The role of the underlying event in the heavy-flavor baryon enhancement

Róbert Vértesi and Zoltán Varga

vertesi.robert@wigner.hu varga.zoltan@wigner.hu

wigner

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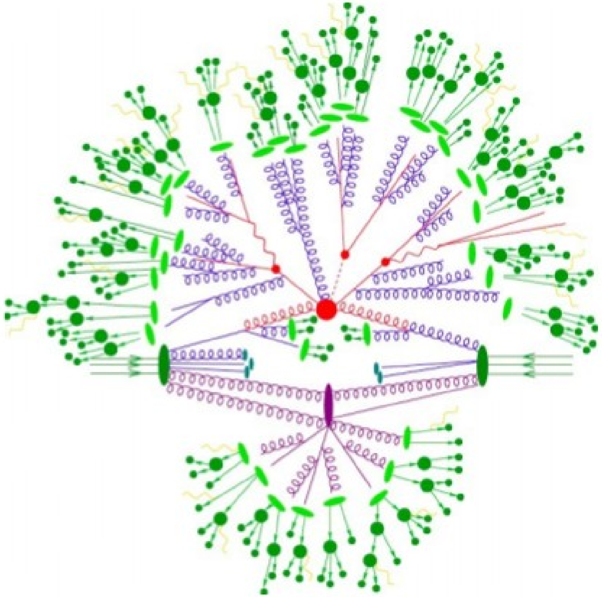
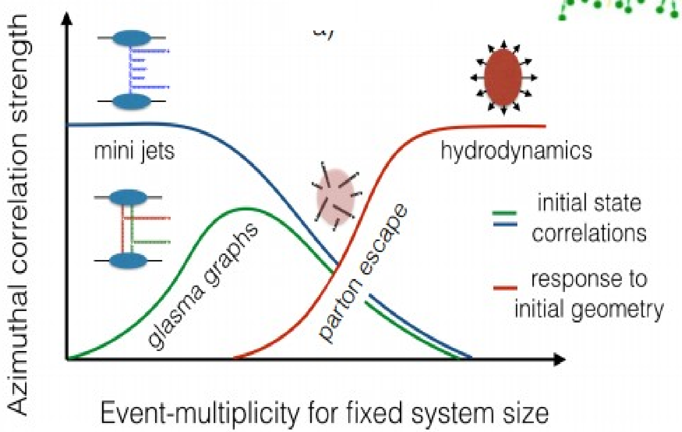
Hot QGP or cold QCD?

- **Does QGP come into being in small systems?**
  - Is energy density high enough?
  - Can hot matter thermalize?



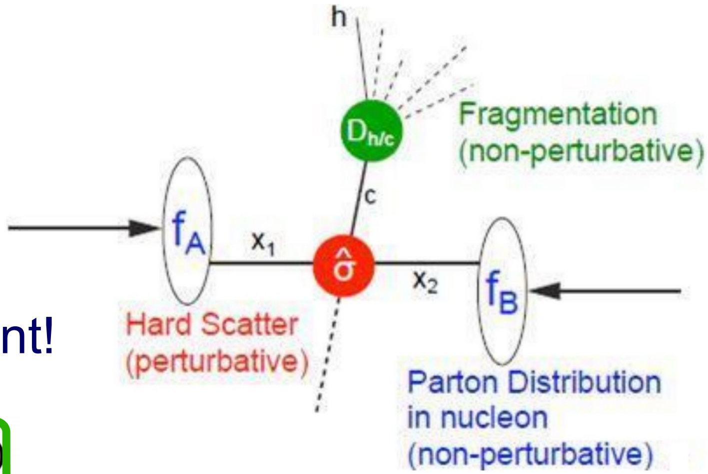
- Current understanding:
  - **Collective behavior does not require QGP**
  - Can be produced by vacuum-QCD effects at the soft-hard boundary

  - **Multi-parton interactions** (MPI)
    e.g. **Schlichting, arXiv:1601.01177**
  - **Color-reconnection**
    (part of some MPI models)
    e.g. **Ortiz-Bencédi-Bello, J.Phys.G 44 (2017)**
  - **Minijets** (semi-hard partons produced by incoming partons or bremsstrahlung)
    e.g. **Eskola, Nucl.Part.Phys. 22, 4, 185 (1998)**



Heavy flavor: production and fragmentation

- **Production of heavy-flavor hadrons:**
  - Parton distribution functions (PDF)
  - Hard scattering process
  - Fragmentation



- Factorization hypothesis: these 3 are independent!

$$\sigma_{hh\to H} = \boxed{f_a(x_1,Q^2)\otimes f_b(x_2,Q^2)} \otimes \boxed{\sigma_{ab\to q\bar{q}}} \otimes \boxed{D_{q\to H}(z_q,Q^2)}$$

Feynman-*x*:
$x_i = p^A_{\parallel} / p^A_{\parallel,max}$
Q : momentum transfer

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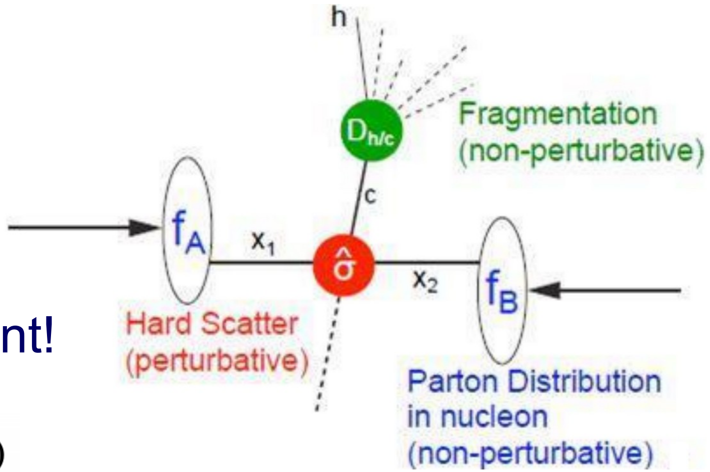

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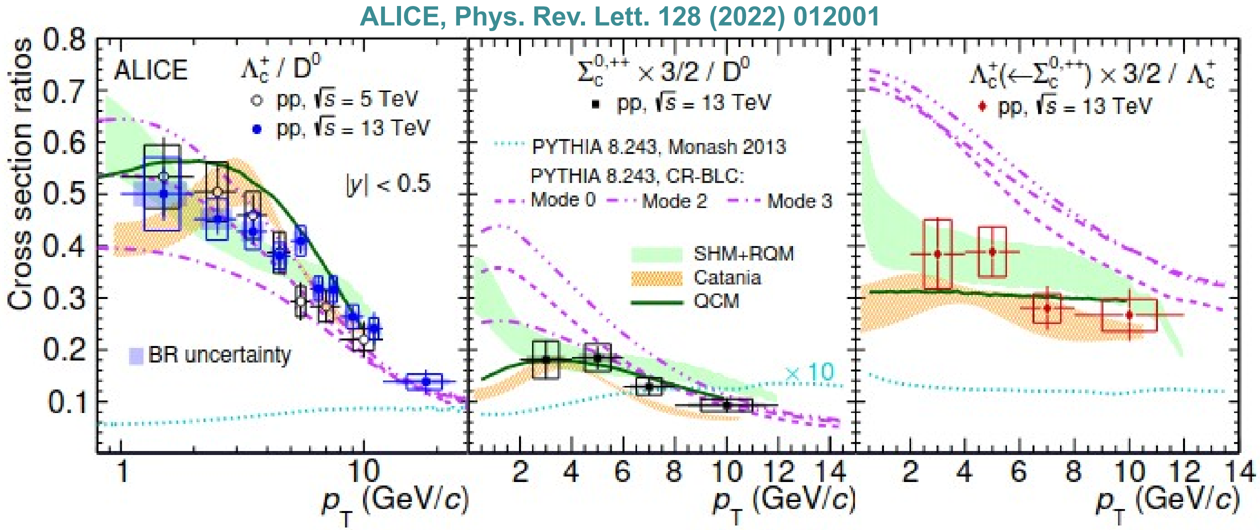
Q : momentum transfer

- **Fragmentation functions are traditionally treated as universal (same across all colliding systems)**

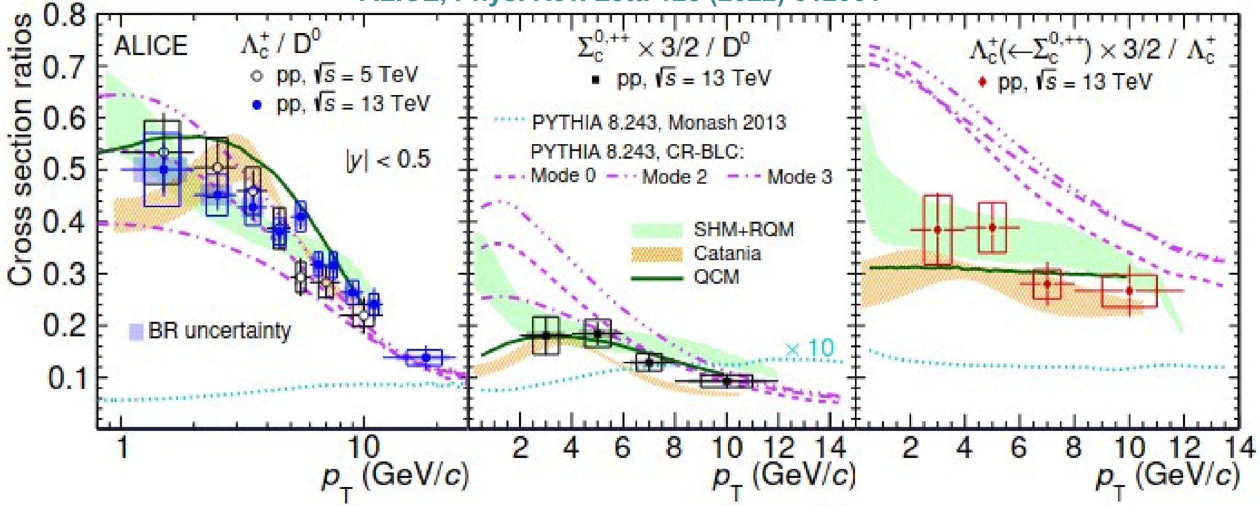
Charm baryon enhancement



- **Charm baryon to meson ratios: sensitive probes of fragmentation**
- Λ_c/D^0 and Σ_c/D^0 underestimated by models based on factorization approach with fragmentation functions from ee collisions: **HF fragmentation universality broken!**

Charm baryon enhancement

ALICE, Phys. Rev. Lett. 128 (2022) 012001



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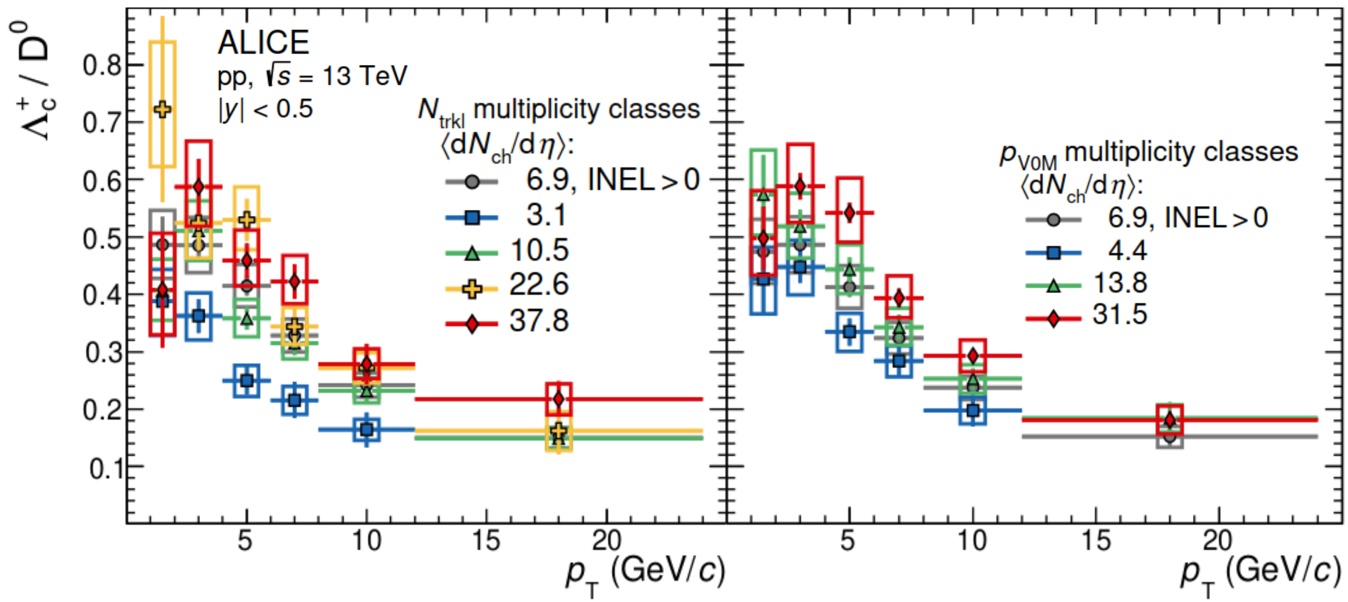
- **PYTHIA 8 CR-BLC**: string formation beyond leading color approximation
  Christiansen-Skands, HEP 08 (2015) 003
- **SH model + RQM:** feed-down from augmented set of charm-baryon states
  He-Rapp, Phys. Lett. B 795 (2019) 117
- **Catania**: fragmentation + coalescence of charm and light quarks
  Plumari et al., Eur. Phys. J. C 78 no. 4, (2018) 348
- **QCM:** coalescence model based on statistical weights + equal quark-velocity
  Song-Shao, Eur. Phys. J. C 78 no. 4, (2018) 344

Charm baryon enhancement vs. multiplicity

ALICE, PLB 829 (2022) 137065



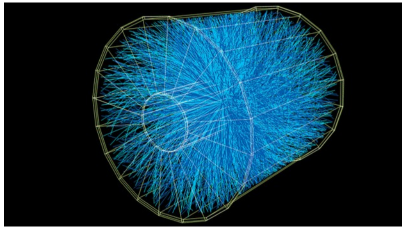
- The enhancement in Λ_c/D^0 depends on the final state multiplicity at mid- and forward rapidity
- **Goal: Understand the origin of the enhancement with detailed event activity studies**

- **Is the enhancement related to the underlying event or jet fragmentation?**
  → Test sensitivity using predictions with **PYTHIA 8 with the CR-BLC model**

Categorizing events by activity

Charged-hadron multiplicity N_{ch} : $|\eta|<1$ N_{fw} : $2<|\eta|<5$

- Number of final-state charged hadrons
- Global parameter, does not take leading process into account



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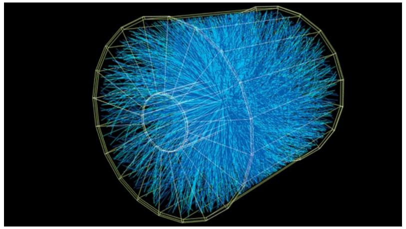

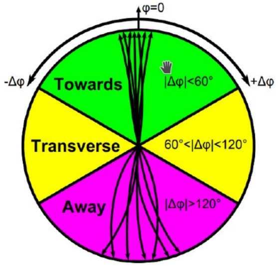

$$R_{\mathrm{T}} = \frac{N_{\mathrm{trans}}}{\langle N_{\mathrm{trans}} \rangle}$$

Relative transverse multiplicity

- Represents the underlying-event
- High-p_{T} trigger hadron => Statistics can be a problem
- Dependence on fragmentation

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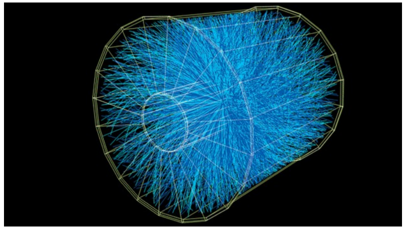

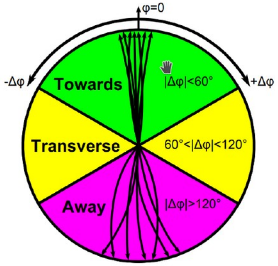

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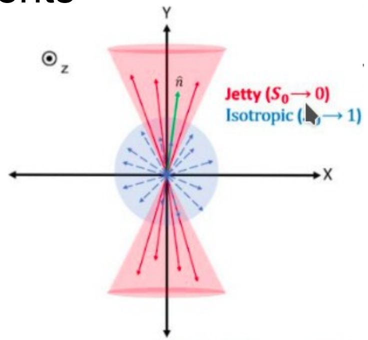
Transverse spherocity

- Isotropic vs. jetty events
- No need for trigger
- Only mid-rapidity

$$S_0 = \frac{\pi^2}{4}\left(\frac{\Sigma_i |\vec{p_{T_i}} \times \vec{n}|}{\Sigma_i \vec{p_{T_i}}}\right)^2$$



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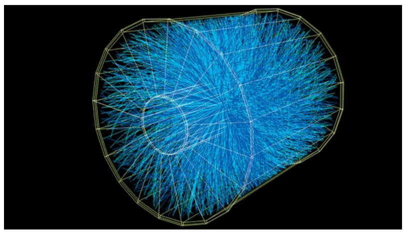

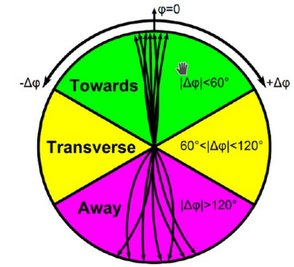

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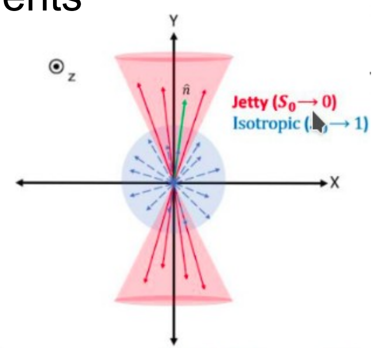
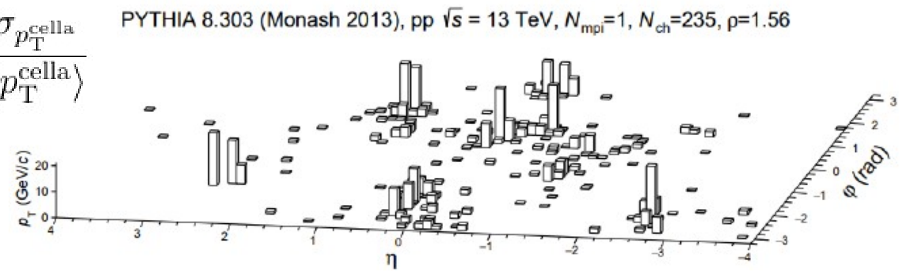


$$\rho = \frac{\sigma_{p_{\mathrm{T}}^{\mathrm{cella}}}}{\langle p_{\mathrm{T}}^{\mathrm{cella}} \rangle}$$



Flattenicity

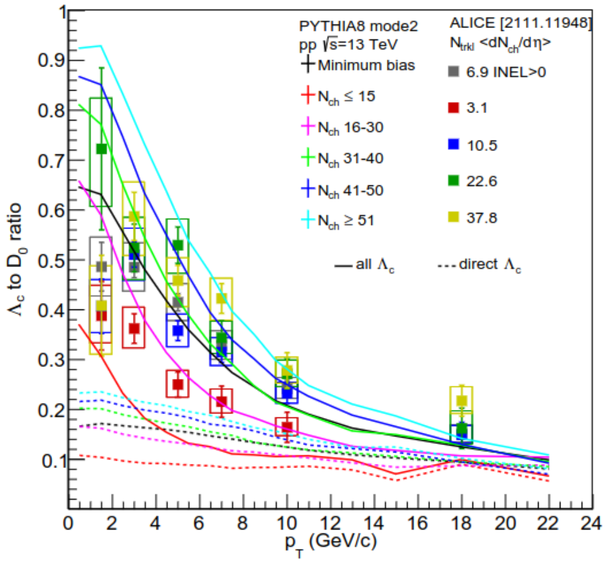
A. Ortiz, G. Paic, arXiv:2204.13733

- Isotropic/hedgehog-like vs. jetty
- No need for trigger
- Full rapidity window (eg. $|\eta|<4$)

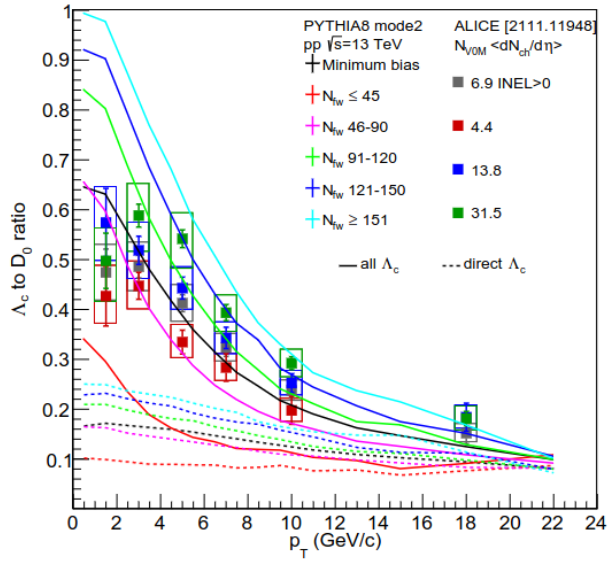
Λ_c/D^0 ratios vs. central and forward multiplicity

J. Phys. G 49 (2022) 7, 075005
J. Phys. G 50 (2023) 7, 075002

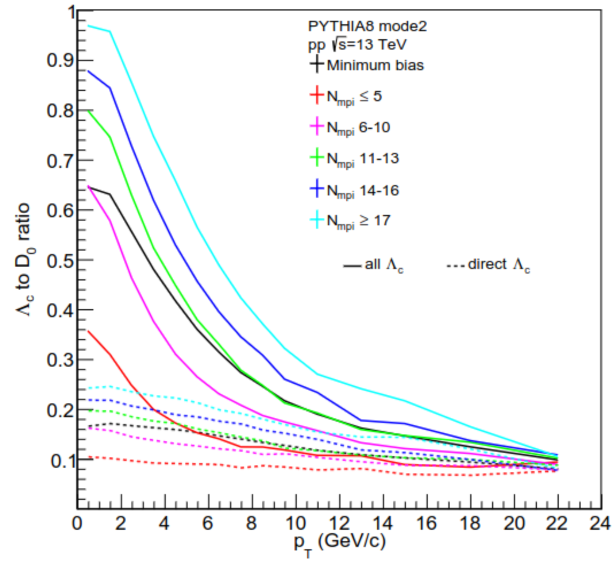
central rapidity N_{ch}



forward rapidity N_{fw}



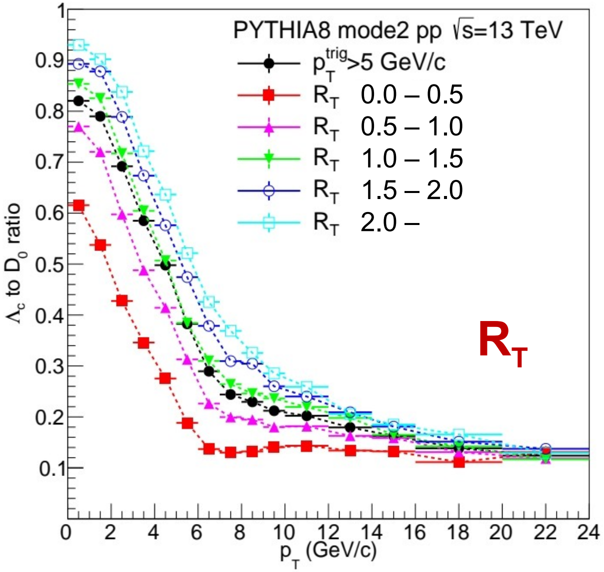
N_{MPI}

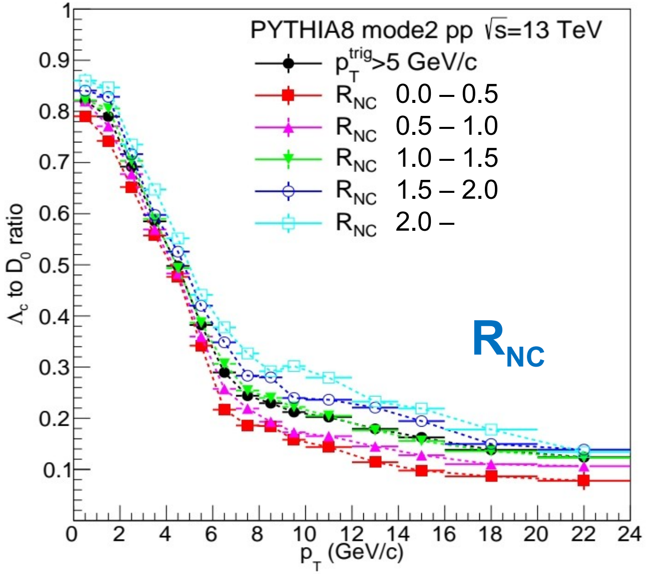


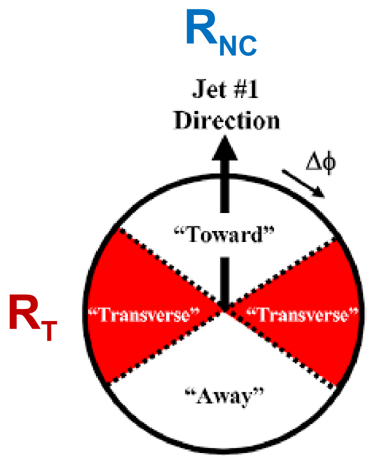
- **Simulation** results **predicted trends observed in ALICE** experimental data
- For N_{fw}: a rapidity gap reduces correlation between leading hard processes and multiplicity
  => Hint that multiplicity dependence is not driven by charm production in jets

Λ_c/D^0 ratios vs. UE and jet activity (triggered)

J. Phys. G 49 (2022) 075005



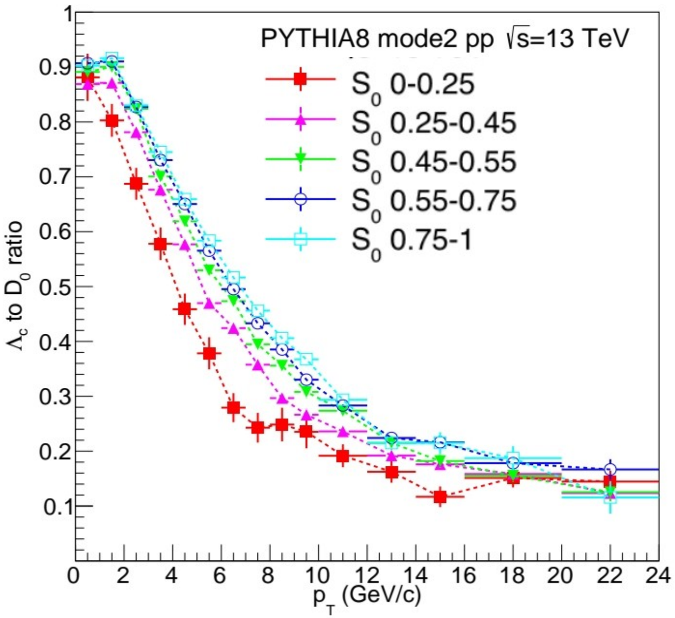




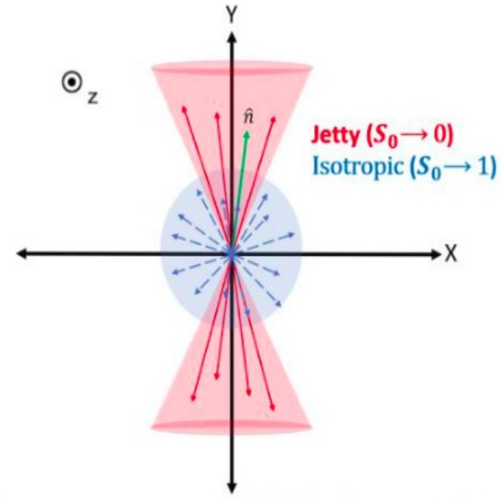
- Events require p_T>5 GeV/c **hadron trigger**
- Significant difference is observable in case of R_T (**UE activity**)
- No significant difference when classified by R_{NC} classes (**jet activity**)

Λ_c/D^0 ratios vs. spherocity (minimum bias)

J. Phys. G 49 (2022) 075005



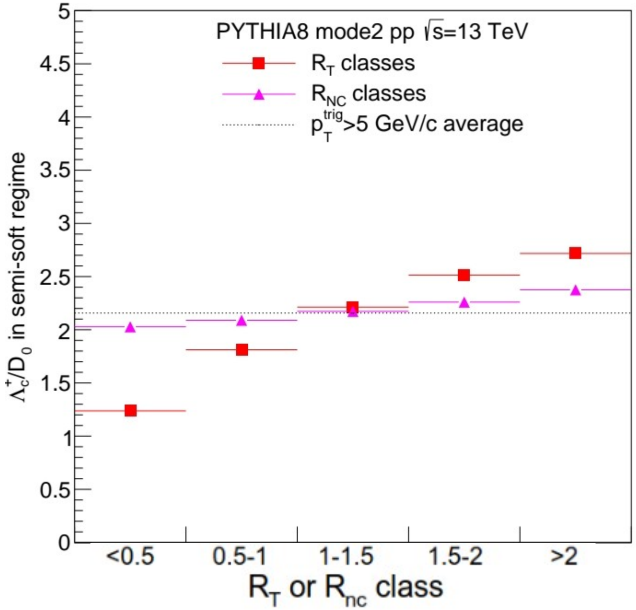
$N_{CH} > 50$

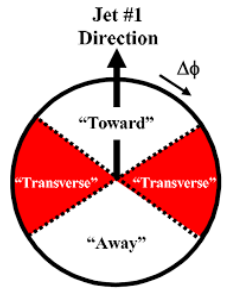


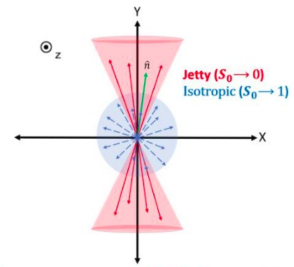
- Spherocity provides a measure for the **jettines**/**isotropy** of events
- **Significant difference** is observed **for different spherocity classes** at fixed event-multiplicity.

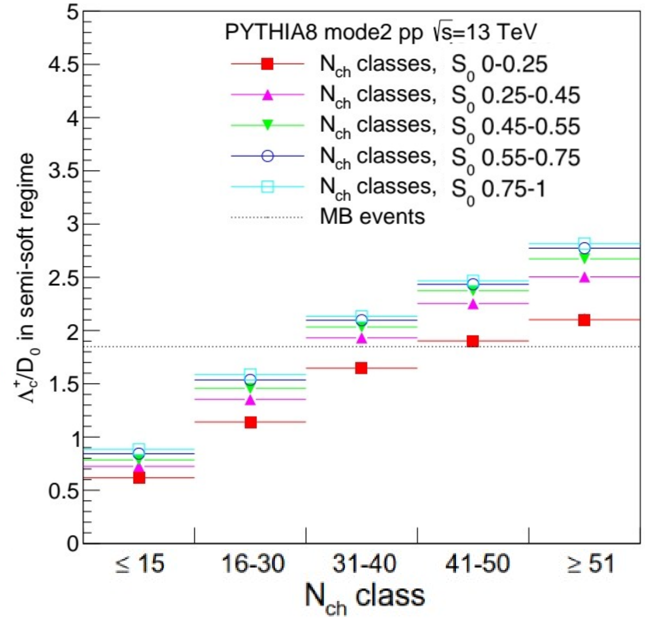
Λ_c/D^0 ratios - summary

J. Phys. G 49 (2022) 075005









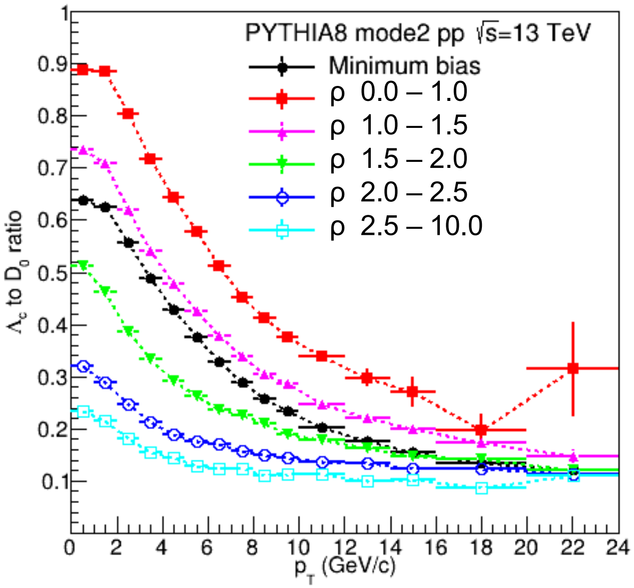
R_T, R_{NC}; $p_T^{trigger}$ > 5 GeV/c

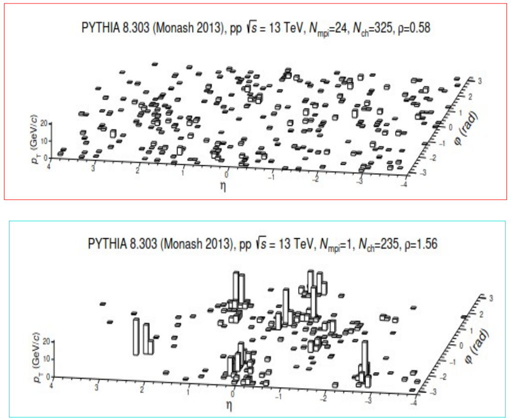
- Hard process required
- **Strong dependence** of ratios on the **UE activity**
- **No pronounced dependence** on the **jet multiplicity**.
- Trigger biases sample and decreases statistics

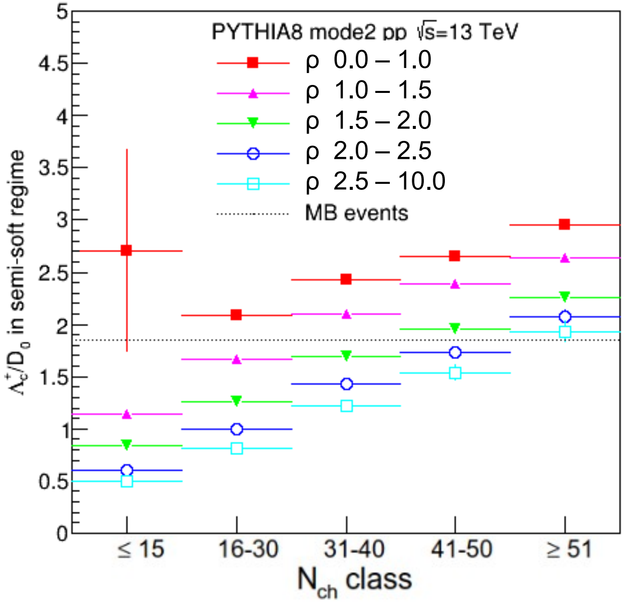
S_0: Jettiness in minimum-bias events

- No need to use a trigger
- At high final-state multiplicity: ratio depends on jettiness
- Low final-state multiplicity: dependence is minute

Λ_c/D^0 yield for different flattenicity classes





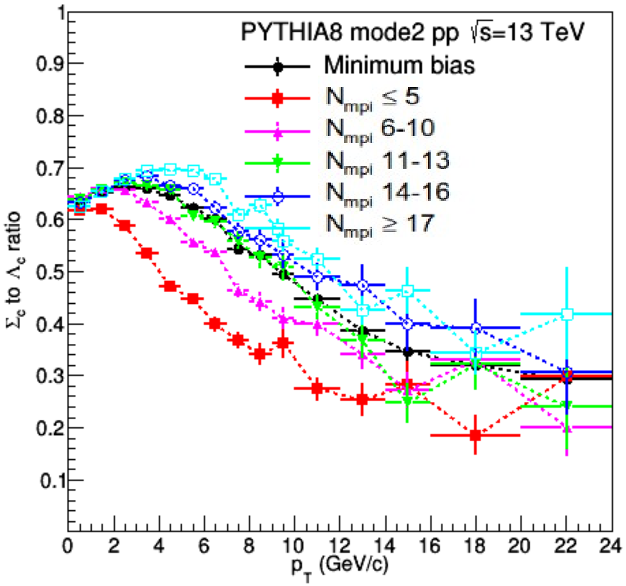


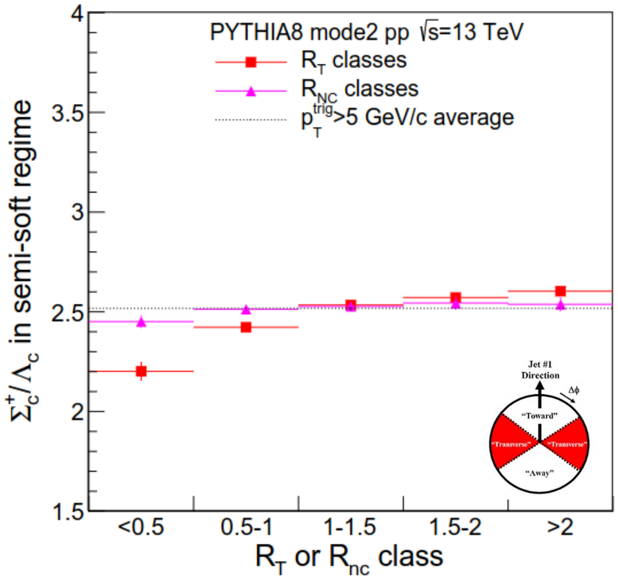
- **Flatenicity strongly bound to the underlying event (correlates with N_{MPI})**
- The $\mathbf{\Lambda_c/D^0}$ ratio decreases with increasing flatenicity
- **Might be a better quantity to address charmed-baryon enhancement**

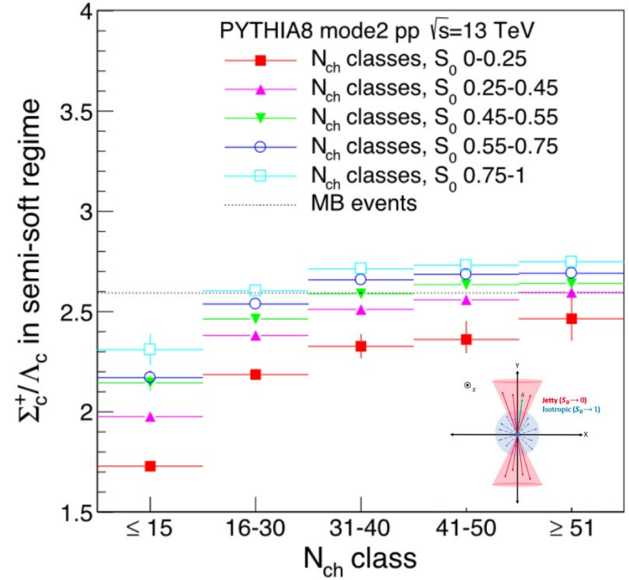
Σ_c vs. Λ_c : Isospin of charmed baryons

J. Phys. G 50 (2023) 7, 075002

Σ_c / Λ_c







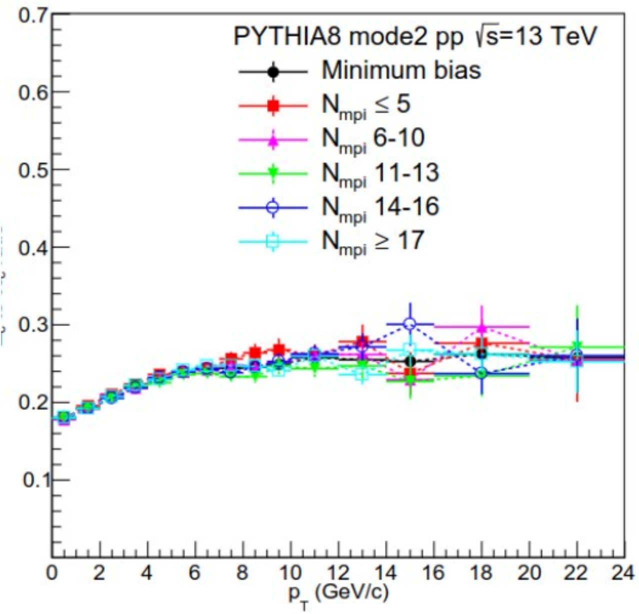
Σ_c (qqc, I=0) vs. Λ_c (qqc, I=1)

- Different trends in Λ_c and Σ_c
- **Trends depend on MPI in the model class**
- **Charmed baryon ratios: sensitive event-shape dependent observables**

Ξ_c and Ω_c: Strangeness in charmed baryons

J. Phys. G 50 (2023) 7, 075002

$\Xi_c(qsc)$ / Λ_c (qqc)



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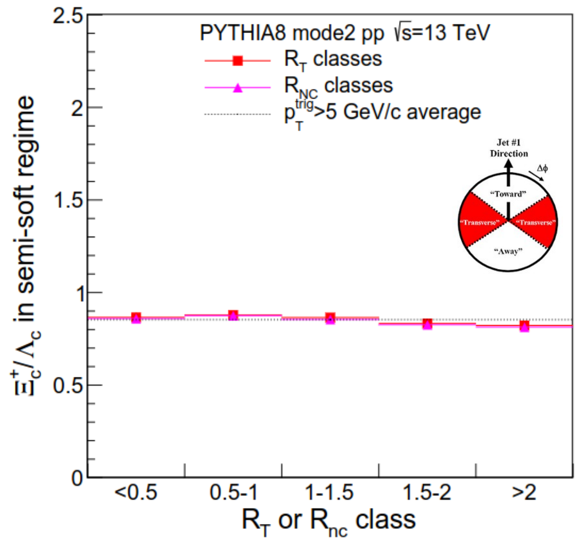
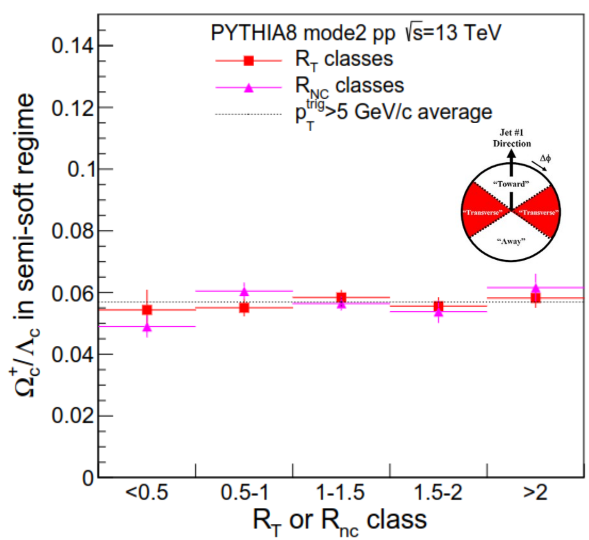


$\Omega_c^0(ssc)$ / Λ_c (qqc)



- **low p_T enhancement** by **charm** <=> **high p_T enhancement** more by **strangeness**
- **Strangeness content: no further sensitivity to the event-property descriptors**
- Charm baryon enhancement driven by a different mechanism than strange baryon enhancement

Summary

- **Enhancement of Λ_C/D^0 in pp collisions compared to e^+e^- collisions questions 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 with color reconnection beyond leading approximation, the Λ_C enhancement comes from the underlying event, not from the jets.**
  - **This is seen with R_T vs. R_{NC} (triggered events) as well as S_0 (minimum bias)**
  - **Flattenicity, a new quantity to represent MPI, may be even more distinctive**

- **The observables are sensitive to differences between mechanisms of strangeness and charm enhancement as well as baryon isospin**


Thank you!

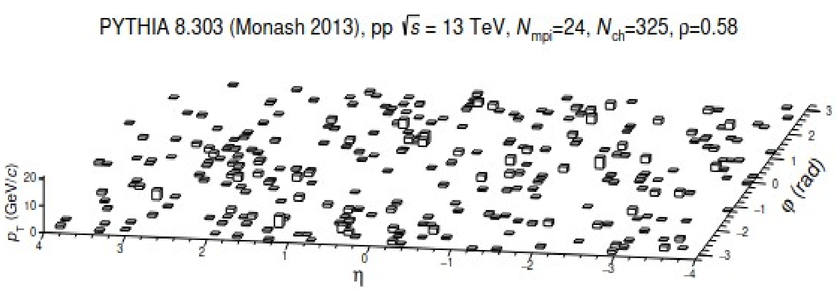
Flattenicity

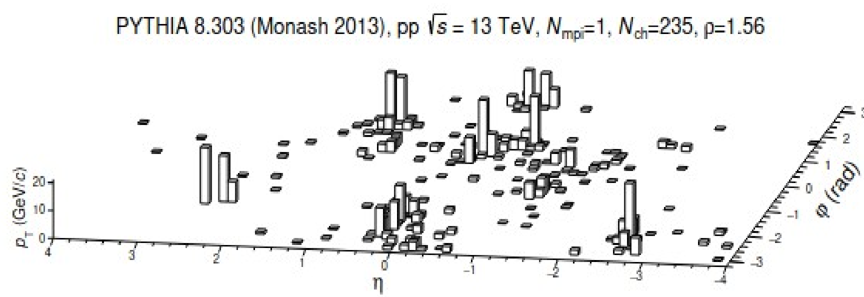
A. Ortiz, G. Paic, arXiv:2204.13733

- 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):

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

- The whole phase space is divided into 80 elementary cells (10 η bins, 8 ϕ bins).
- Charged particles within |η| < 4 and p_T > 0.15 GeV/c (ALICE 3 acceptance).

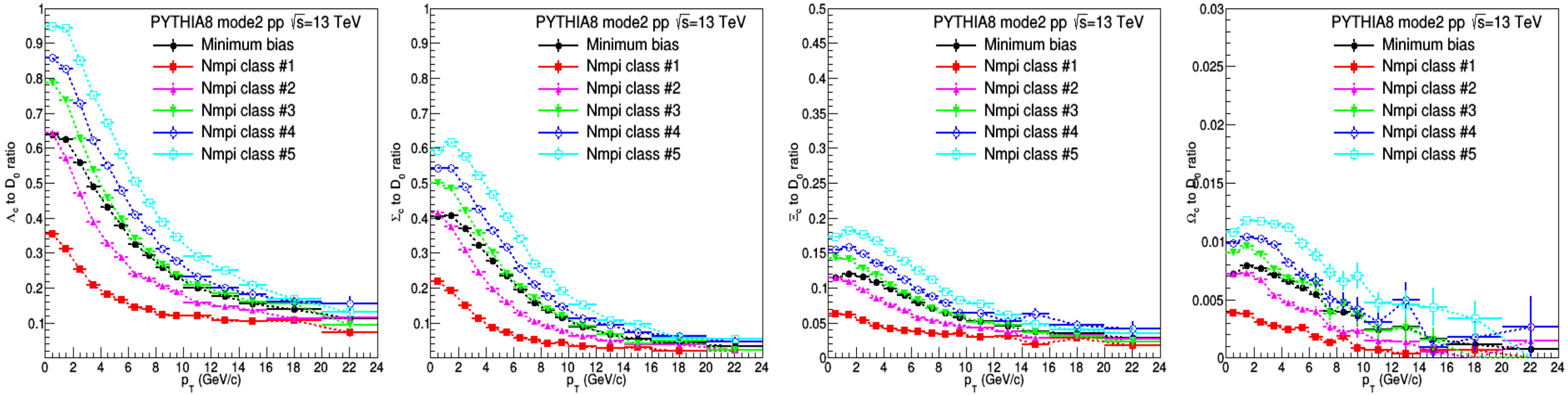




Event descriptor classes

class	#1	#2	#3	#4	#5
N_{ch}	$\leq$15	16–30	31–40	41–50	$\geq$51
N_{fw}	$\leq$45	46–90	91–120	121–150	$\geq$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
ρ	0 – 1	1 – 1.5	1.5 – 2	2–2.5	>2.5

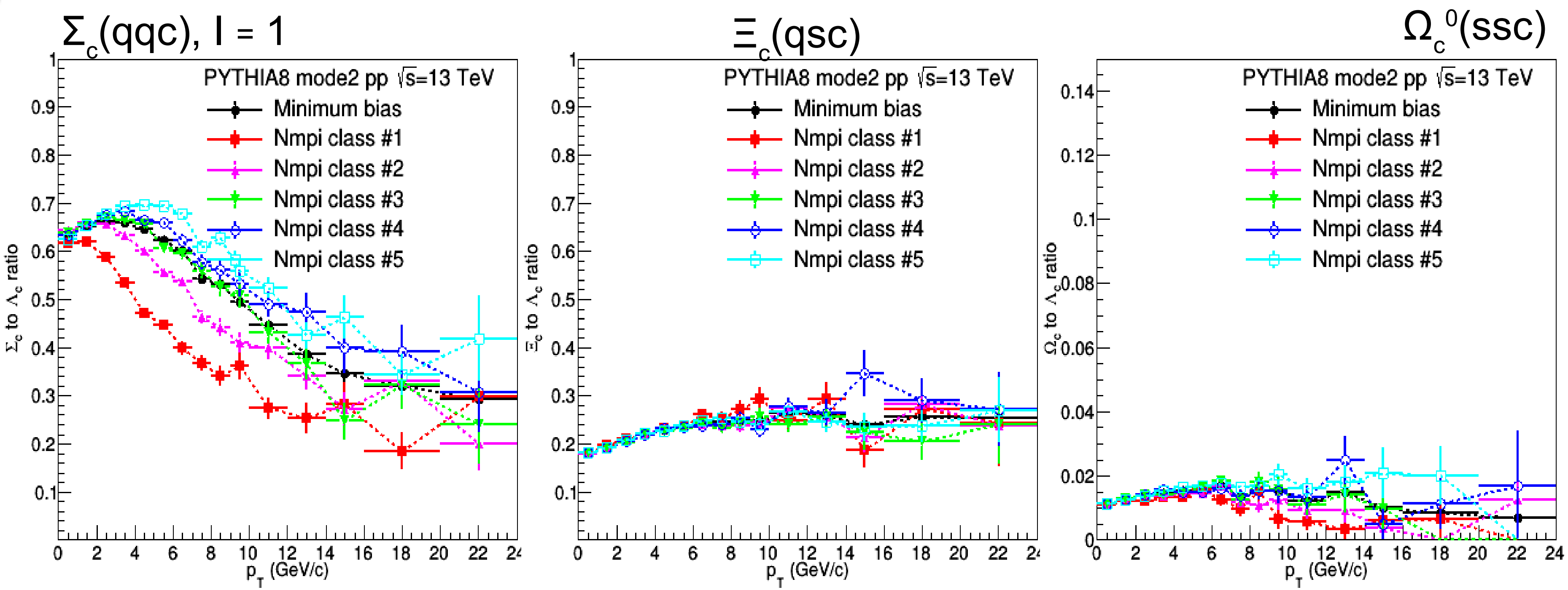
Charmed baryon-to-meson ratios vs. N_{MPI}



Λ_c(qqc), I = 0 $\quad$ Σ_c(qqc), I = 1 $\quad$ Ξ_c(qsc) $\quad$ Ω_c^0(ssc)

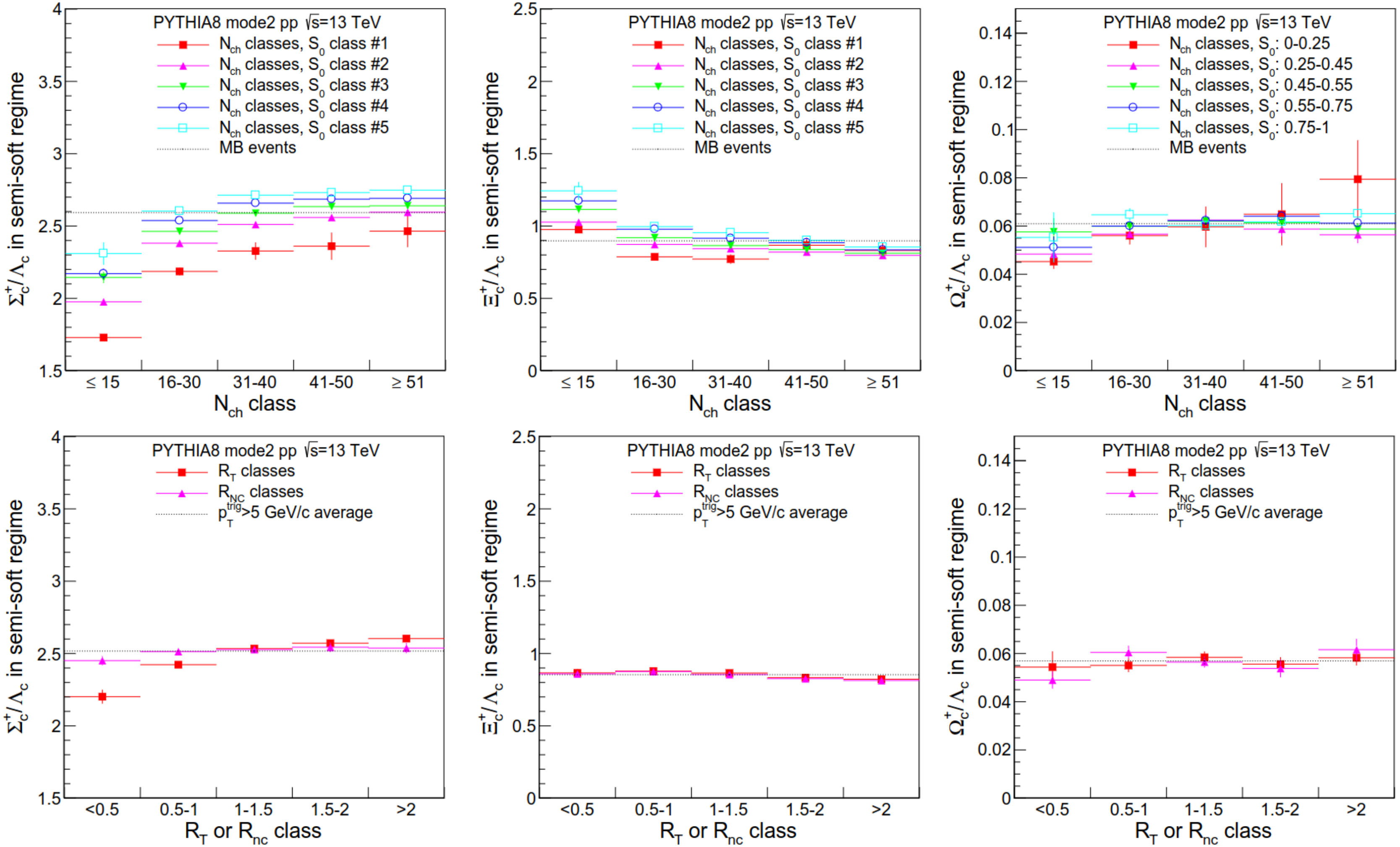
- Similar trend for all baryon/meson ratios.
- For the Λ_c there is a significant feed-down from Ξ_c.

Charmed baryon-to-baryon ratios vs. N_{MPI}



- 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**

Charmed baryon-to-baryon (summary plots)



Ξ_c and Ω_c: Strangeness in charmed baryons

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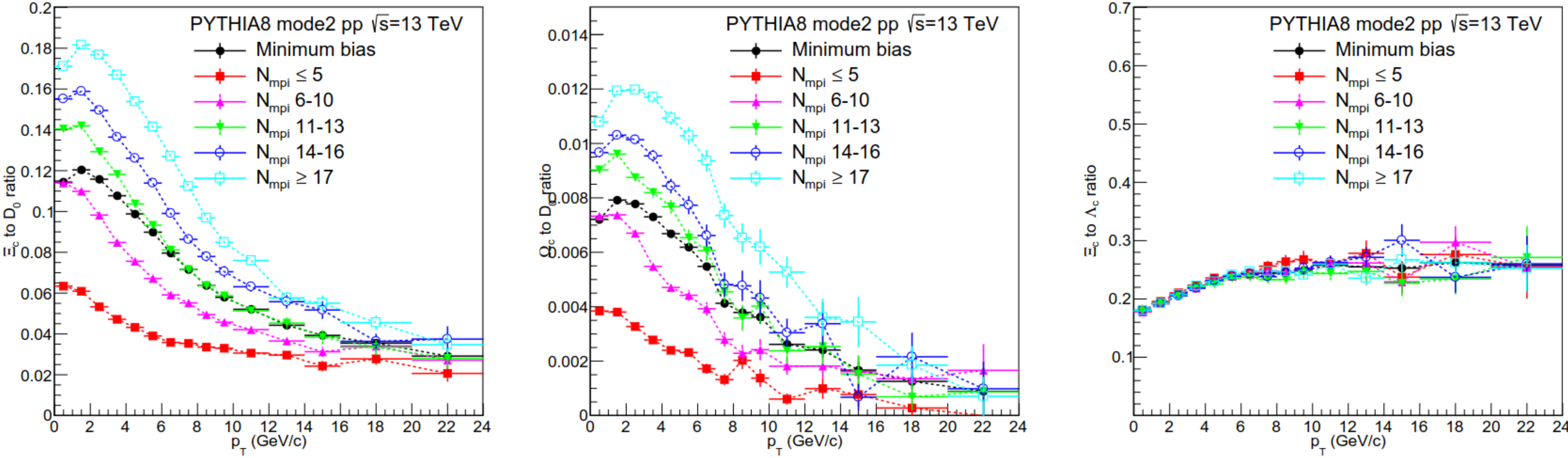
Ξ_c(qsc) / D^0 Ω_c^0(ssc) / D^0 Ξ_c(qsc) / Λ_c(qqc)



- There is a **low p_T enhancement** connected to the **charm content**
- There is a **high p_T enhancement** connected to the **strange content** (above that of the charm enhancement)

Ξ_c and Ω_c: Strangeness in charmed baryons

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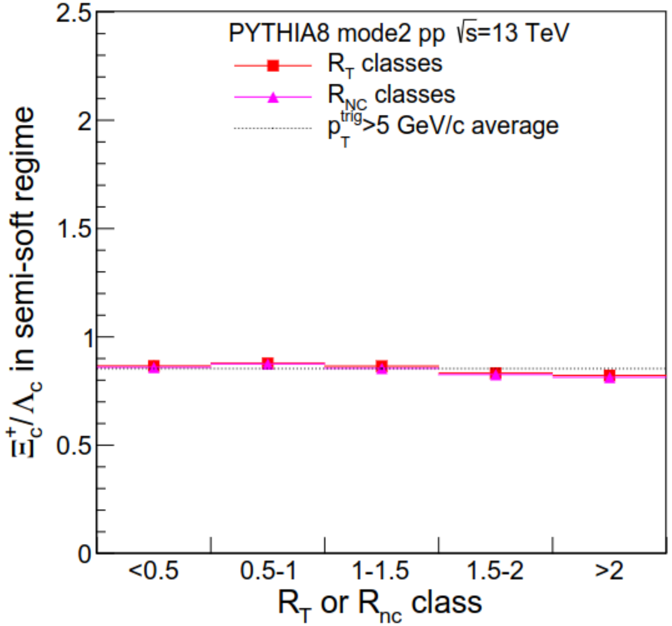
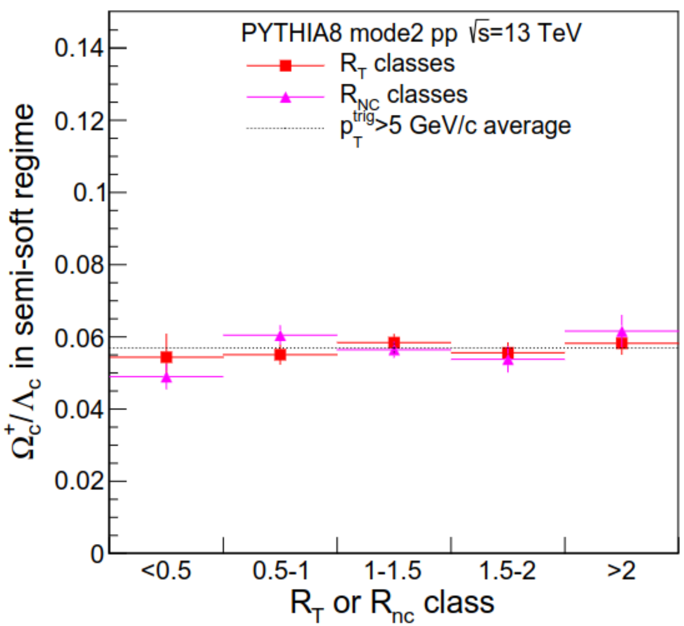
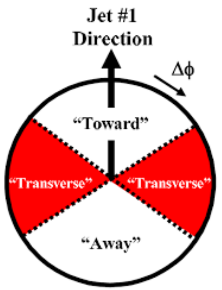
Ξ_c(qsc) / Λ_C (qqc)



Ω_c^0(qsc) / Λ_C (qqc)





- Strangeness content does not induce further sensitivity to the event-property descriptors
- **Charm baryon enhancement is driven by a different mechanism than strange baryon enhancement**

Σ_c vs. Λ_c : Isospin of charmed baryons

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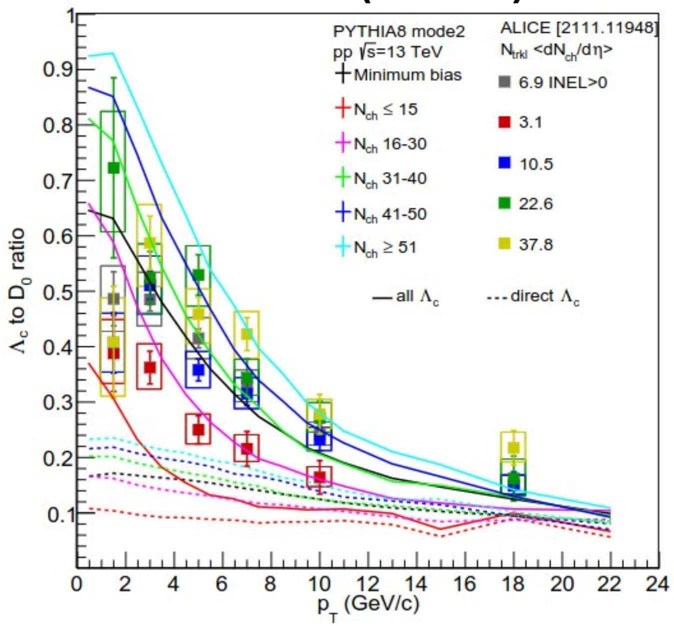
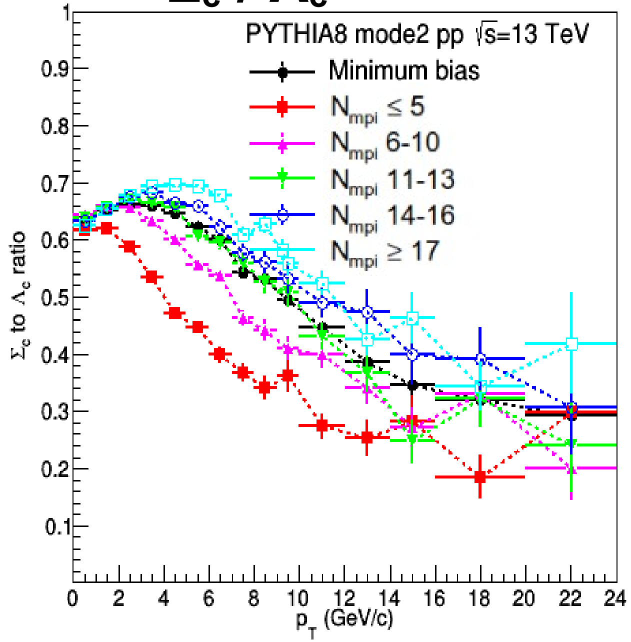
Λ_c/D^0 and $(\Sigma_c \to \Lambda_c)/D^0$



Σ_c / Λ_c



Σ_c (qqc, I=0) vs. Λ_c (qqc, I=1)

- **Different trends in direct Λ_c and $\Sigma_c \to \Lambda_c$**
- Trends depend on MPI in the model class

Σ_c vs. Λ_c : Isospin of charmed baryons

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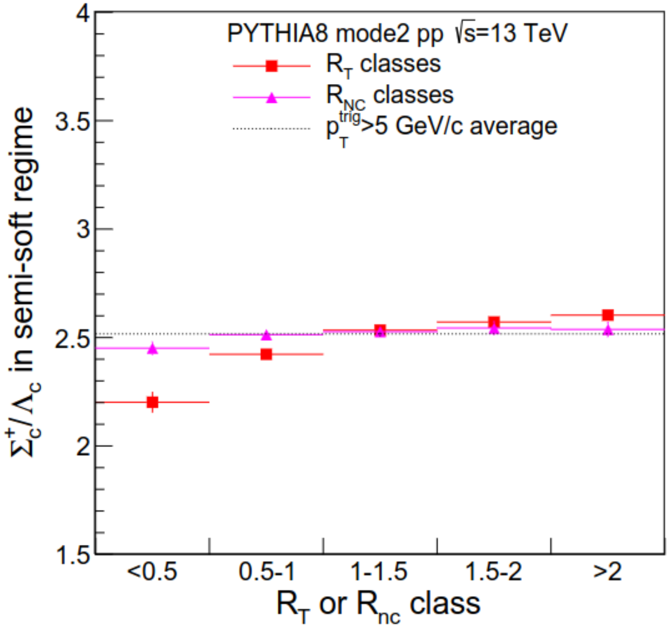
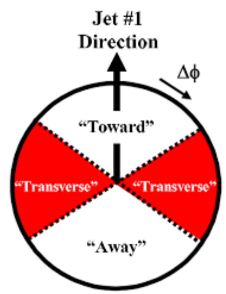
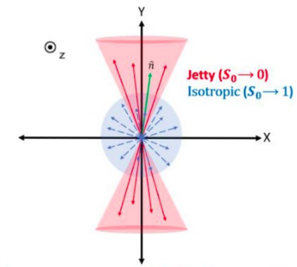
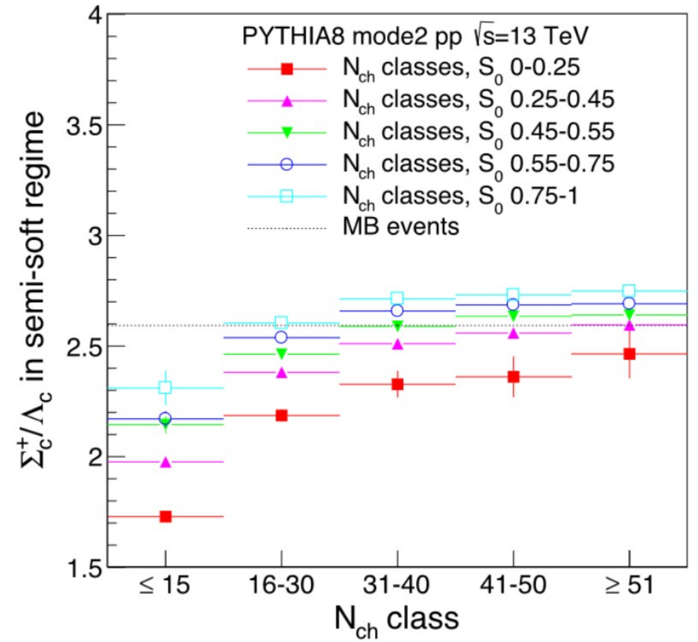
Σ_c / Λ_c







Σ_c / Λ_c



- Σ_c (qqc, I=0) vs. Λ_c (qqc, I=1)

- **Charmed baryon ratios are sensitive event-shape dependent observables**