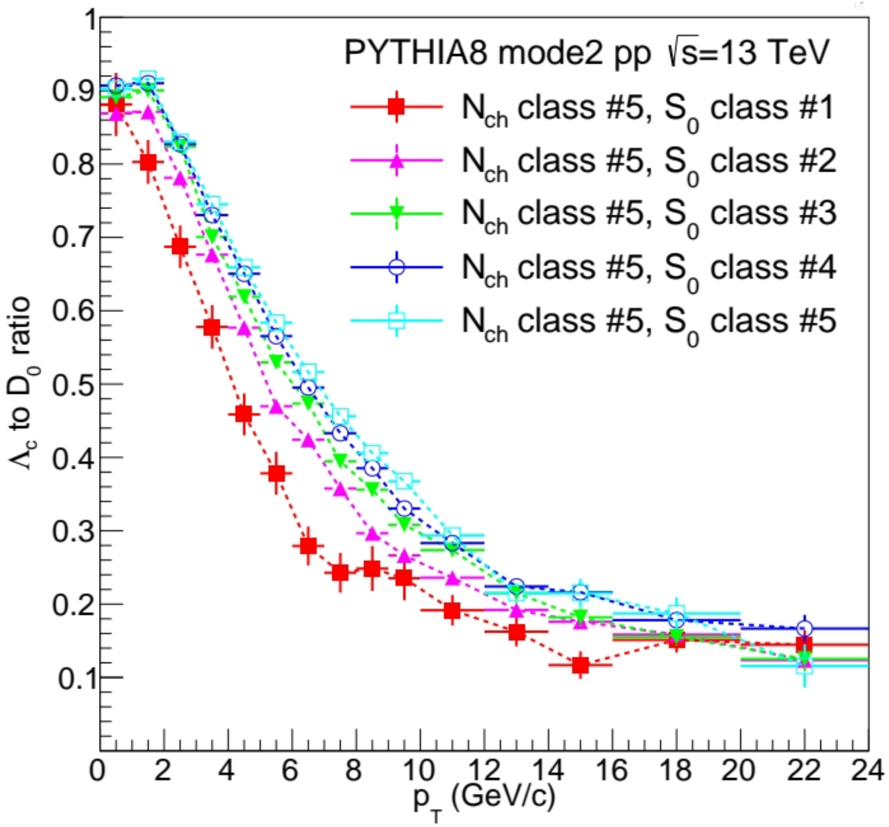
Jet activity classifier

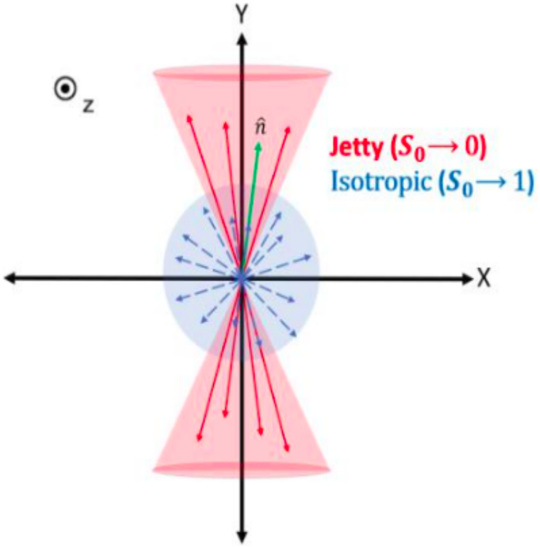


- Events require p_T>5 GeV/c **hadron trigger**.
- Significant difference is observable in case of **R_T** (**UE activity**).
- No significant difference when classified by **R_{NC}** classes (**jet activity**).

Λ_c/D^0 yield in Min Bias Events



$N_{CH} > 50$



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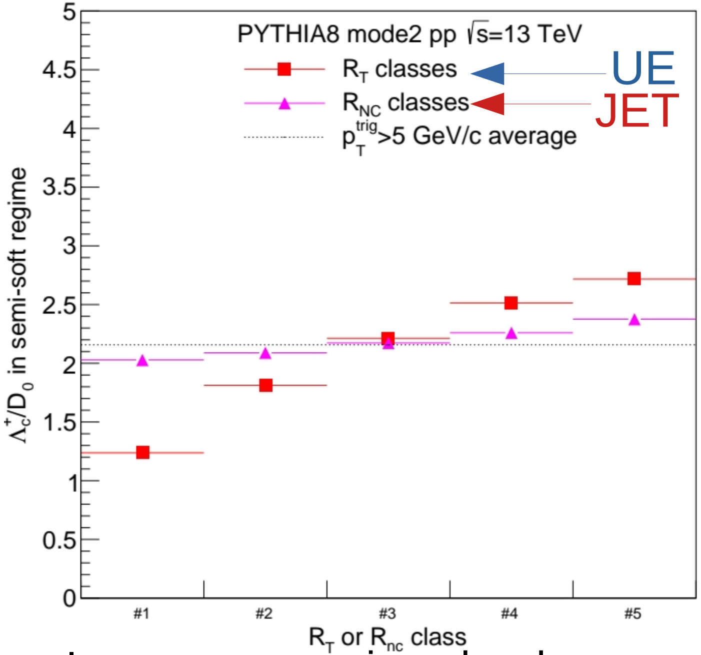
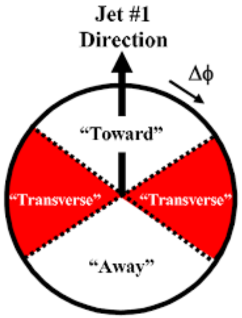
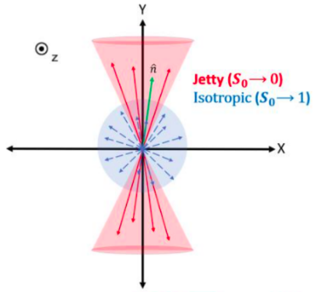
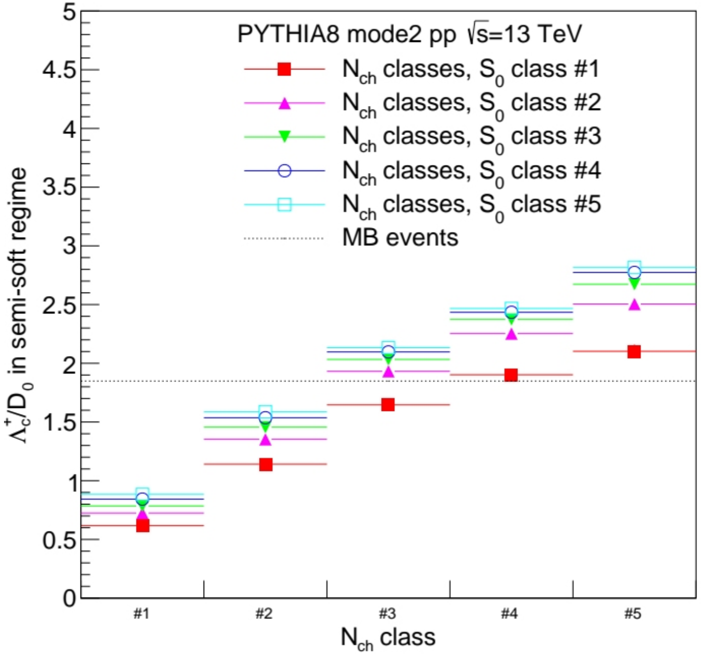
- Spherocity provides a measure for the **jettines**/**isotropy** of events.
- **Significant difference** is observed **for different spherocity classes** at fixed event-multiplicity.

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





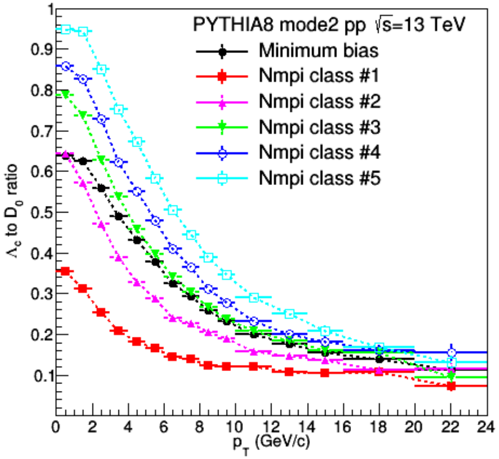




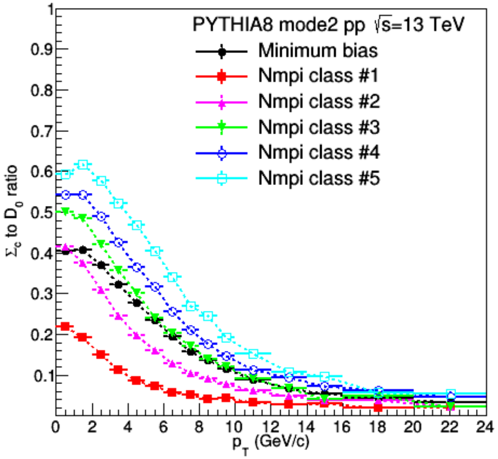
- In case we require a hard process ($P_T^{trigger}$ > 5 GeV/c)
  - **Strong dependence** of ratios on the **UE activity**,
  - **No pronounced dependence** on the **jet multiplicity**.
- In minimum-bias events
  - In case of high final-state multiplicity, ratio depends on jettiness,
  - Dependence is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

Other (higher-mass) charmed baryon to meson ratios

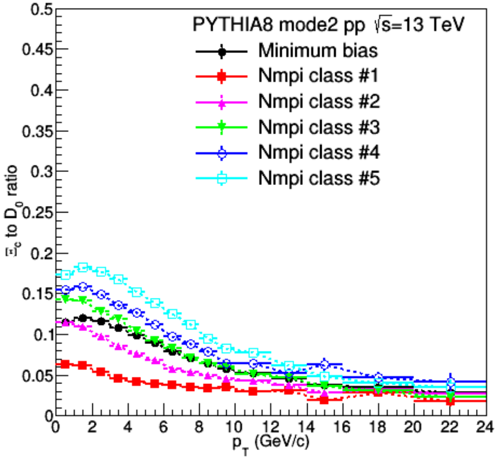
Z.V., A.M., R.V., arXiv:2302.09740 (accepted in J.Phys.G)



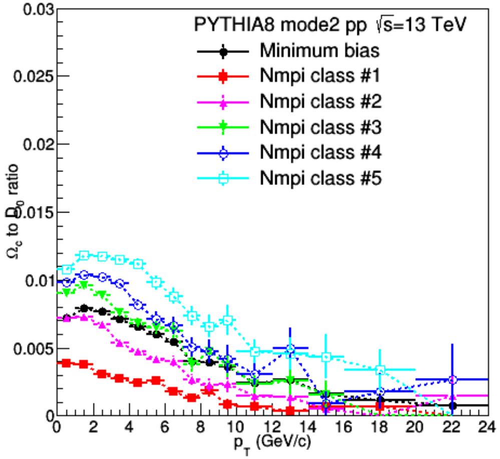
Λ_c(qqc), I = 0



Σ_c(qqc), I = 1



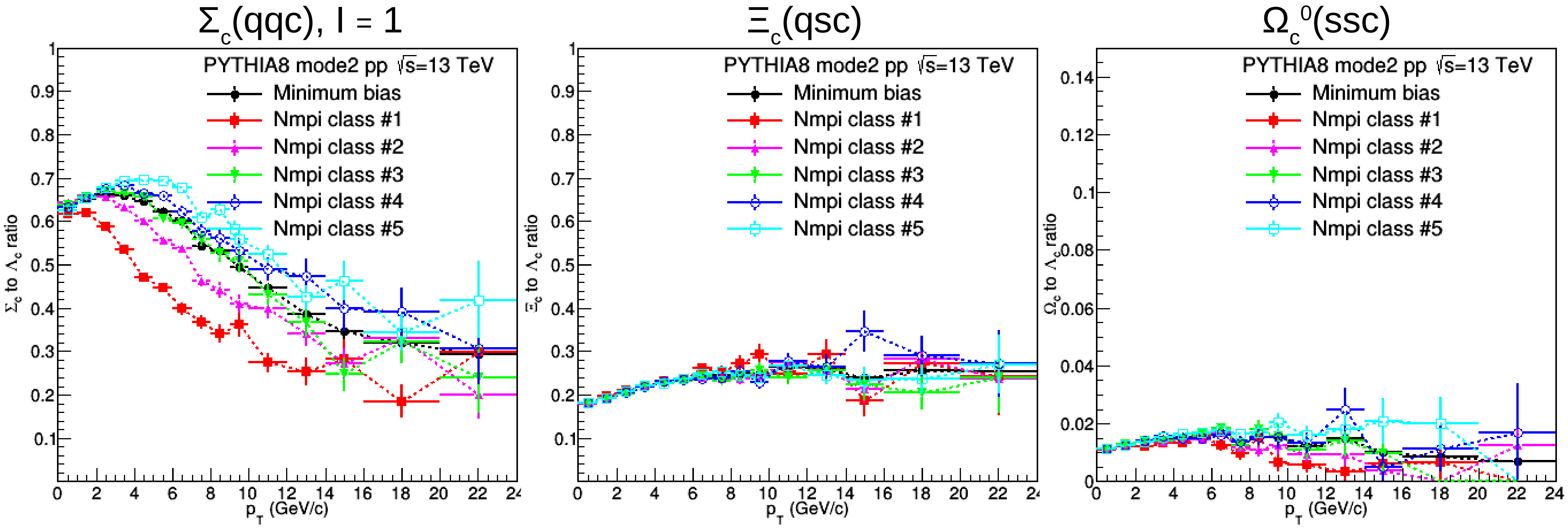
Ξ_c(qsc)



Ω_c^0(ssc)

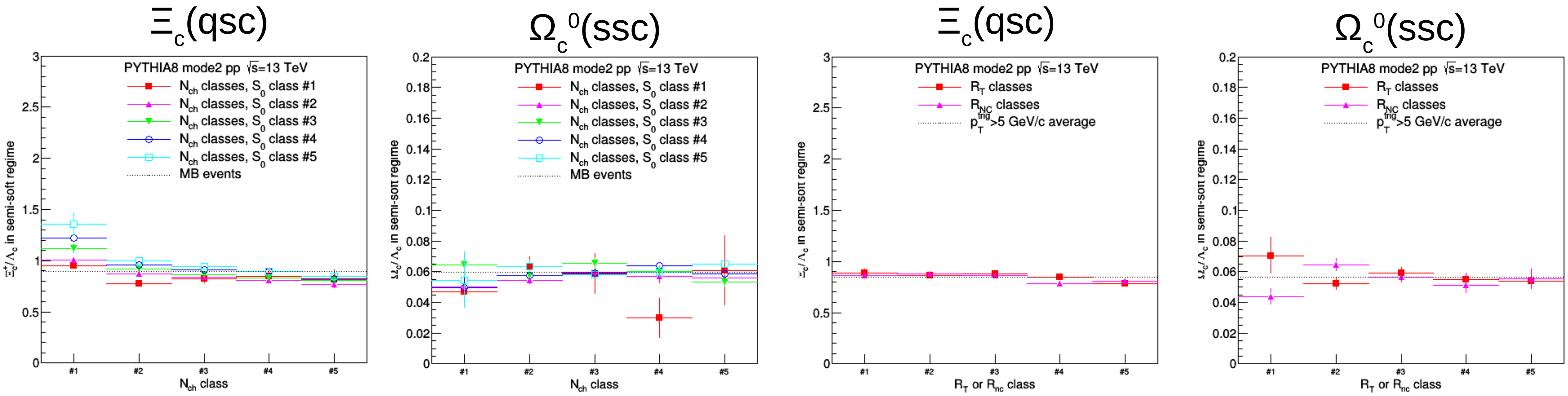
- Study extended for **higher-mass baryons**.
- Similar trend for all baryon/meson ratios, just as for the Λ_c/D^0 yield ratio.
- Note: For the Λ_c there is a significant feed-down from Ξ_c.

Baryon to baryon ratios



- There is a **low p_T enhancement** connected to the **charm content**
- There is a **high p_T enhancement** connected to the **strange content**
- **Strange enhancement is different from charm enhancement**

Integrated plots for strange content



- Strangeness content has only slight effect in semi-soft (coalescence) regime.

class	#1	#2	#3	#4	#5
N_{ch}	≤15	16–30	31–40	41–50	≥51
N_{fw}	≤45	46–90	91–120	121–150	≥151
R_T	<0.5	0.5–1	1–1.5	1.5–2	>2
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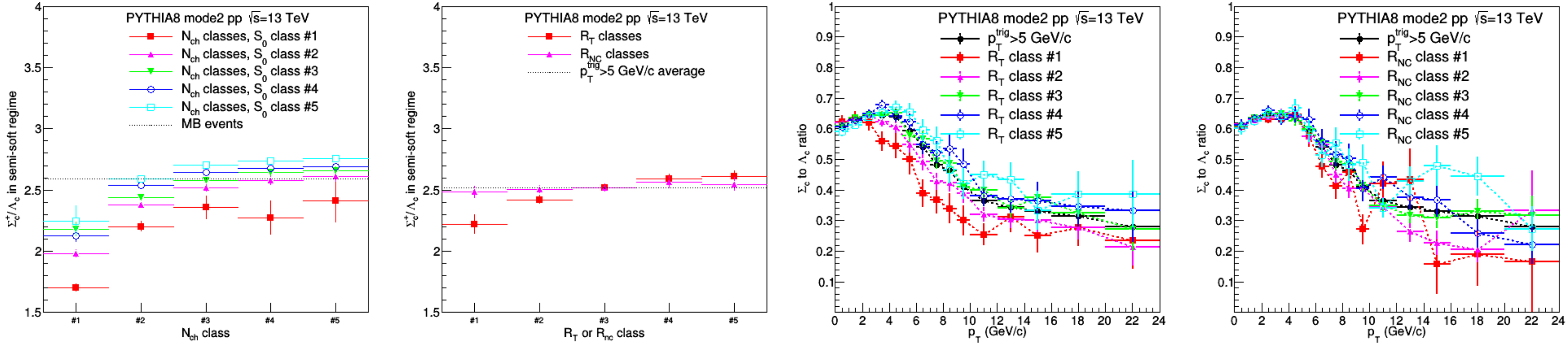
S_0	0–0.25	0.25–0.45	0.45–0.55	0.55–0.75	0.75–1

Integrated plots for strange content

$\Sigma_c(qqc)$, I = 1



- Difference in the enhancement in semi-soft region (from UE), caused by the isospin effect.

class	#1	#2	#3	#4	#5
N_{ch}	≤15	16–30	31–40	41–50	≥51
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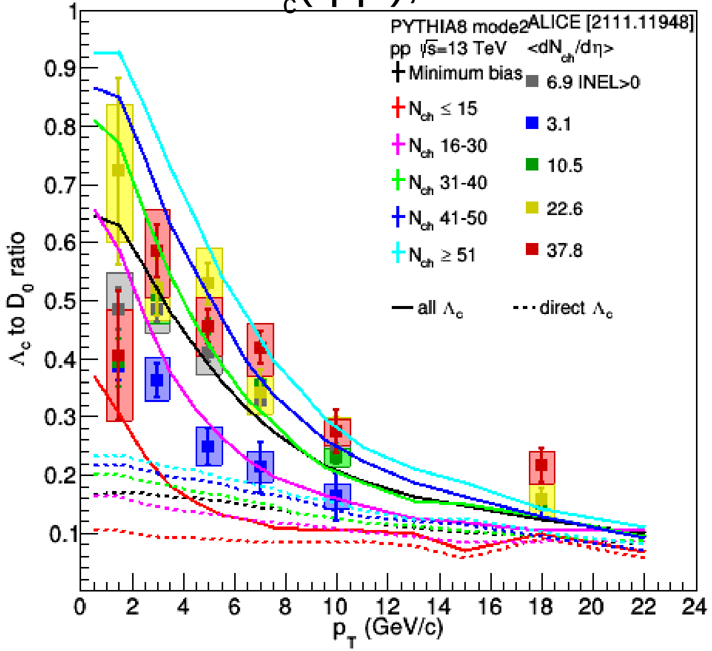
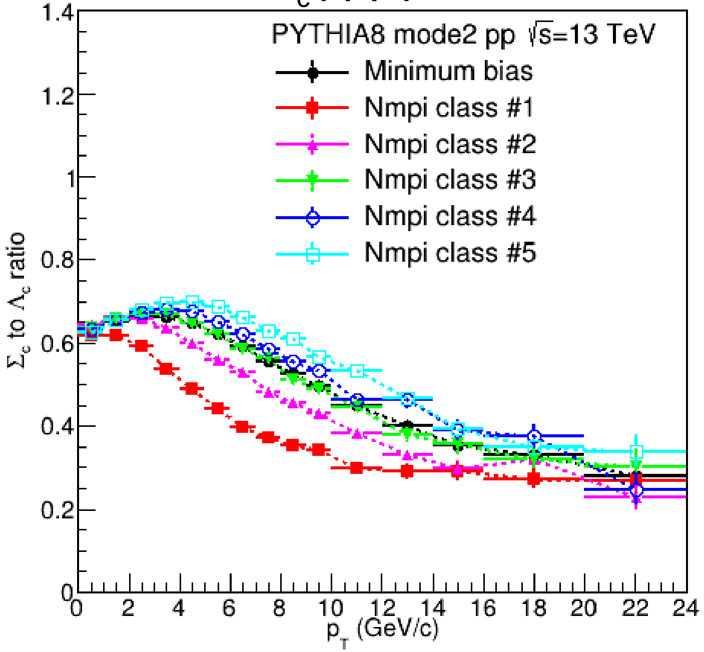
S_0	0–0.25	0.25–0.45	0.45–0.55	0.55–0.75	0.75–1

Λ_c and Σ_C - the isospin-related effect

Λ_c(qqc), I = 0



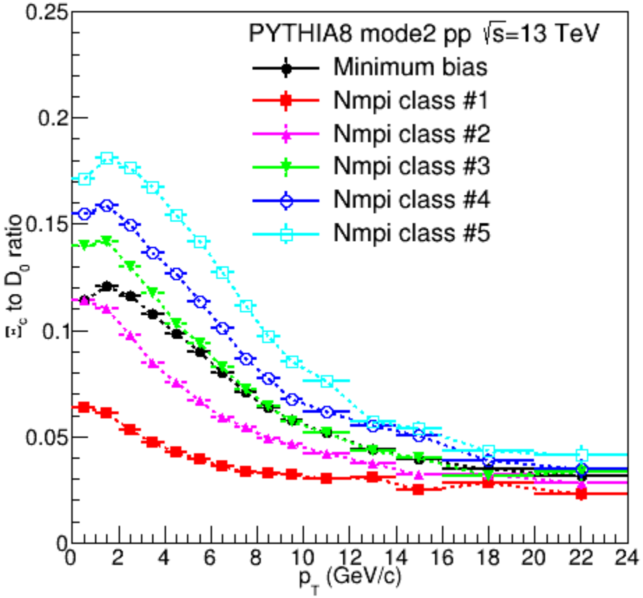
Σ_c(qqc), I = 1



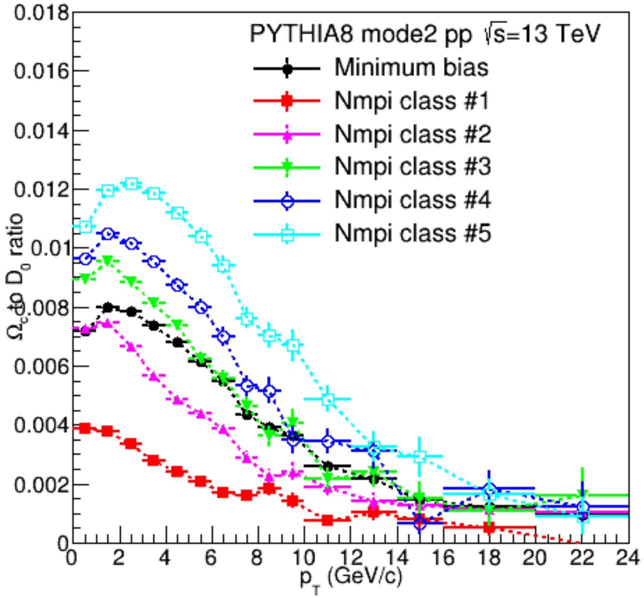
- For the Λ_c there is a **significant feed-down from Ξ_c**:
  - 1. The result is expected to be an admixture of prompt Λ_c^+ and $\Xi_c^{0,+}$
  - 2. Pattern can be attributed to presence or lack of strange content
- Difference in the enhancement in semi-soft region (from UE), might be caused by an **isospin-related effect**.

Charm and Strange enhancement

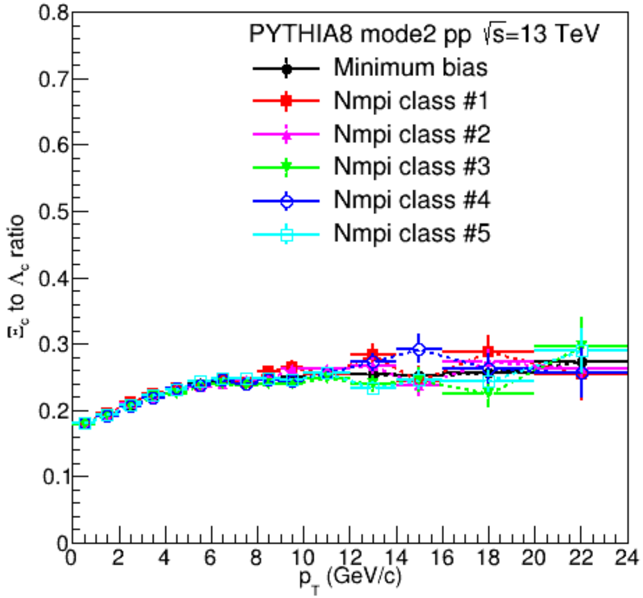
Ξ_c(qsc)



Ω_c^0(ssc)



Λ_c(qqc)



- **Strange enhancement trend slightly different in p_T, but no dependence on event activity class!**

Flatenicity

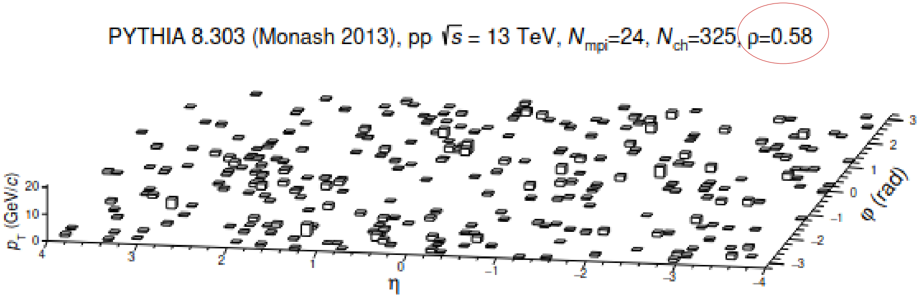
A. Ortiz, G. Paic, arXiv:2204.13733

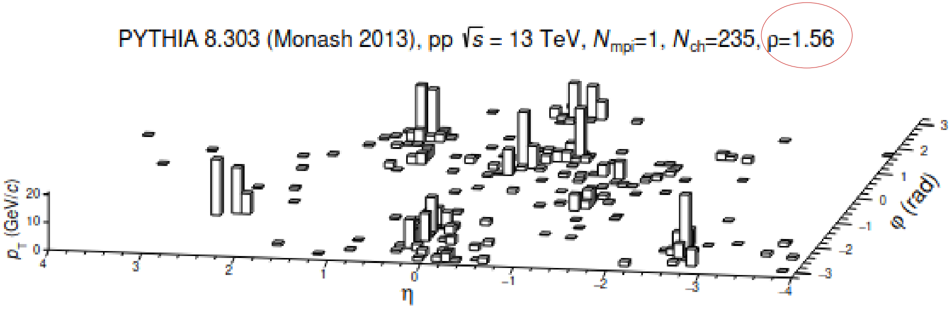
- Motivated by looking into very rare "hedgehog" events in pp collisions (reported first by **UA1** and **CDF** collaborations).
- **Flatenicity (ρ):** the relative standard deviation of the p_T^{cell} distribution (event-by-event):

$$\rho = \sigma_{p_T^{cell}} / \langle p_T^{cell} \rangle \,.$$

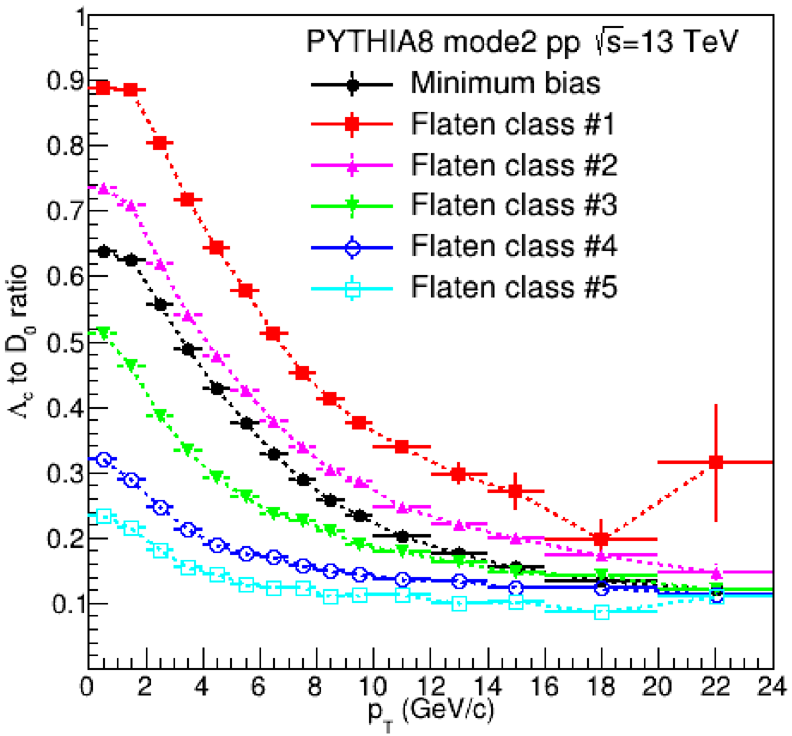
- The whole phase space is divided into 80 elementary cells (10 η bins, 8 ϕ bins).

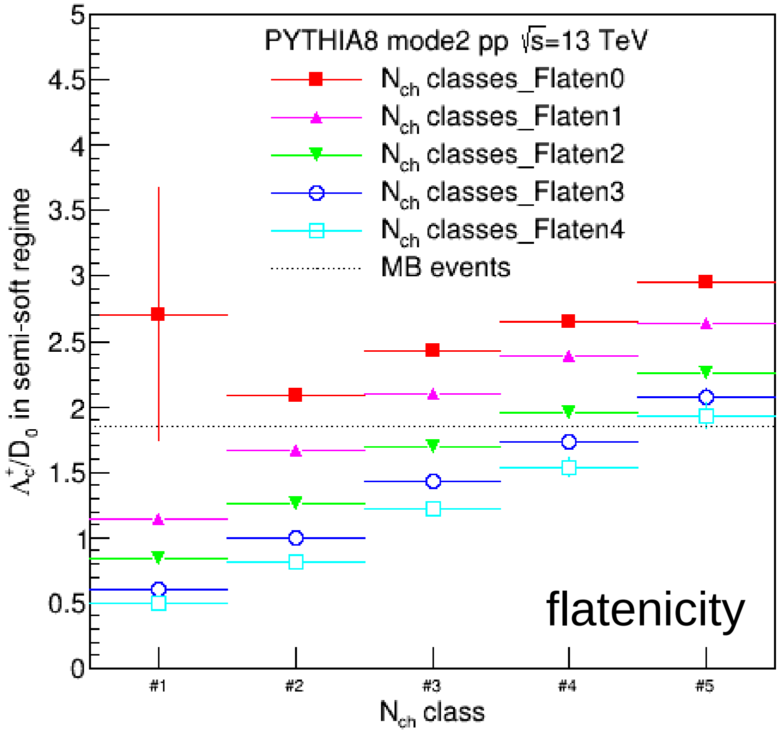
- Charged particles within $|\eta| < 4$ and $p_T > 0.15$ GeV/c (ALICE 3 acceptance).





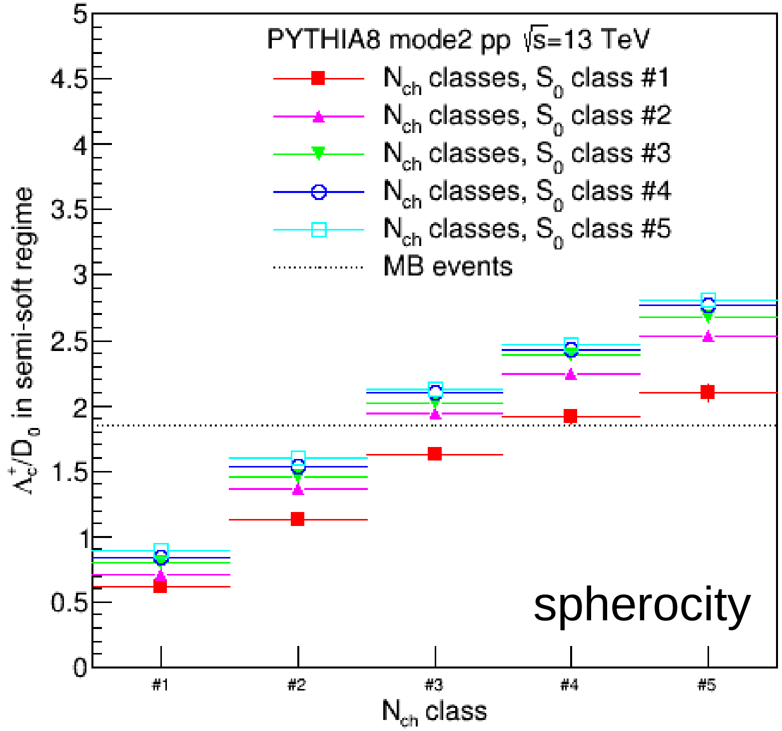
Λ_c/D^0 yield for the flatenicity classes

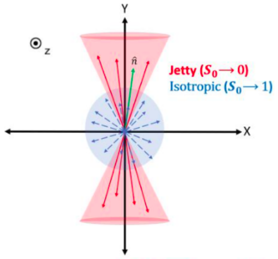


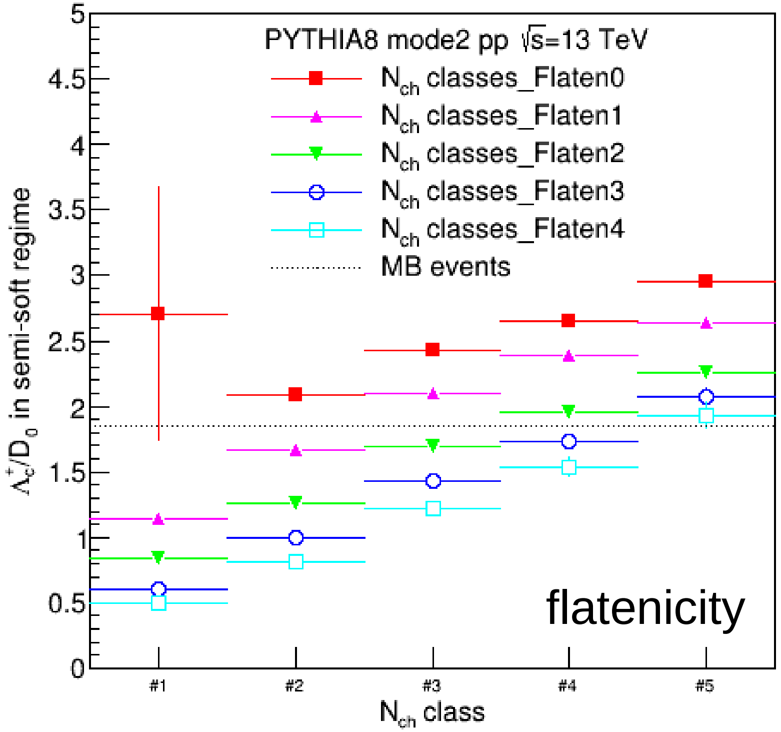


- For lower flatenicity, the event is more flat up to high rapidities.
- The Λ_c/D^0 ratio decreases with increasing flatenicity.
- **Flatenicity correlates with N_{ch}**, might be a better quantity than spherocity to represent MPI.

Λ_c/D^0 yield for the flatenicity classes







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Summary

- Enhancement of Λ_C/D^0 in pp collisions compared to e^+e^- collisions question the **universality** of charm fragmentation.
- We propose event-activity classifiers which provide great sensitivity to the production mechanisms

  → directly accesible experimental observables in LHC Run 3
- In a model class considering color reconnection beyond leading approximation, the **Λ_C enhancement** comes from the **underlying event**, **not** from the **jets**.
- The observables are **sensitive to** differences between mechanisms of **strangeness** and **charm enhancement**.
- **Flatenicity** might be a better quantity than spherocity to **represent MPI**, and it is **measurable in ALICE 3**.
- See articles for more details:

  Z.V., R.V., J. Phys. G: Nucl. Part. Phys. 49 (2022) 075005 (arXiv:2111.00060)

  Z.V., A.M., R.V., arXiv:2302.09740 (accepted in J.Phys.G)

Thank you for your attention!