Event-shape-dependent heavy flavor analysis in small systems

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...and the colleagues from ALICE

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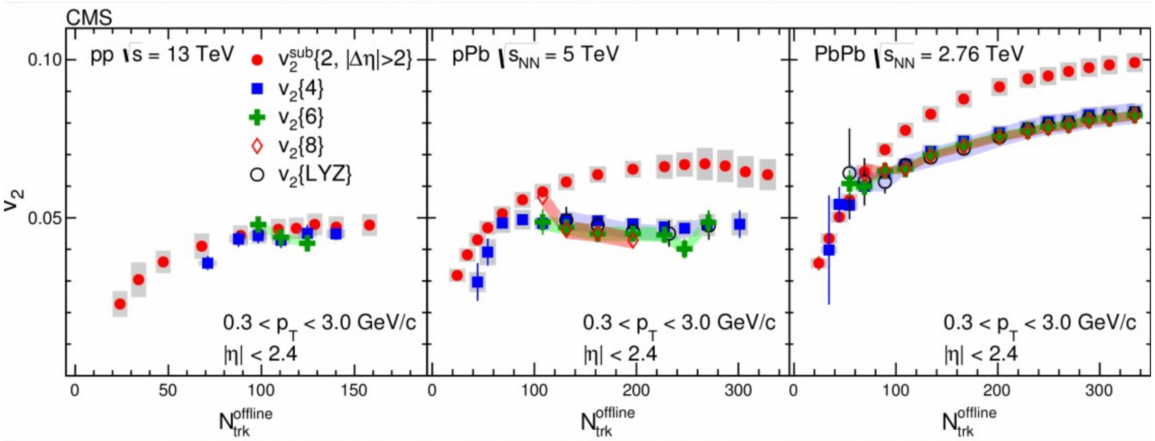
Motivation: collectivity in small systems

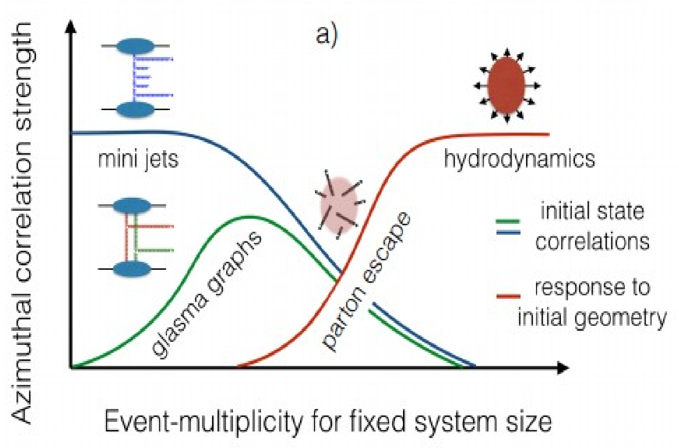
- In heavy-ion collisions a strongly coupled quark–gluon plasma forms and behaves as a near-perfect fluid
- At the LHC, collective-like patterns (long-range ridge, finite v_n) also appear in pp and p-Pb at high final-state multiplicity
- Open question: **does a QGP droplet form in small systems**, or do these patterns have another origin?

CMS, Phys. Lett. B 765 (2017) 193



Hot QGP or vacuum-QCD?

- Collective behavior **does not necessarily require a thermalized QGP**
- Semi-soft vacuum-QCD processes at the soft–hard boundary can generate the same signatures:
  - **Multi-parton interactions** (MPI)
    eg. **Schlichting, arXiv:1601.01177**
  - **Color-reconnection**
    (part of some MPI models)
    eg. **Ortiz-Bencédi-Bello, J.Phys.G 44 (2017)**
  - **Minijets** (semihard partons produced by incoming partons or bremsstrahlung)
    eg. **Eskola, Nucl.Part.Phys. 22, 4, 185 (1998)**



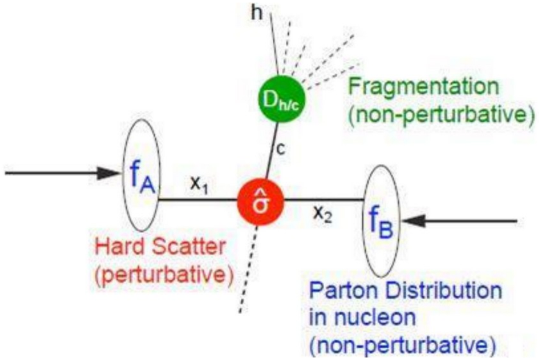
- Strategy: use **event-shape-differential heavy-flavor observables** to expose the underlying mechanism rather than averaging over it

Heavy flavor: production and fragmentation

- Heavy-flavor cross-section in the **factorization** picture

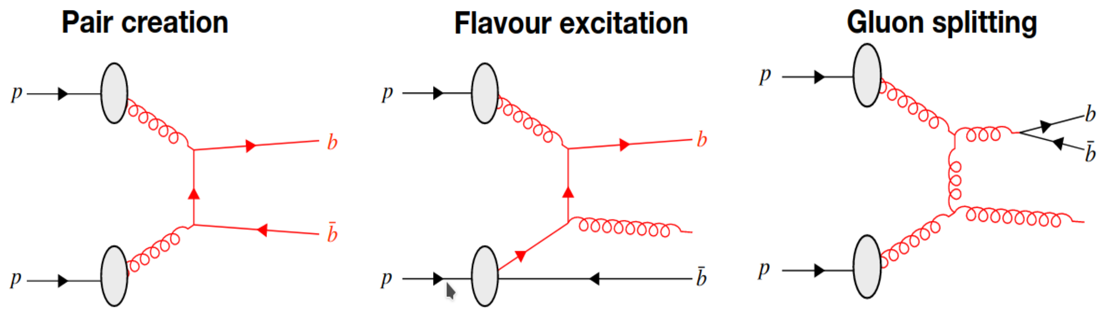
$$\sigma_{hh\to H} = f_a(x_1,Q^2)\otimes f_b(x_2,Q^2)\otimes\sigma_{ab\to q\bar{q}}\otimes D_{q\to H}(z_q,Q^2)$$

  - Fragmentation functions are traditionally treated as universal (often fixed from e+e-)



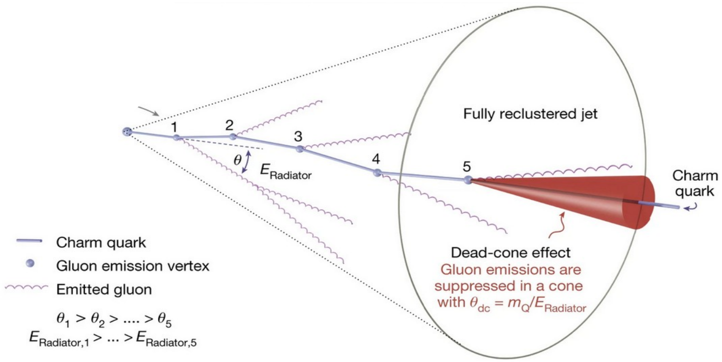
- Heavy quarks (m_c, $m_b \gg \Lambda_{QCD}$)
  → produced early, perturbatively accessible

  - **LO**: Flavor creation (FLC)
  - **NLO**: Gluon splitting (GSP), flavor excitation (FEX)



Why heavy flavor is a good probe

- Color charge and dead cone effects:
  → Harder fragmentation than light flavor
- Early production:
  - Heavy quarks tag the early, hard part of the event, but also take part in semi-hard processes that are responsible for the underlying event
- This motivates systematic, event-shape-differential studies of correlations and baryon ratios

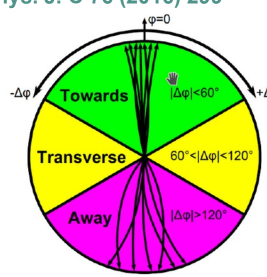


ALICE, Nature 605 (2022) 440

Categorizing events by activity

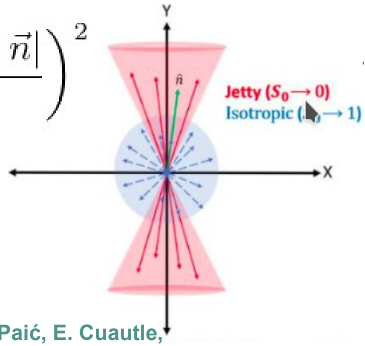
Classifier	What it captures	Trigger	Acceptance
N_{ch}	Central multiplicity	no	$\|\eta\|<1$
N_{fw}	Forward multiplicity	no	$2<\|\eta\|<5$
R_T	Underlying event activity	yes (p_T>5 GeV/c)	Transverse region
R_{NC}	Near-side jet cone activity	yes	Cone R<0.5
S_0	Transverse spherocity (jetty vs. isotropic)	no	mid-rapidity
ρ	Flattenicity (hedgehog vs. jetty, full η)	no	$\|\eta\|<4$

T. Martin, P. Skands, S. Farrington, Eur. Phys. J. C 76 (2016) 299



$$R_T = \frac{N_{trans}}{\langle N_{trans}\rangle}$$

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

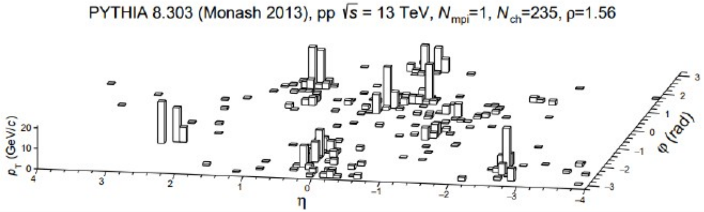


A. Ortiz, G. Paić, E. Cuautle, Nucl. Phys. A 941 (2015) 78

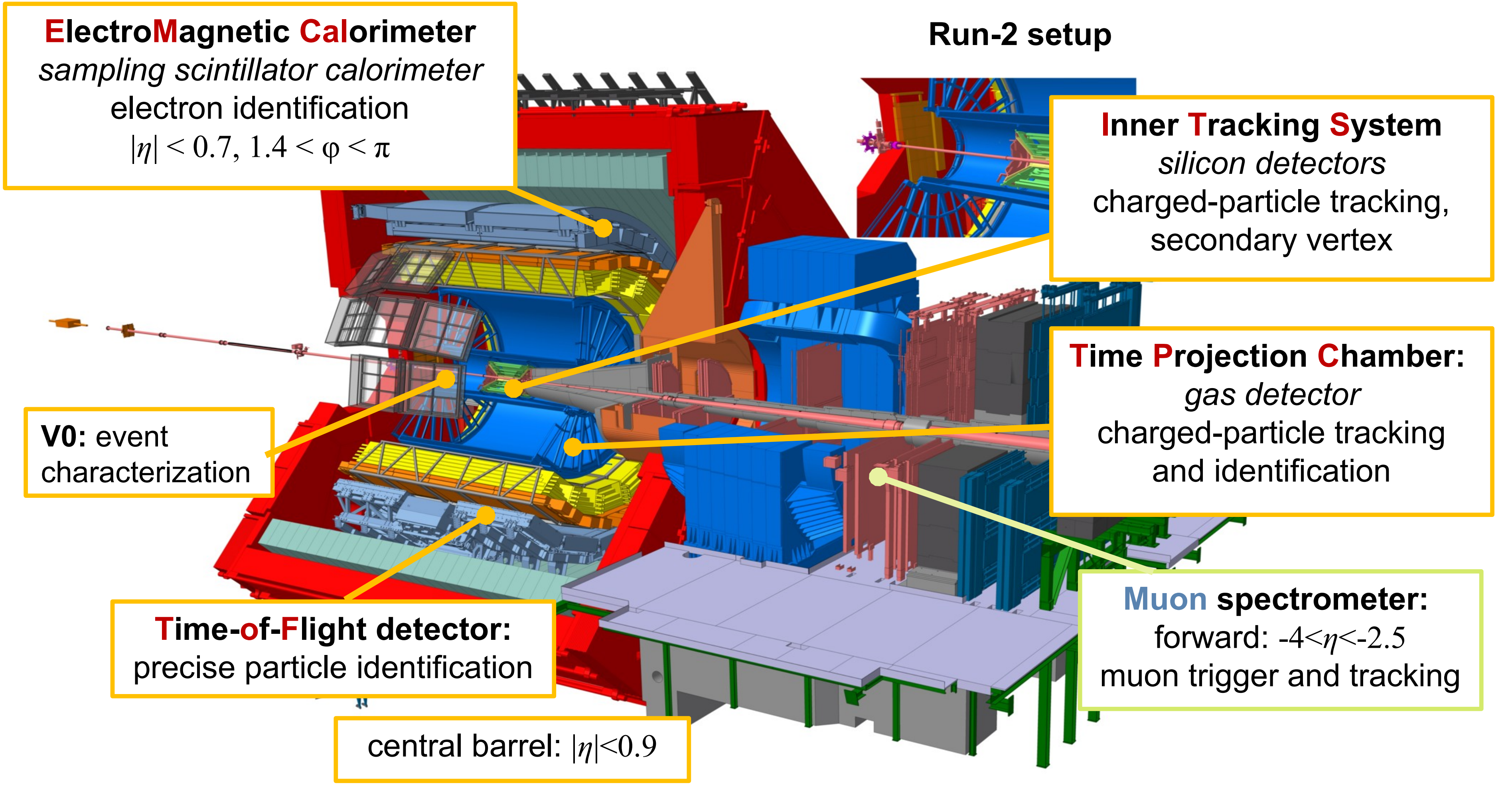
$$\rho = \frac{\sigma_{p_T^{cell}}}{\langle p_T^{cell}\rangle}$$

A. Ortiz, G. Paić, Rev. Mex. Fis. Suppl. 3 (2022), 040911

PYTHIA 8.303 (Monash 2013), pp $\sqrt{s}$ = 13 TeV, N_{mpi}=1, N_{ch}=235, ρ=1.56



Results from the ALICE experiment



Heavy-flavor production vs. multiplicity

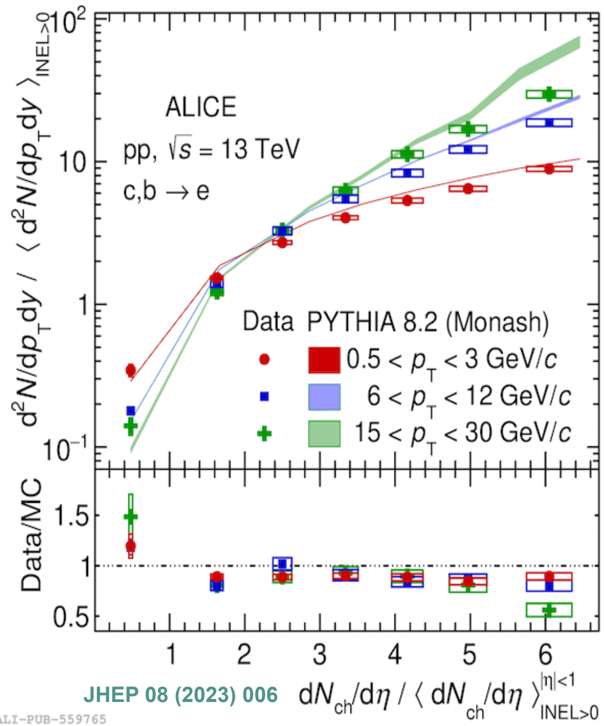
Steeper-than-linear dependence of self-normalized yields on multiplicity at $\sqrt{s}$ = 13 TeV

- Strong constraints for models
- Sensitive to autocorrelation: good simultaneous description of jets and UE needed

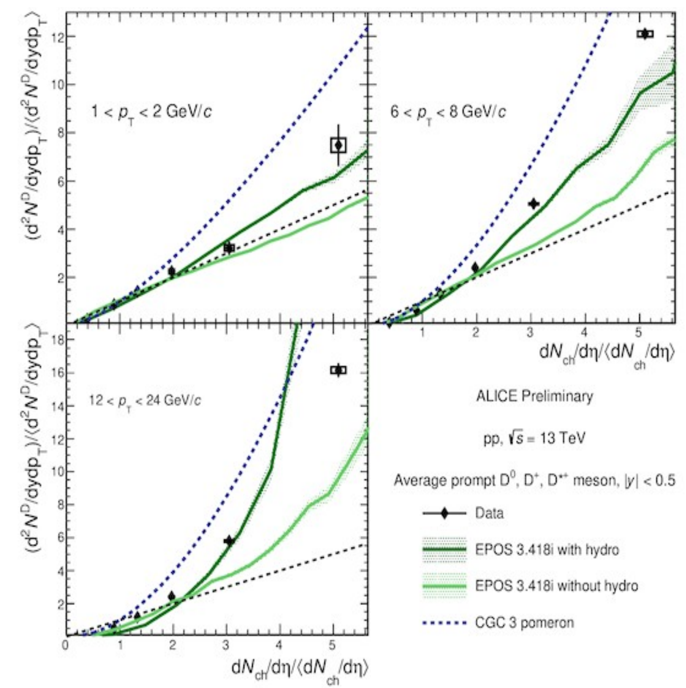
Performance of models:

- **PYTHIA 8 with MPI** (pQCD-based with PS and Lund fragmentation) adequately describes data
- **EPOS** parton model with hydrodynamic evolution captures trends

PYTHIA: Comput.Phys.Commun. 191 (2015) 159
EPOS: Nucl.Phys.B Proc.Suppl. 175 (2008) 81
CGC 3 pomeron: PRD 101 (2020) 094020

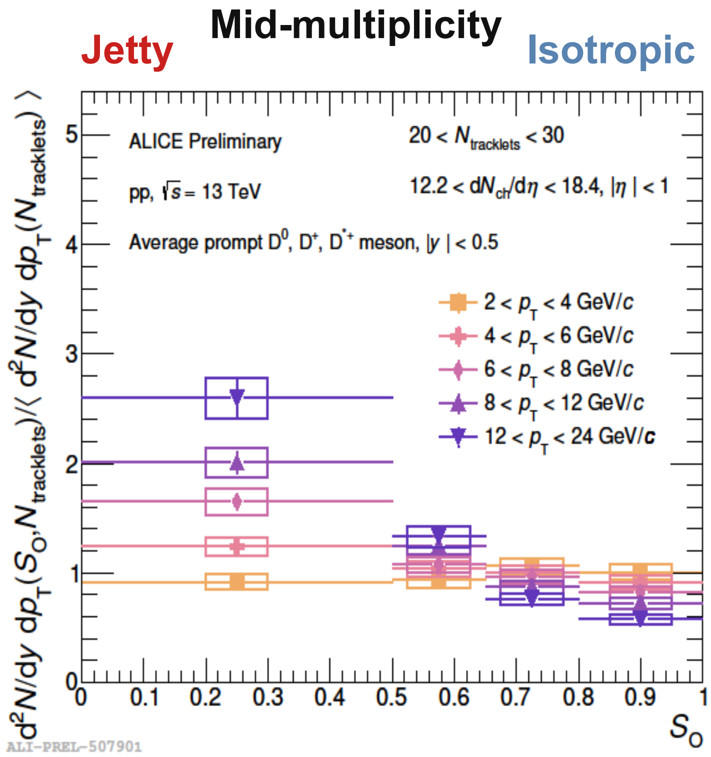


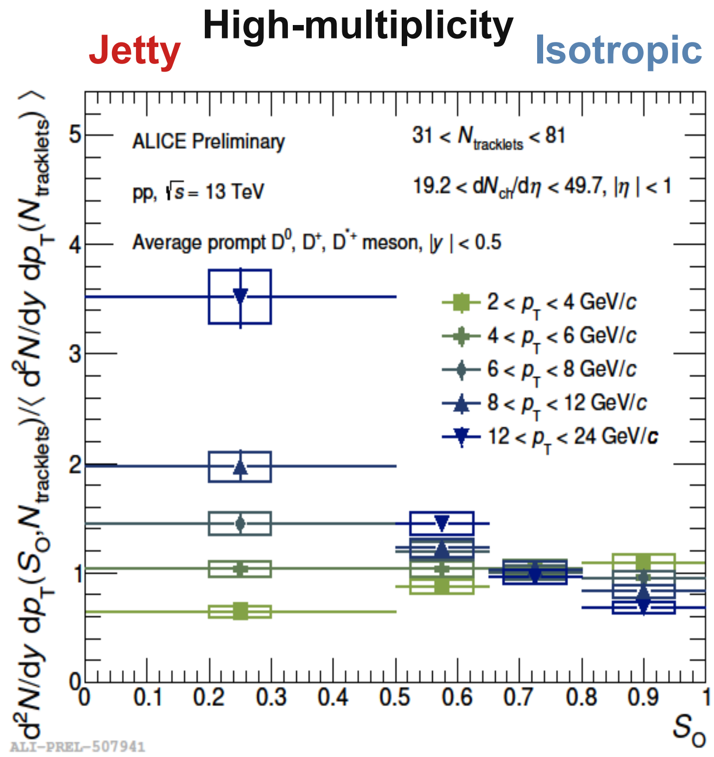
HF electrons (c + b)



D mesons (c)

D-meson self-normalized yields vs. spherocity

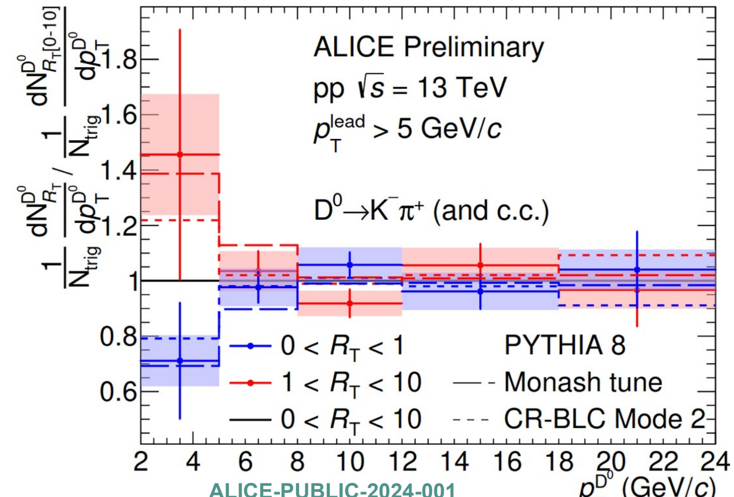


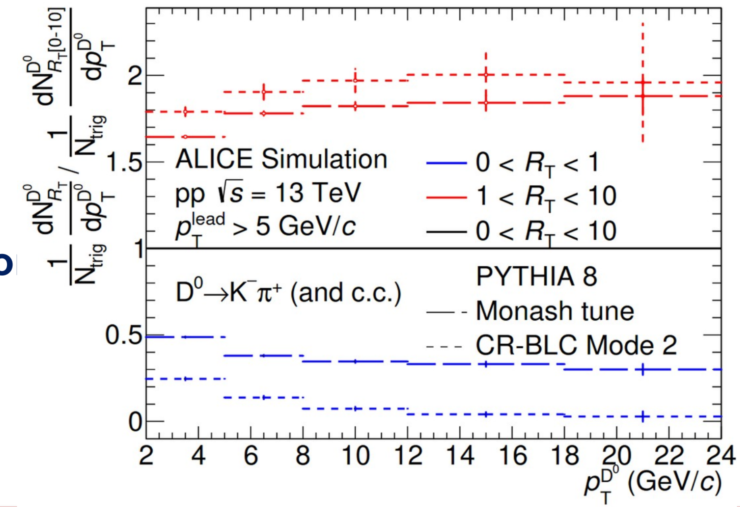


- Hint of an enhanced D-meson production toward higher multiplicity in jetty events
- Effect of hard scatterings leading to average increase in charged-particle multiplicity

D-meson production vs. R_T

- Statistics allowed measurement only in **Toward** region:
  - High p_T: D^0-meson production is independent of transverse activity – these hadrons are produced in connection to the leading process
  - Low p_T: a hint of transverse-activity dependence
  - PYTHIA 8 with Monash and CR-BLC mode 2 tunes describes the data within uncertainties
- **Transverse** region:
  - PYTHIA 8 with Monash and CR-BLC Mode 2 tunes suggests dependence on transverse activity at any p_T
  - Heavy-flavor production is strongly influenced by UE
- **Run 3 luminosity will make it feasible to measure D-meson production in the transverse region**

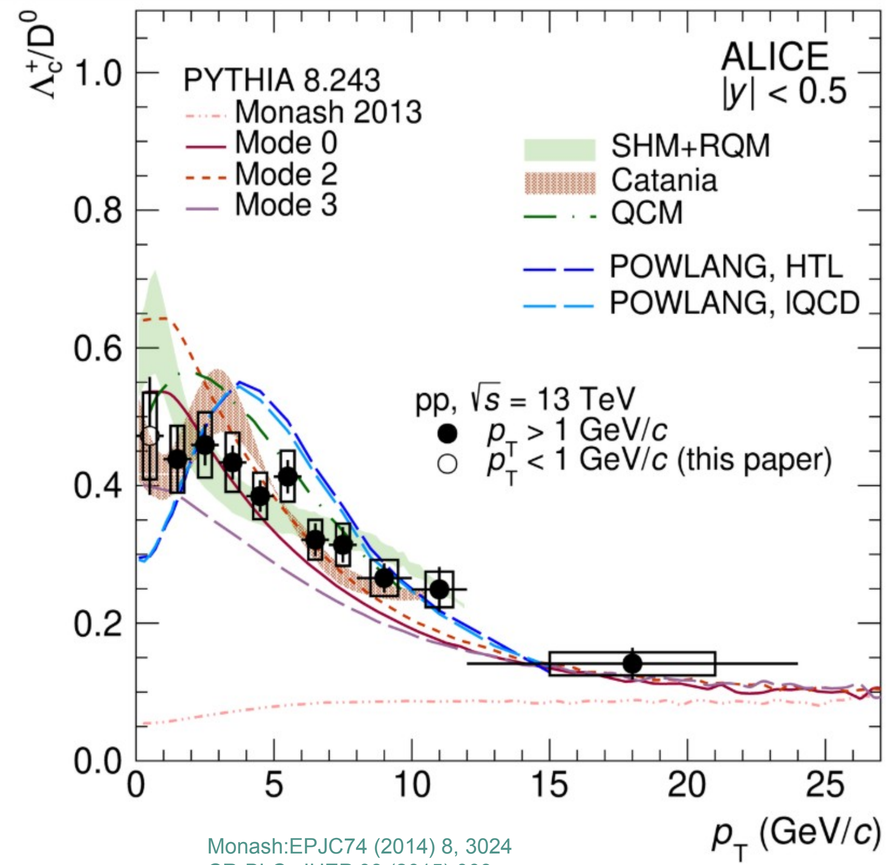




Monash:EPJC74 (2014) 8, 3024
CR-BLC: JHEP 08 (2015) 003

Charmed-baryon enhancement

- **charm baryon vs. meson**
- Significant enhancement in **prompt Λ_c^+** to D^0 ratio at low to intermediate p_T vs. e^+e^- and e^-p collisions
  - PYTHIA 8 Monash tune (based on e^+e^- and e^-p fragmentation) fails to describe the trends
- Several proposed models reproduce the behavior
  - Color-reconnection with color string junctions (CR-BLC modes 0, 2, 3)
  - Statistical hadronization model with extra charm-baryon resonances (SHM+RQM)
  - Quark coalescence models (Catania and QCM)
  - POWLANG (assuming QGP-like medium)

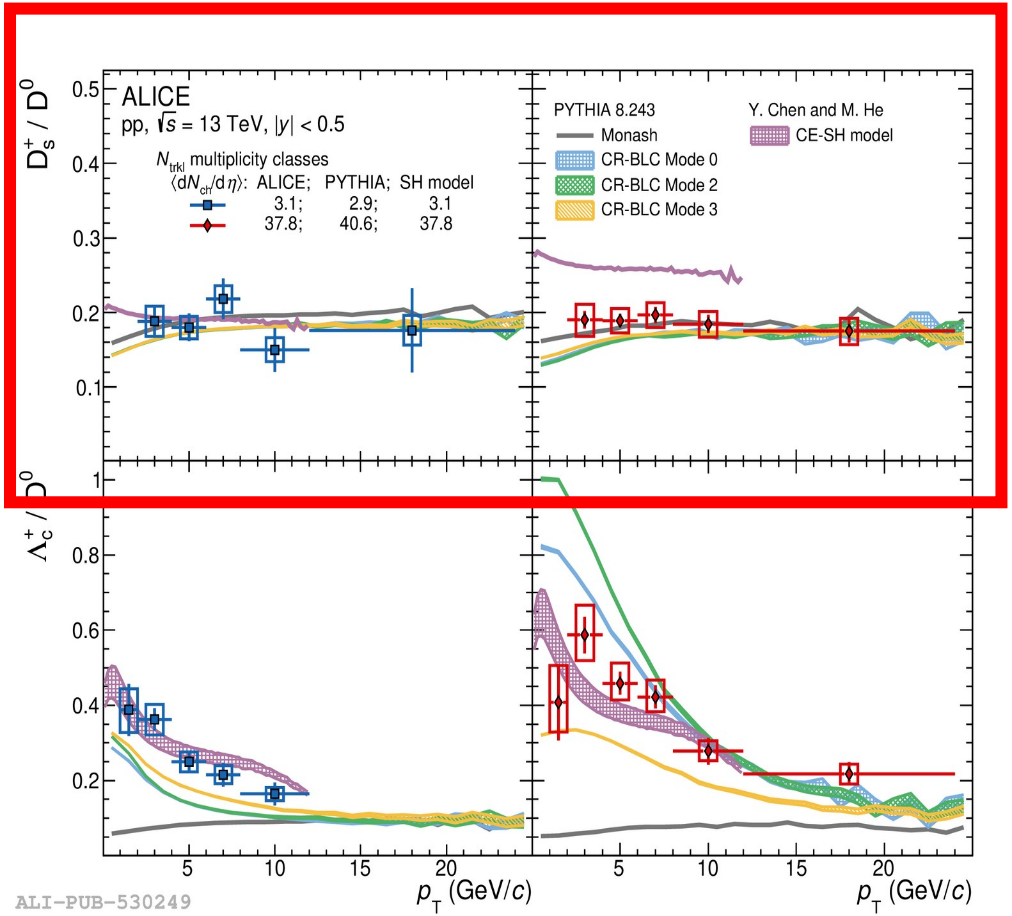


Monash:EPJC74 (2014) 8, 3024
CR-BLC: JHEP 08 (2015) 003
SHM+RQM: PLB 795 (2019) 117
Catania: EPJC 78 no. 4, (2018) 348
POWLANG: JHEP 03 (2016) 123
EPOS4: PRC 108 (2023) 064903

Charmed hadron yields vs. multiplicity

Charmed strange-to-nonstrange mesons

- Independent of p_T and multiplicity
- Described well by PYTHIA tunes
- CE-SH (canonical ensemble + statistical hadronization) model overestimates data at high multiplicities



Monash:EPJC74 (2014) 8, 3024
CR-BLC: JHEP 08 (2015) 003
CE-SH: PLB 815 (2021) 136144

PLB 829 (2022) 137065

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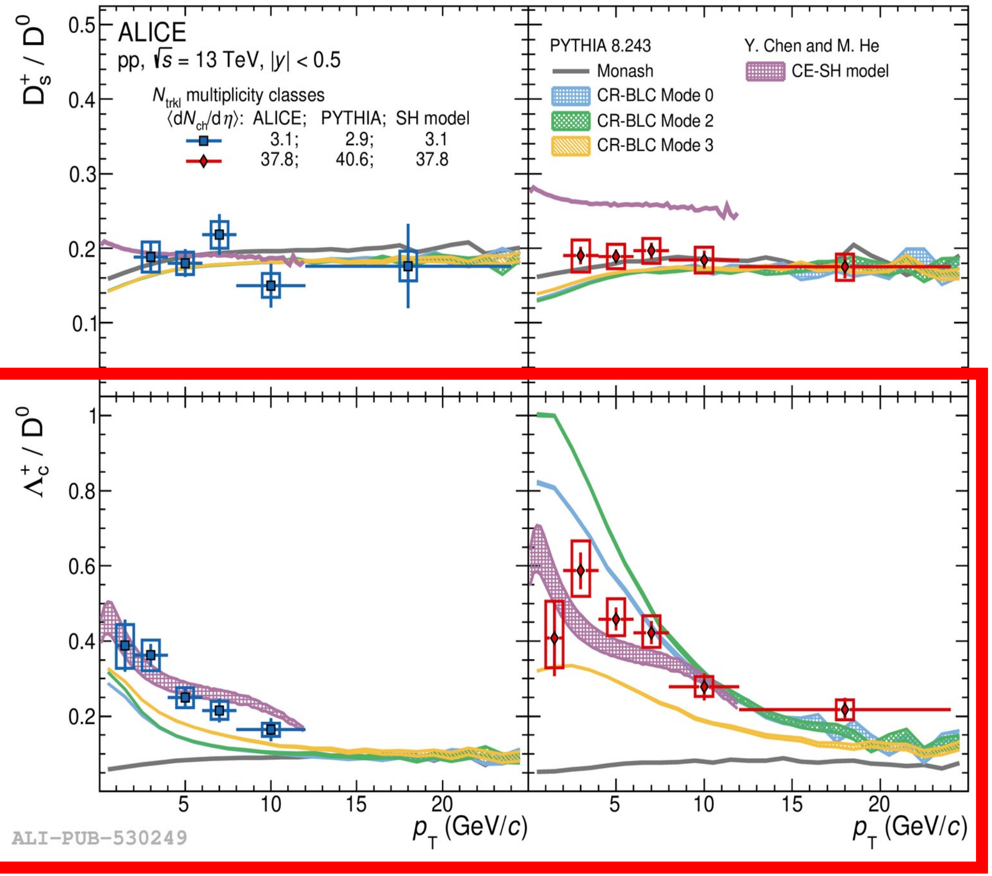
Charmed baryon-to-meson ratio

- Significant dependence on multiplicity at low p_T (5.3σ difference)
- PYTHIA 8 with CR-BLC qualitatively describes the multiplicity dependence
- CE-SH model also describes the trends



Monash:EPJC74 (2014) 8, 3024
CR-BLC: JHEP 08 (2015) 003
CE-SH: PLB 815 (2021) 136144

PLB 829 (2022) 137065

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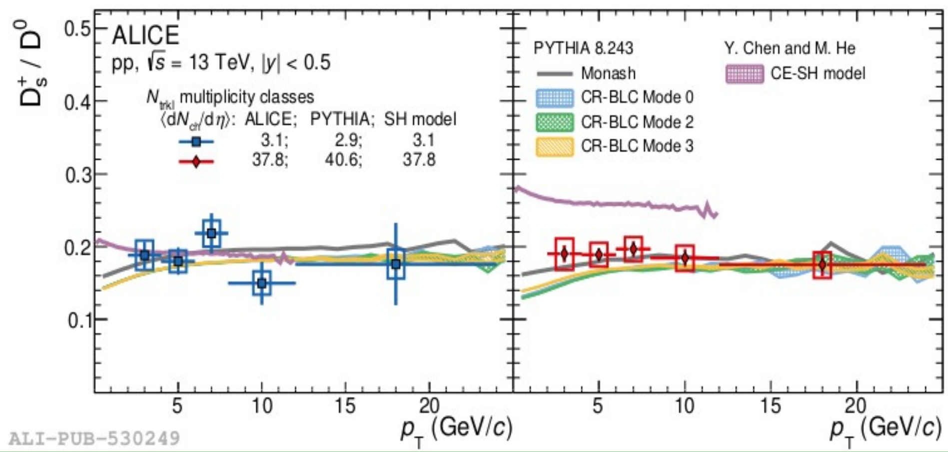
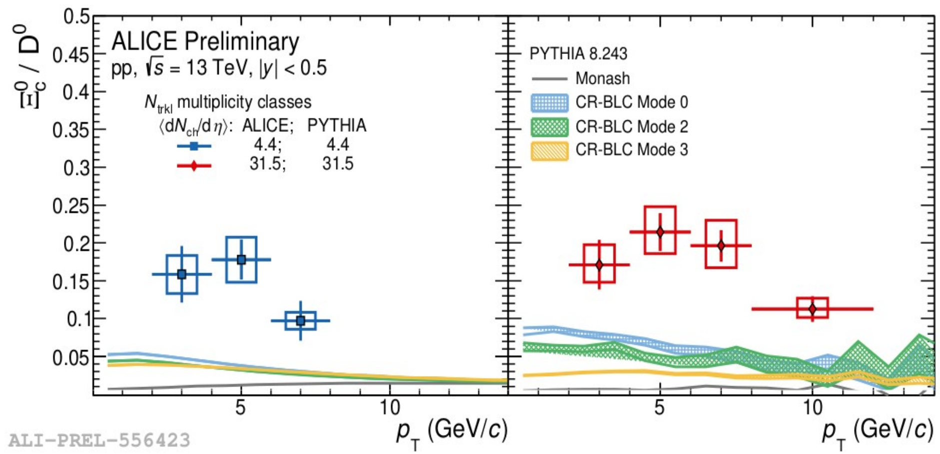


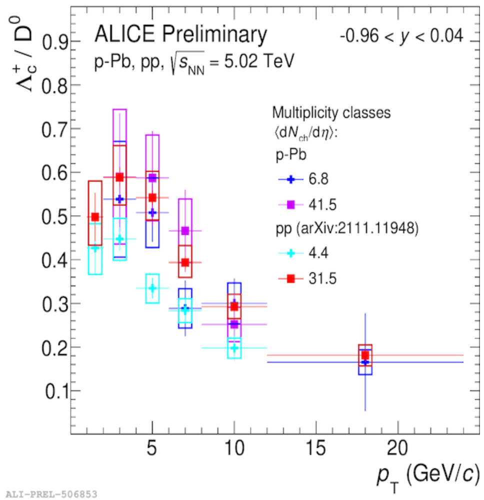
Charmed-strange baryon-to-meson ratio

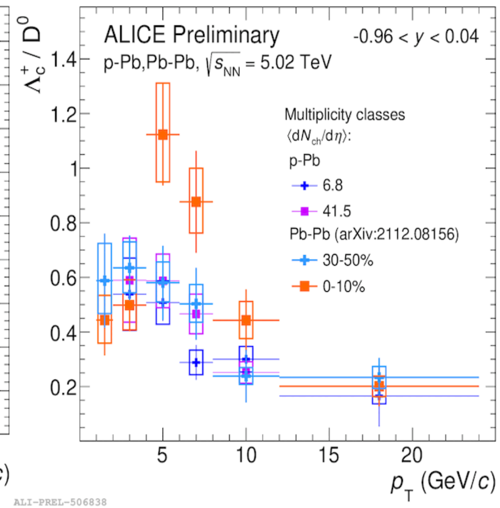
- Hint of p_T-dependence
- no multiplicity dependence within uncertainties
- Significantly underestimated by PYTHIA CR-BLC at all multiplicities



Monash:EPJC74 (2014) 8, 3024
CR-BLC: JHEP 08 (2015) 003
CE-SH: PLB 815 (2021) 136144

Charm baryon-meson ratios in **HI collisions**

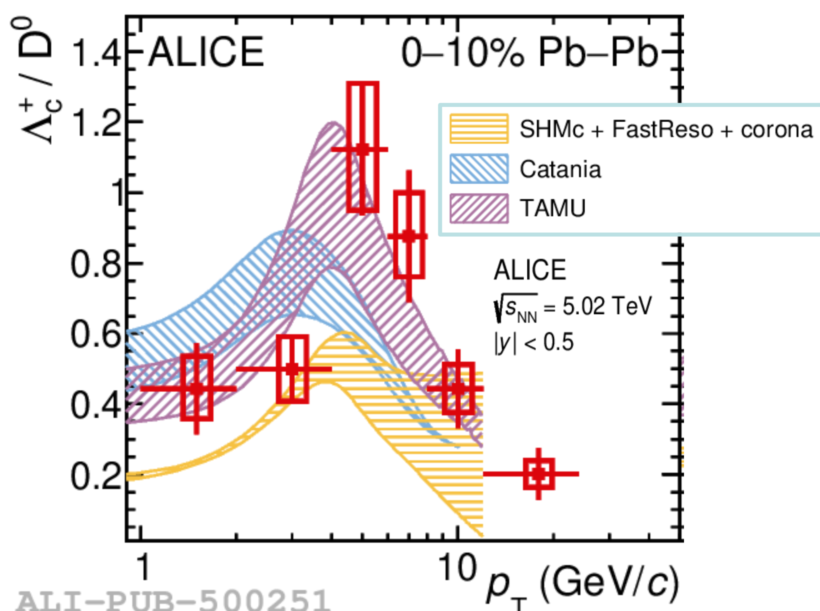




Λ_c^+/D^0 ratio in Pb-Pb collisions vs. models

- Data qualitatively described by TAMU and Catania, SHMc slightly underestimates it
- **Interplay of radial flow and recombination**
- Different p_T redistribution for mesons and baryons

SHMc: JHEP 07 (2021) 03
Catania: EPJC 78 no. 4, (2018) 348
TAMU: PRL 110 (2013) 15



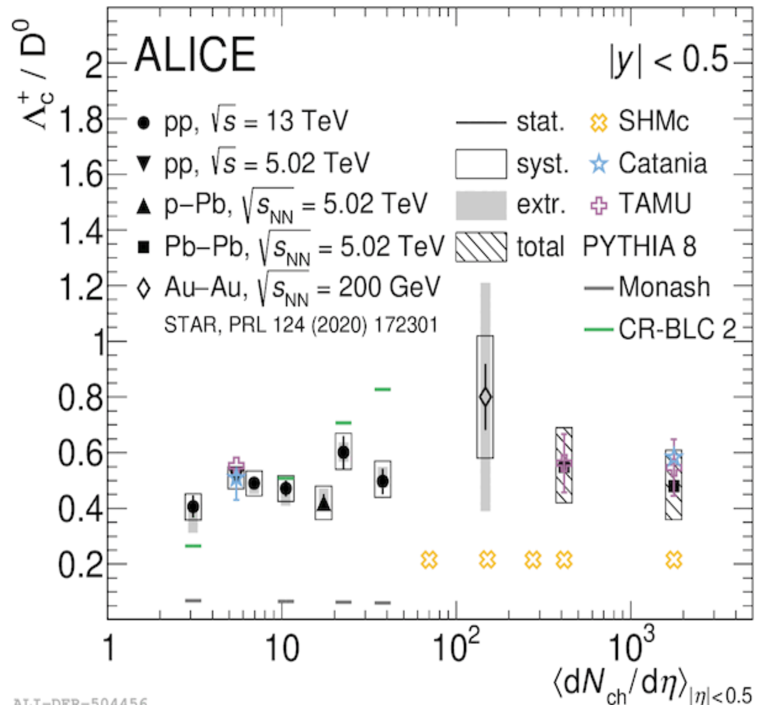
Multiplicity-dependence of the Λ_c^+/D^0 ratio

- Similar enhancement pattern to that in light baryon-to-meson ratios
- High-multiplicity pp, low- and high-mult p–Pb, and semicentral Pb–Pb are similar
- Strong separation for low-multiplicity pp: Threshold effect?
- **Radial-flow-like pattern in central Pb-Pb**

Charm hadron ratios vs. multiplicity

p_T-integrated Λ_c^+/D^0 ratios:

- Dependence on multiplicity, from low-p_T pp up to central Pb-Pb collisions
- Despite strong N_{ch}-dependent trends at mid-p_T, **no evidence of p_T-integrated N_{ch}-dependence**
- Significantly higher values than in e^+e^- and ep
- Collision-energy dependence is weak: STAR 200 GeV and ALICE 5.02 TeV consistent
- Model performance:
  - Increase predicted by PYTHIA 8 CR-BLC is not supported
  - SHMc (Pb–Pb): flat trend, but underestimates data
  - TAMU, Catania: similar for pp and Pb–Pb



PLB 829 (2022) 137065

SHMc: JHEP 07 (2021) 03
Catania: EPJC 78 no. 4, (2018) 348
TAMU: PRL 110 (2013) 15
Monash:EPJC74 (2014) 8, 3024
CR-BLC: JHEP 08 (2015) 003

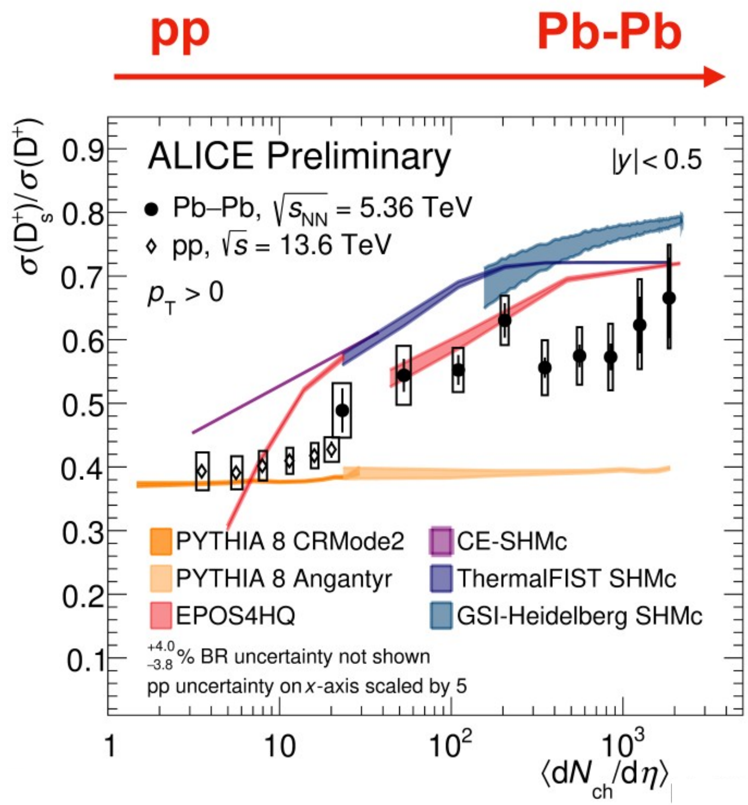
D_s^+/D^+ ratio as function of multiplicity

Slide based on: Alessandro Grelli, Beauty 2026

- **No evolution with multiplicity in pp collisions**
  - Ratio consistent with **LEP average**: 0.408 ± 0.040
  - Support hadronisation via fragmentation only in pp

- Total production of D_s^+ **increases with multiplicity in Pb-Pb** collisions
  → picture consistent with **coalescence** in a deconfined strangeness-enhanced medium.

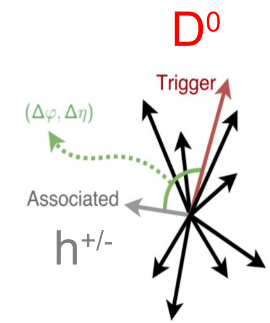
- Models fail to describe the D_s^+/D^+ evolution across collision systems.
  - **Measurement in O-O needed** to complement the intermediate multiplicity region



Catania: V. Minissale et al., Phys. Lett. B 821 (2021) 136622
CE-SHMc: Y. Chen et al. PLB 815 (2021) 136144
GSI SHMc: A. Andronic et al. JHEP 07 (2021) 035
ThermalFIST SHMc: V. Vovchenko, PRC 100 (2019) 054906
EPOS4HQ, Zhao et al., PRC 110 024909
PYTHIA 8: T. Sjöstrand et al., Comput. Phys. Commun. 191 (2015), 159

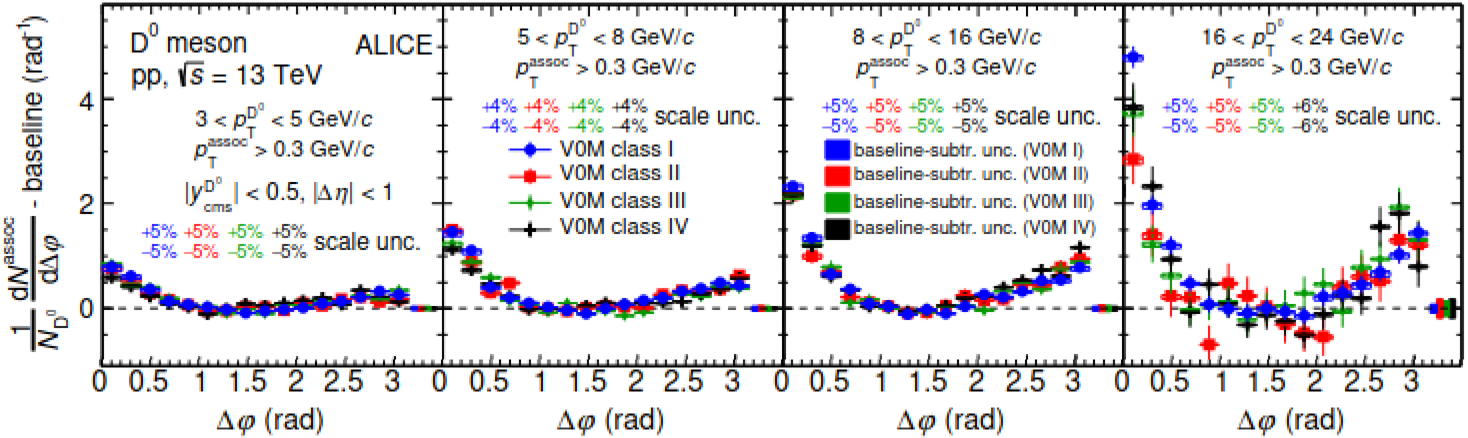
Correlations: production & fragmentation

- **Azimuthal correlation:** jet structure without reconstruction + more
  - Can also be used at low momenta
  - **Near-side** azimuthal correlation: heavy-quark fragmentation
  - **Away-side** peak: recoil jet
  - Further influences: **underlying event, initial- and final-state radiations**



- **D-h correlations:**

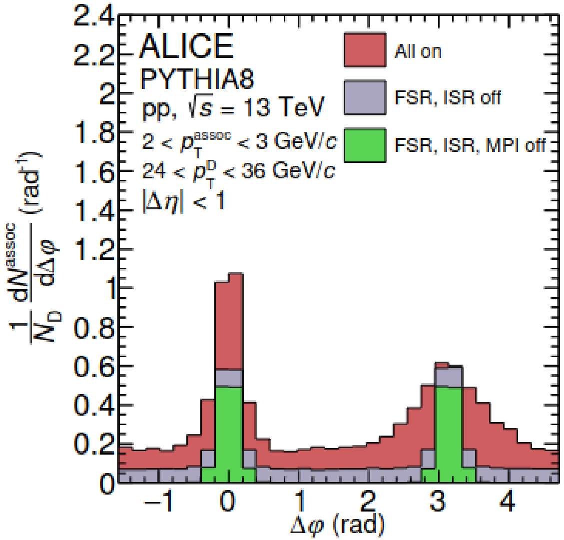
ALICE, EPJ C 82 (2022) 335



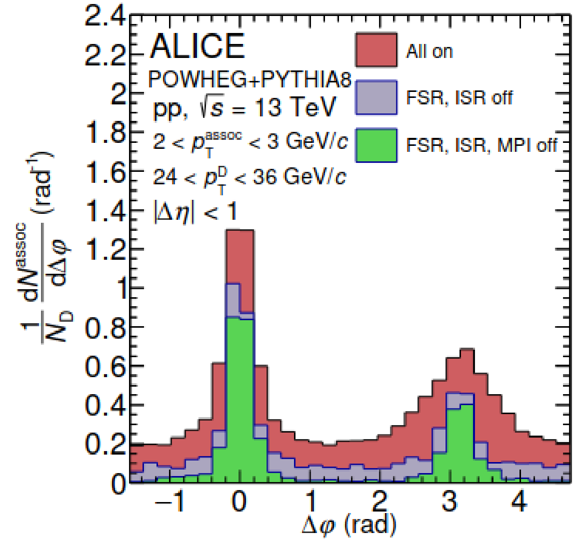
- No significant dependence on the activity of the final state (V0 multiplicy)

D-h correlations vs. partonic processes

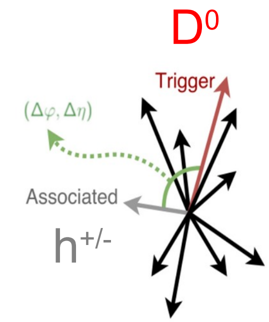
ALICE, EPJ C 82 (2022) 335



PYTHIA 8
LO matrix element + ISR + FSR



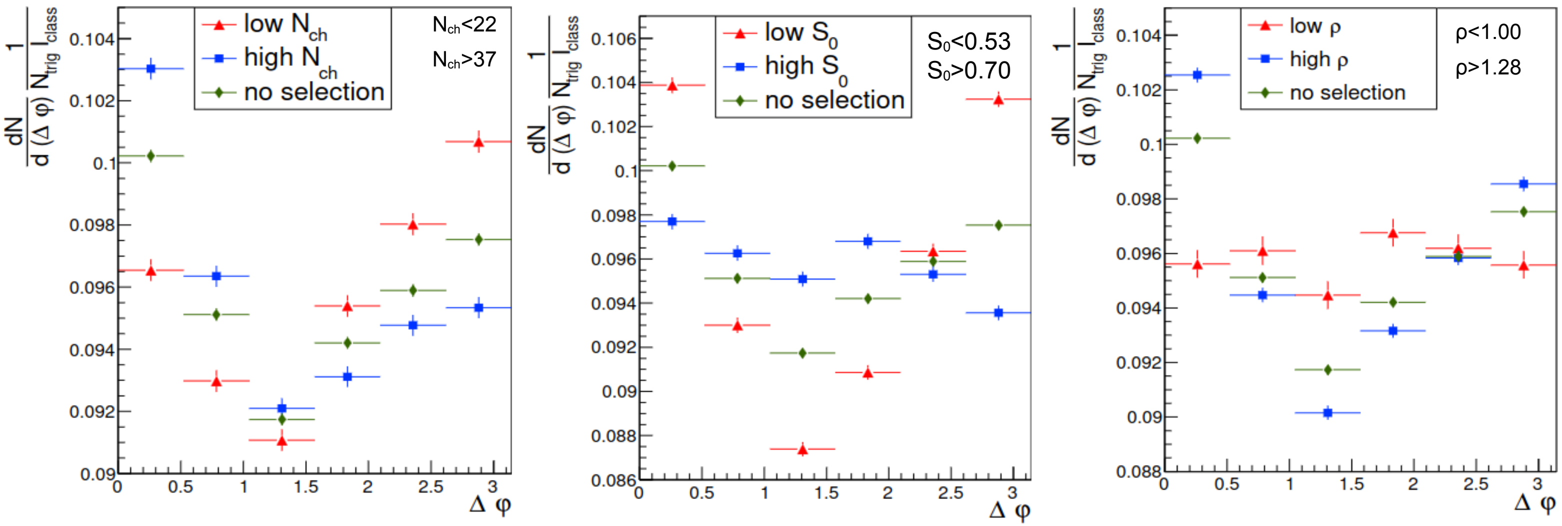
POWHEG+PYTHIA8
NLO matrix element+ ISR + FSR

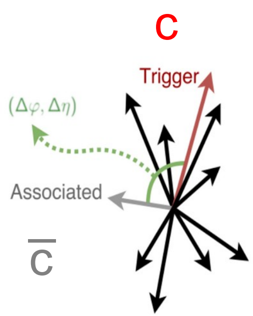


- Separate parton level processes with simulations (ISR, FSR, MPI)
- **Peaks:** more contribution from **initial hard process** in NLO, more **FSR + ISR** in LO
- **Underlying event**: Important role of **multiparton-interactions**
- **D-h correlations do not restrict strongly the partonic processes**

c-$\bar{c}$ correlations vs. N_{ch}, spherocity, flattenicity

Universe 9 (2023) 7, 308



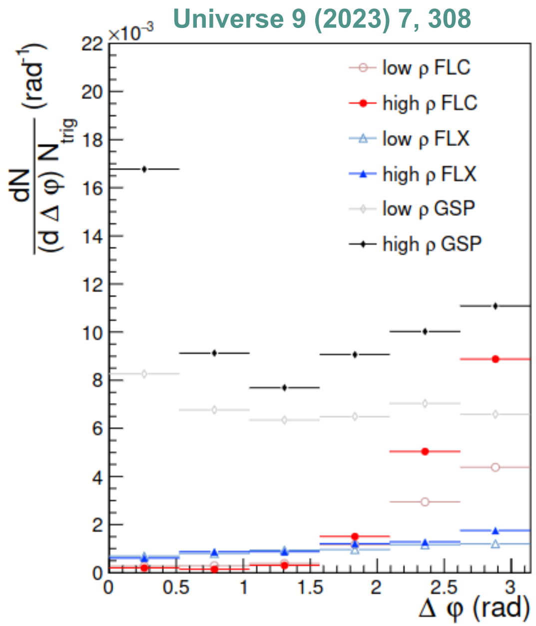


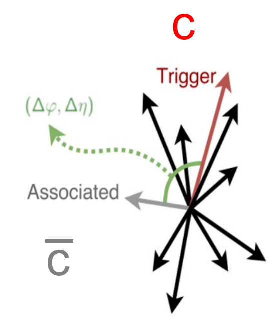
- **Multiplicity**: low-multiplicity events give a sharper away-side peak (simpler back-to-back topology); high-multiplicity events wash it out
- **Spherocity:** low-S_0 (jetty) events → stronger near- and away-side correlation.
  high-S_0 (isotropic) events → more random
- **Flattenicity** highlights the correlation structure: high-ρ events give both a sharper near- and away-side peak
- Among N_{ch}, S_0, ρ, **flattenicity is the most selective** for correlation structure.

Origin of correlations: QCD creation processes

Low-ρ: ρ<1.00
High-ρ: ρ>1.28

p_T > 4 GeV/c



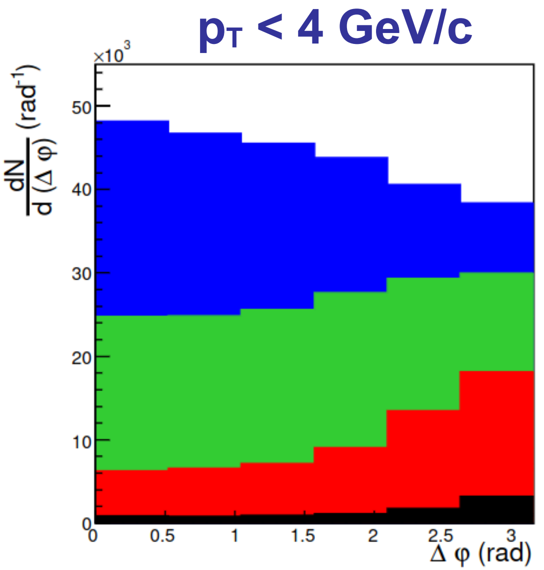


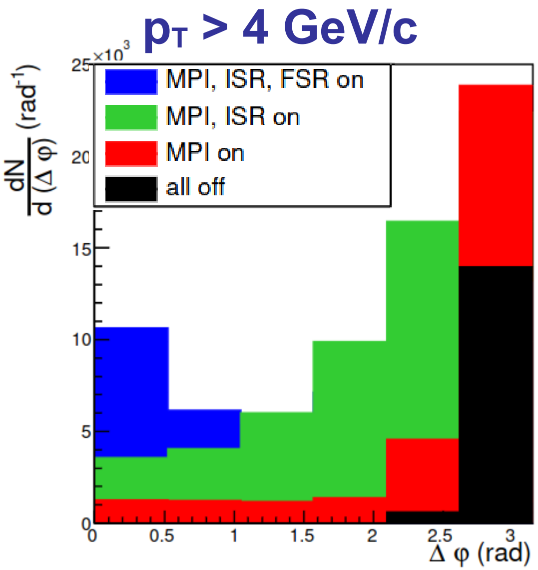
- Trace each trigger c back to its first c ancestor → tag FLC / FLX / GSP
  - GSP dominates at the near-side peak
  - FLC produces a sharp away-side peak
  - FLX adds less visibly to the away side
- **Flattenicity cut geometrically separates GSP** (near-side, high-ρ) from the mostly random away-side (low-ρ)

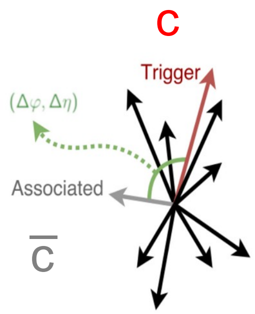
Origin of correlations: parton-level processes

High-ρ
(ρ>1.28)

Universe 9 (2023) 7, 308





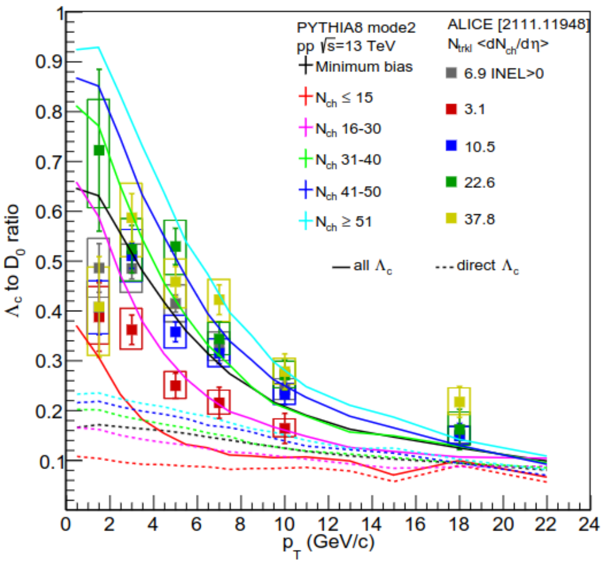


- Decompose by PYTHIA parton-level stage (ISR, FSR, MPI), split by momentum
  - Away side: initial hard process + ISR + MPI
  - Near side: mostly FSR
- A flattenicity selection isolates the FSR contribution from MPI/ISR
  - → **Flattenicity is a practical handle to select specific QCD processes** in future D^0-D^0 / jet-jet correlations

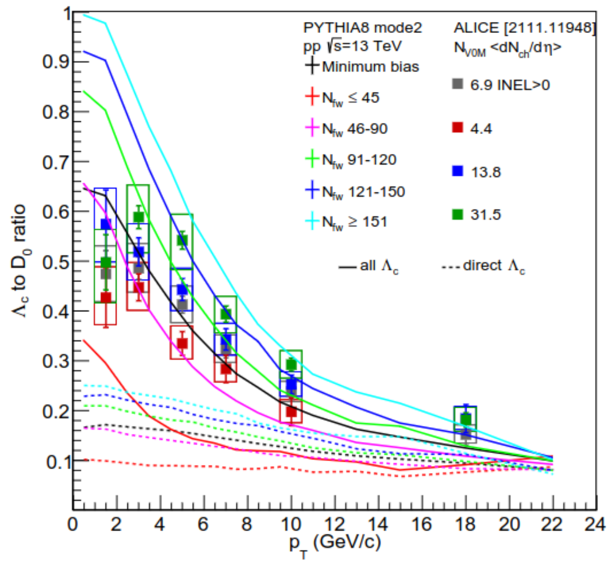
Charm baryons in simulations: Λ_c^+/D^0 ratios

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

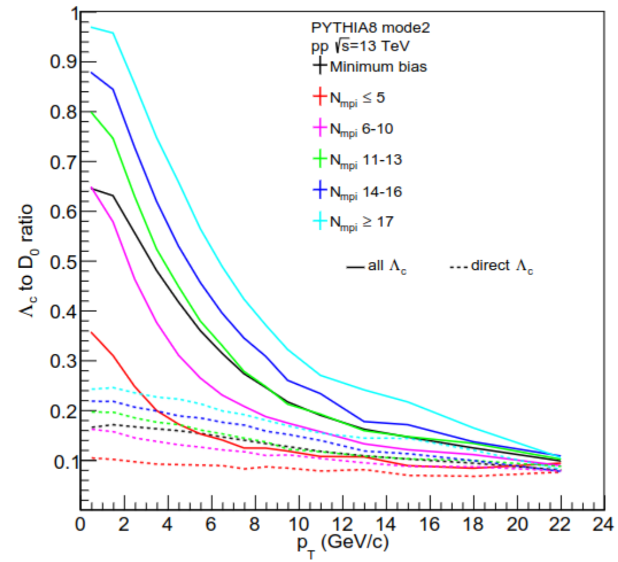
central rapidity N_{ch}



forward rapidity N_{fw}



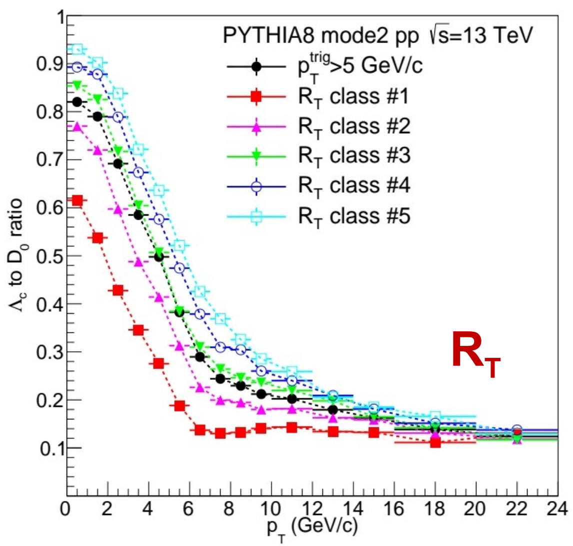
N_{MPI}

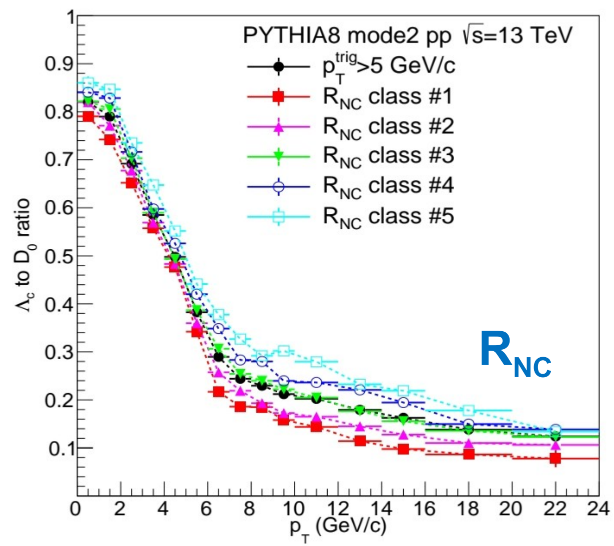


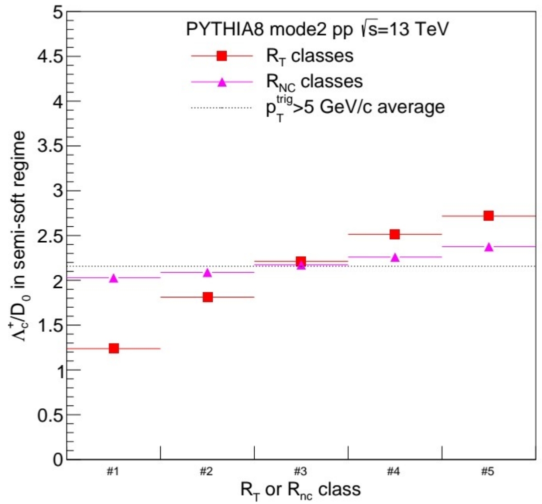
- PYTHIA 8.303 **CR-BLC mode2** (reproduces Λ_c^+/D^0), 1 B pp $\sqrt{s}$=13 TeV
- **Λ_c^+/D^0 rises with both central (N_{ch}) and forward (N_{fw}) multiplicity**; simulations reproduce the ALICE trends.
- N_{fw} imposes a rapidity gap ($2<|\eta|<5$) → reduces autocorrelation between the charmed jet and the multiplicity estimator. Same enhancement with the gap ⇒ hint that the multiplicity dependence is not driven by charm production inside jets

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

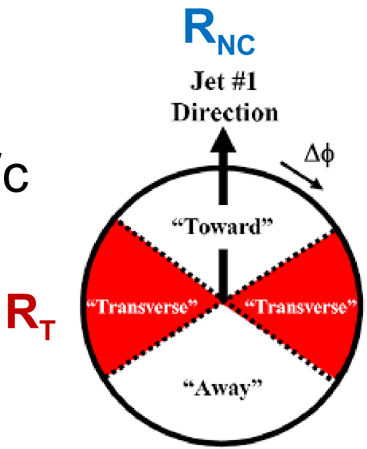
J. Phys. G 49 (2022) 075005





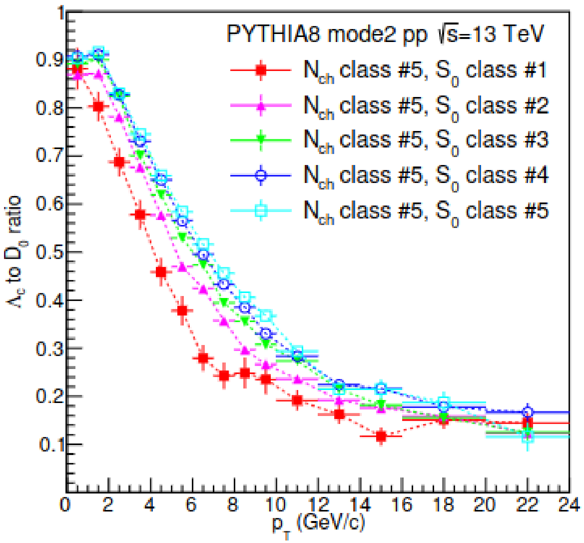


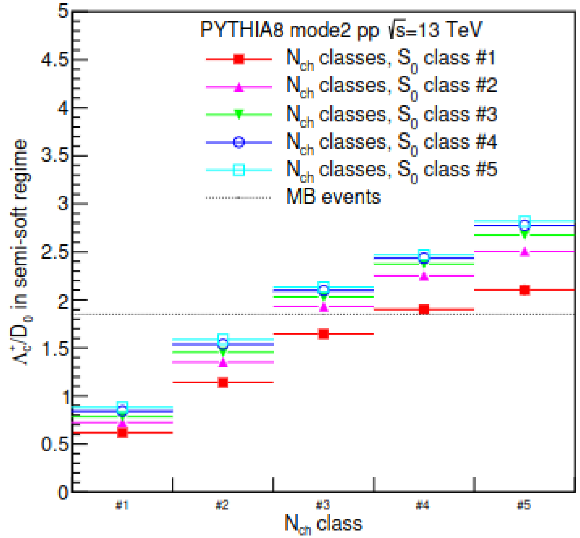
- Events require p_T>5 GeV/c **hadron trigger**
- Integrate over the semi-soft /coalescence regime $2<p_T<6$ GeV/c
- **R_T (UE activity)**: nearly threefold rise from low to high class
- **R_{NC} (jet activity)**: only a slight dependence (UE-residual)
- Excess Λ_c^+/D^0 production linked to the **UE**, not the jet



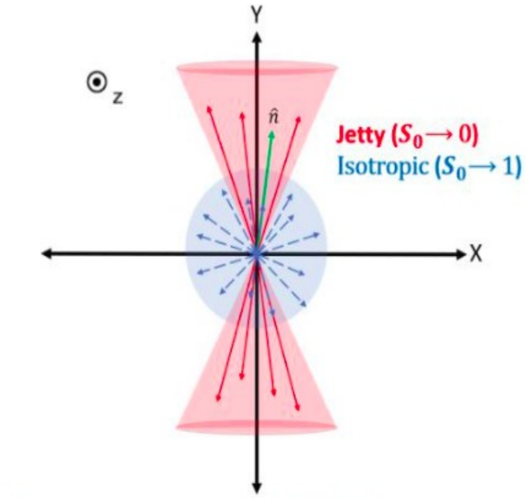
Λ_c^+/D^0 ratios vs. spherocity (minimum bias)

J. Phys. G 49 (2022) 075005





$N_{CH} > 50$

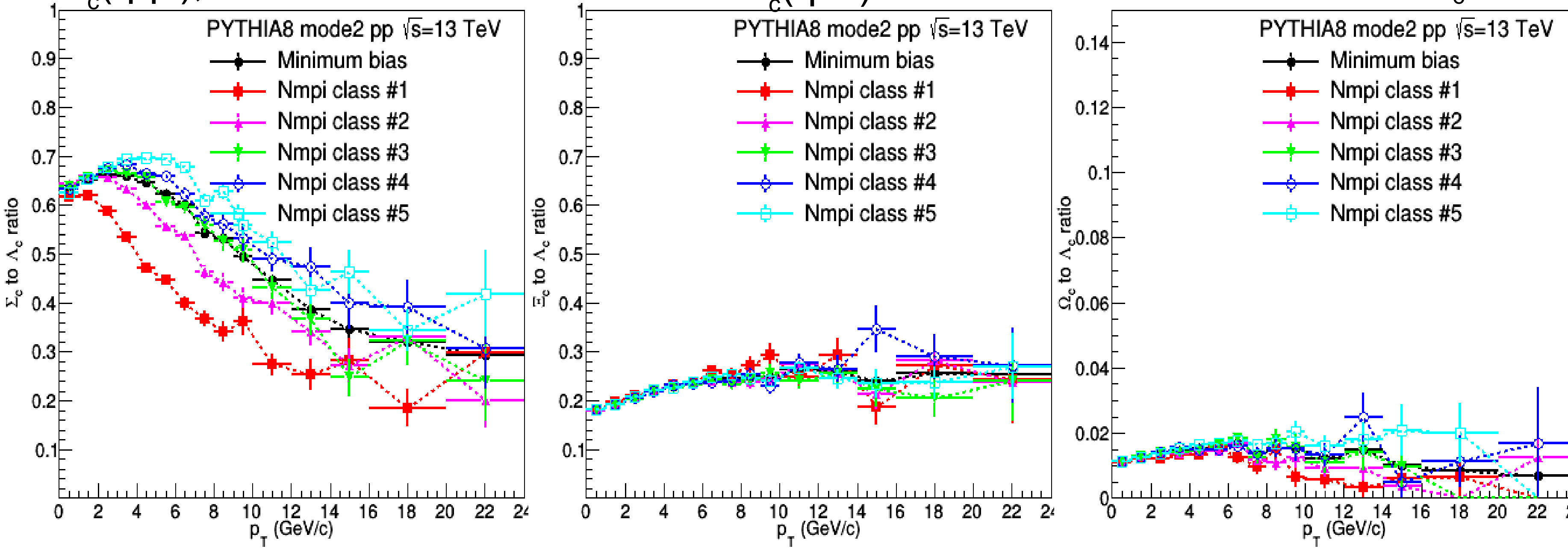


- **S_0 needs no trigger** → avoids the bias and statistics loss of triggered samples
- At high N_{ch}: clear separation between jetty (low S_0) and isotropic (high S_0) — isotropic events show the larger enhancement.
- At low N_{ch}: little room for the UE → dependence is weaker

- → Enhancement is a UE phenomenon; S_0, R_T are discriminating handles, R_{NC} is not.

Isospin and strangeness: B-to-B ratios

Σ_c(qqc), I = 1 J. Phys. G 50 (2023) 7, 075002 Ξ_c(qsc) Ω_c^0(ssc)

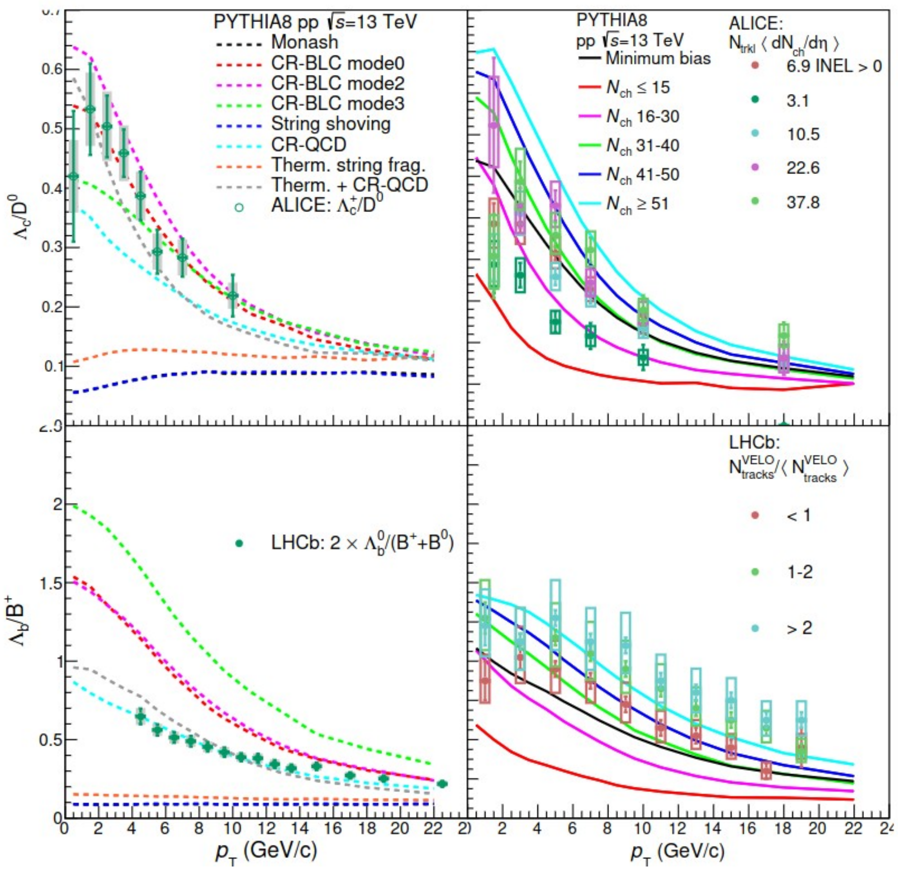


- There is a low p_T enhancement in the ratio connected to the isospin of the **charm content**
  - The enhancement is connected to event activity
- No significant event-activity dependence comes with **strange content**

From charm to beauty

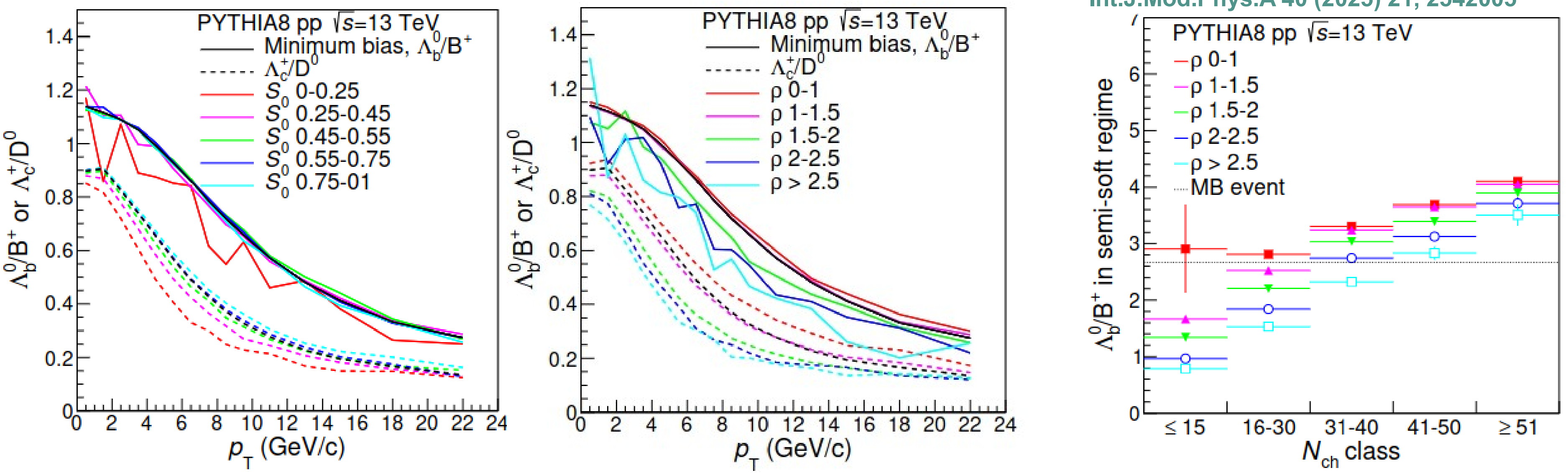
- LHCb and ALICE: beauty baryon-to-meson ratios (Λ_b^0/B^+) show charm-like low-p_T enhancement
- PYTHIA 8.309: **CR-BLC** (charm) + **CR-QCD** with color junctions (beauty); also thermodynamical & rope/shoving fragmentation tested
- Λ_c^+/D^0 best described by **CR-BLC mode 2**; Λ_b^0/B^+ extent reproduced by CR-QCD (CR-BLC overshoots low-p_T LHCb by ~2×)
- **Both flavors rise with multiplicity**

Int.J.Mod.Phys.A 40 (2025) 21, 2542005



Flattenicity as the universal UE proxy

Int.J.Mod.Phys.A 40 (2025) 21, 2542005



- **Spherocity**: separation is much weaker for beauty
  → S_0 is an insensitive UE measure here
- **Flattenicity**: clean separation for **both** charm and beauty, in **every N_{ch} bin**
  → multiplicity-independent
- Broad rapidity range ⇒ free from mid-rapidity jet bias
  → **effective proxy for UE/MPI activity**
- Cross-flavor consistency: **heavy-flavor baryon enhancement stems from MPI/UE**

Summary and outlook

ALICE event-activity-dependent heavy-flavor measurements:

- Opportunity to understand the complexity of pp collisions
  → **Fragmentation is not universal**
- Examine the interplay of hot and cold nuclear, and vacuum effects
  → Λ_c^+/D^0: **Large systems can still be described within the standard thermal equilibrium + hydrodynamical evolution picture**
- → Models fail to describe the D_s^+/D^+ evolution across collision systems

Simulations

- **Correlations:** flattenicity separates parton-level processes; isolates FSR; selects QCD creation channels
- **Charm-baryon enhancement:** In the frames of the CR-BLC model, it is an UE/MPI effect (R_T, S_0 sensitive; R_{NC} not)
- **Beauty:** Flattenicity is the robust, trigger-free UE classifier across flavors

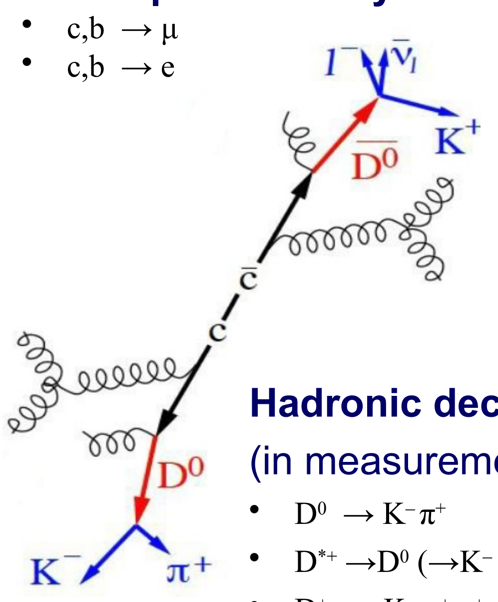
- Simulations provide predictions and sensitivity — ultimately verified only by detailed data
- LHC Run 3 (high-precision Λ_b^0/B^+ ratios) and ALICE 3 (D^0-D^0 correlations) will test predictions directly

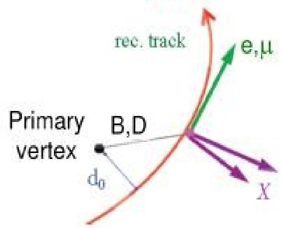

Thank you!

Reconstruction of heavy flavor decays

Semileptonic decays

- c,b $\rightarrow \mu$
- c,b $\rightarrow$ e





Identification

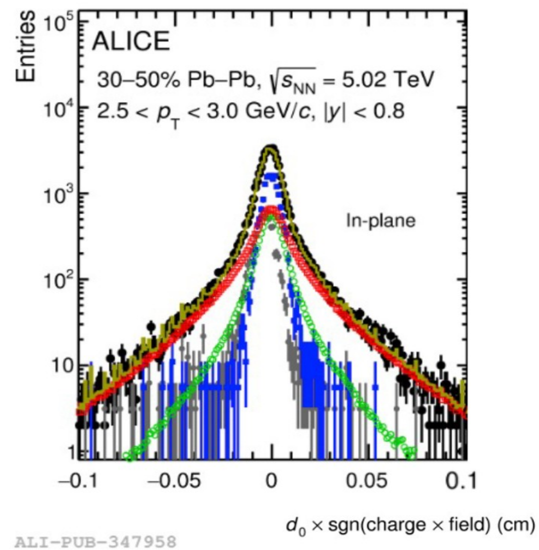
- PID of daughter hadrons
- Topological selection
- Secondary vertex in the ITS

Lifetime of heavy flavor: $c\tau$ (D) ~ 100-300 μm
$c\tau$ (B) ~ 400-500 μm
Secondary vertex resolution: < 100 μm

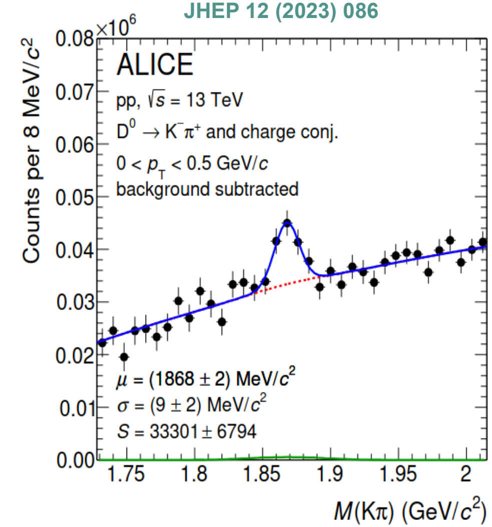
Hadronic decays

(in measurements shown)

- $D^0 \rightarrow K^-\pi^+$
- $D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+)\pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D_S^+ \rightarrow \Phi(\rightarrow K^+ K^-)\pi^+$
- $\Lambda_c^+ \rightarrow p K^- \pi^+$
- $\Lambda_c^+ \rightarrow pK^0_S(\rightarrow\pi^+\pi^-)$
- $\Xi_c^0 \rightarrow \Xi^- \pi^+$
- $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$



JHEP 12 (2023) 086



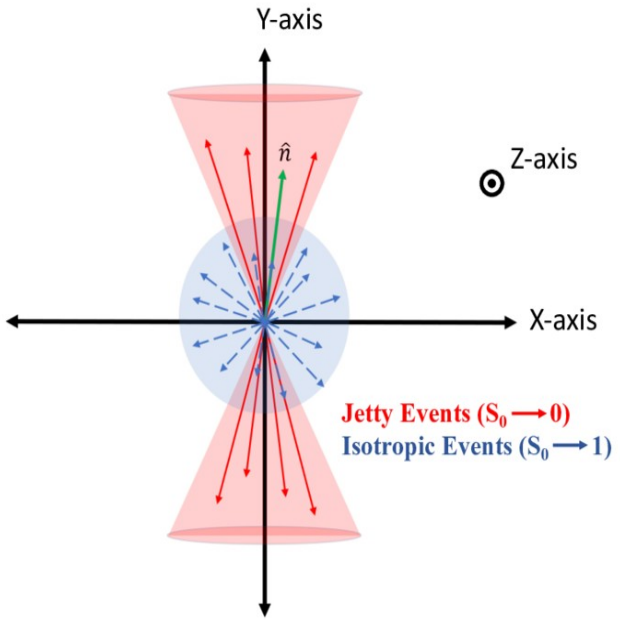
Peak extraction
(D^0 example)

Transverse spherocity S_0

- Event-shape observable to express jettyness vs. isotropy

$$S_0 = \frac{\pi^2}{4}\left(\frac{\sum_i |\vec{p}_{\mathrm{Ti}} \times \hat{n}|}{\sum_i p_{\mathrm{Ti}}}\right)^2$$

- Sensitive to initial hard scatterings and underlying event
- **Jetty events** ($S_0 \to 0$) dominated by hard QCD processes
- **Isotropic events** ($S_0 \to 1$) dominated by soft QCD processes



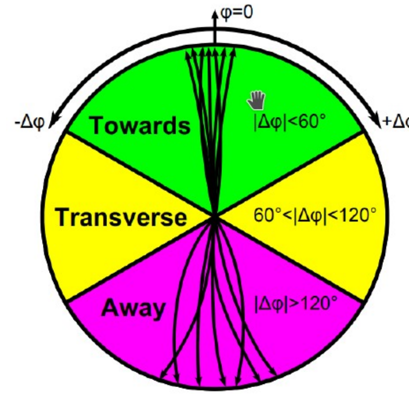
Transverse event activity R_T

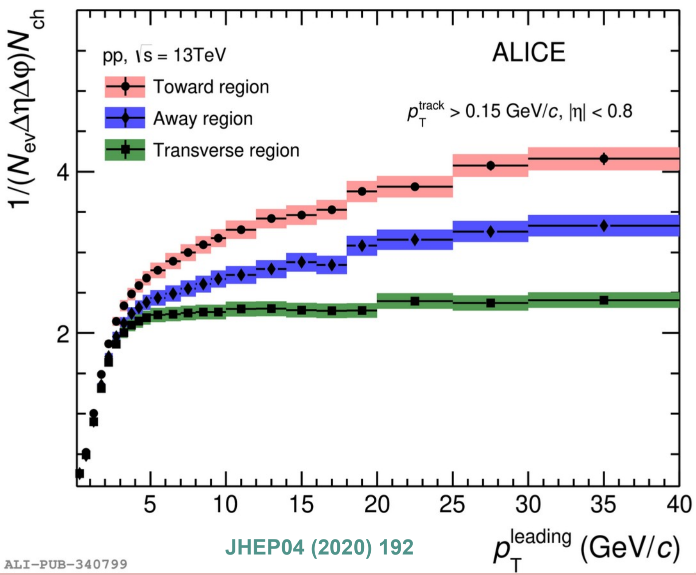
- Event-activity observable representing the underlying event (UE)

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

N_T^{ch} : event multiplicity in the transverse region

- High-p_T leading particle required
- **Toward** and **Away** regions typically contain the leading and subleading jet
- **Transverse** region is mostly independent of the hard scattering process for leading particle p_T >5 GeV/c, and mostly contains the UE
  - R_T < 1 : low underlying-event activity
  - R_T > 1 : high underlying-event activity
- In models with multiple-parton interactions (MPI), R_T is strongly correlated with the number of MPIs





JHEP04 (2020) 192

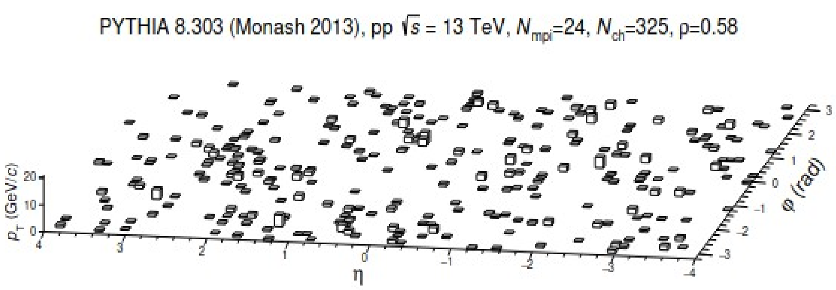
Flattenicity

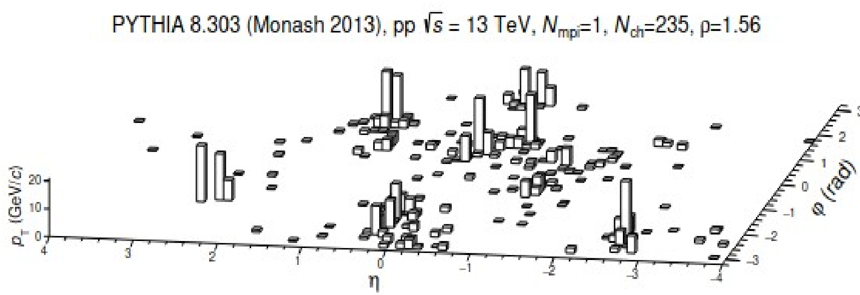
A. Ortiz, G. Paic, Rev. Mex. Fis. Suppl. 3 (2022) 040911

- Motivated by rare "hedgehog" events in pp collisions (first noted by UA1 and CDF) with no jetty structure
- **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

- All five activity classifiers binned into classes #1–#5, chosen to hold ~equal event counts (so a "class" is a percentile, not a fixed physics scale)

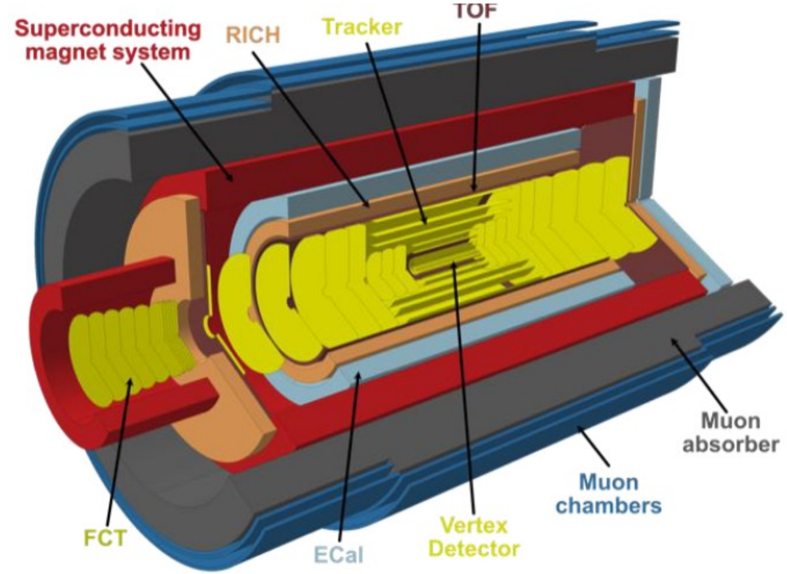
class	#1	#2	#3	#4	#5
N_{ch}	≤ 15	16–30	31–40	41–50	≥ 51
N_{fw}	≤ 45	46–90	91–120	121–150	≥ 151
R_{T}	<0.5	0.5–1	1–1.5	1.5–2	>2
R_{NC}	<0.5	0.5–1	1–1.5	1.5–2	>2
S_0	0–0.25	0.25–0.45	0.45–0.55	0.55–0.75	0.75–1
ρ	0 – 1	1 – 1.5	1.5 – 2	2–2.5	>2.5

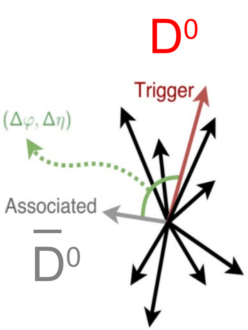
Charm-charm correlations: ALICE 3

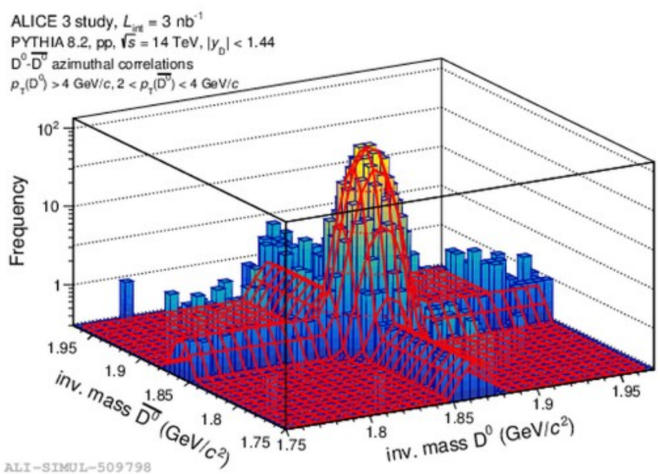
ALICE 3: the detector of the future

ALICE, arXiv:2211.02491 (LoI)

- Compact multi-purpose detector
- “Ultra-thin” semiconductor technology
- 20-50x higher luminosity







E.Frajna (ALICE), Quark Matter 2022

- Measurements of D^0-$\overline{D}^0$ correlations
- **Separation of individual pQCD processes** (pair production, gluon splitting, flavor excitation) will be possible

How the c–c̄ creation process is tagged

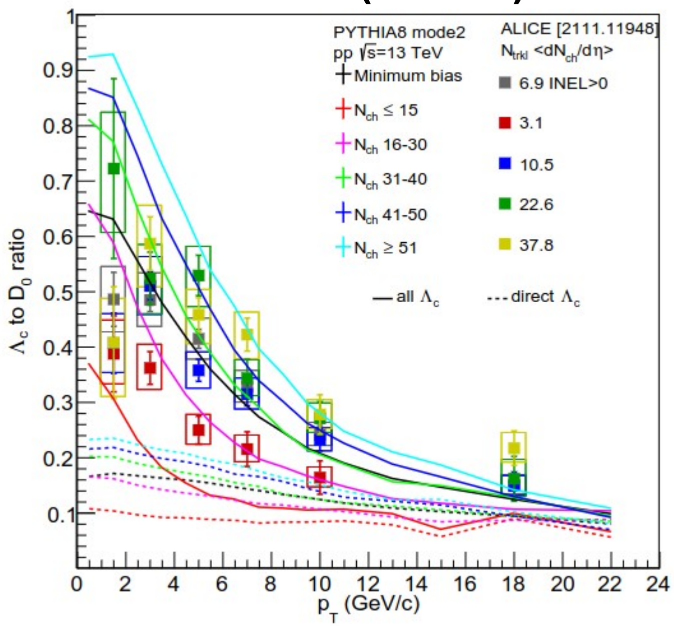
- Trace the trigger charm back to the **first charm in its ancestry**, then read the **PYTHIA status codes of its parents**:
  - only **gluon parents not tied to the hardest process** → **gluon splitting (GSP)**
  - gluon parents **and** the quark is incoming to the hardest sub-process → **flavor excitation (FLX)**
  - both parents incoming light quarks/gluons of the hardest process producing the c → **flavor creation (FLC)**
- Charm not from the hardest process (rare, subsequent soft processes) is grouped into **GSP**

Norrbin–Sjöstrand EPJ C 17 (2000) 137

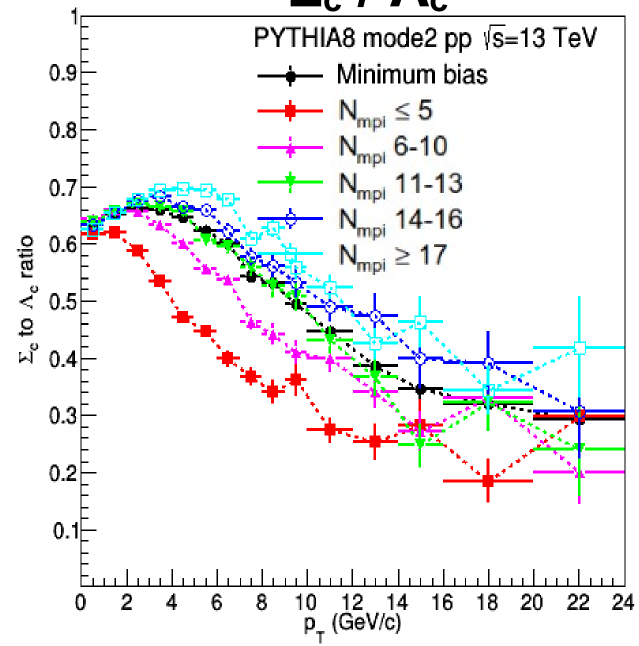
Σ_c vs. Λ_c : Isospin of charmed baryons

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

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



Σ_c / Λ_c

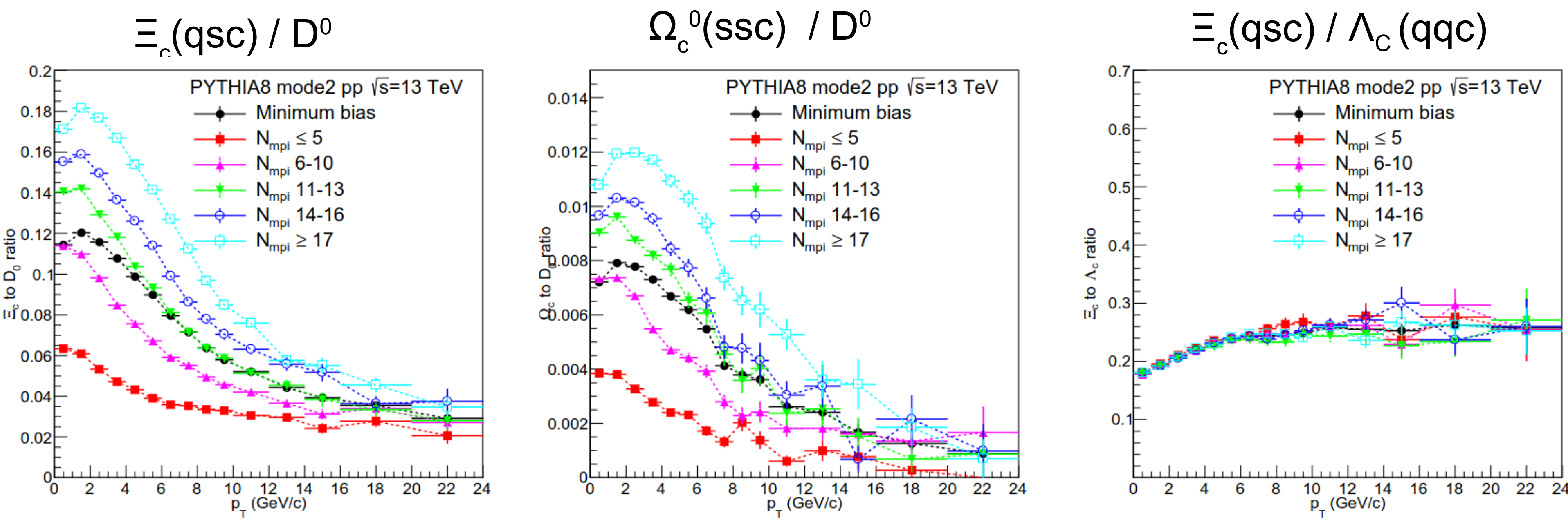


Σ_c (qqc, I=0)
Λ_c (qqc, I=1)

- Λc^+ gets a **large feed-down**, mostly from **Σc^0, decay Λc^+ dominates at low-pT,** direct Λc^+ is flat and dominates high pT
- Both ordered by event activity → not a kinematics artifact
- $\Sigma c/\Lambda c$ ordered by N_MPI ⇒ enhancement is isospin-sensitive

Ξ_c and Ω_c: Strangeness in charmed baryons

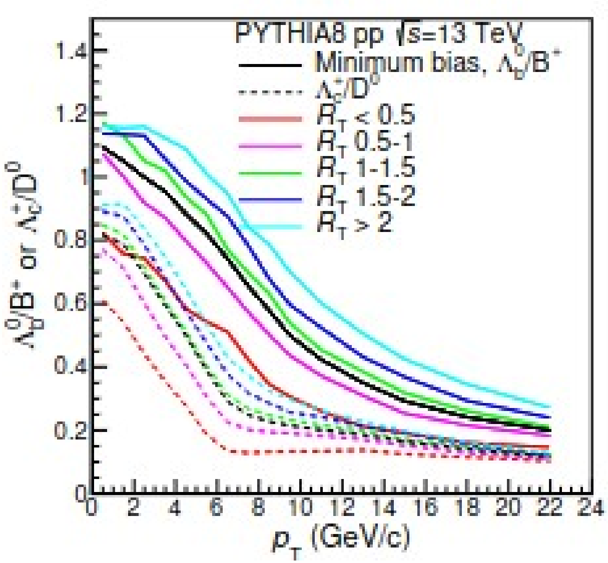
J. Phys. G 50 (2023) 7, 075002

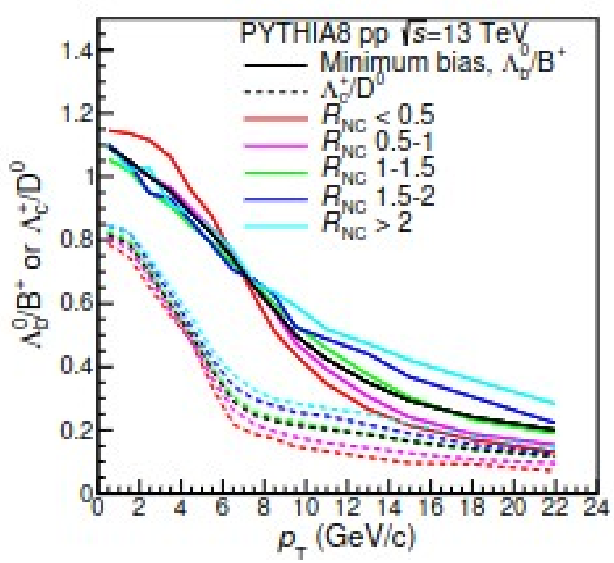


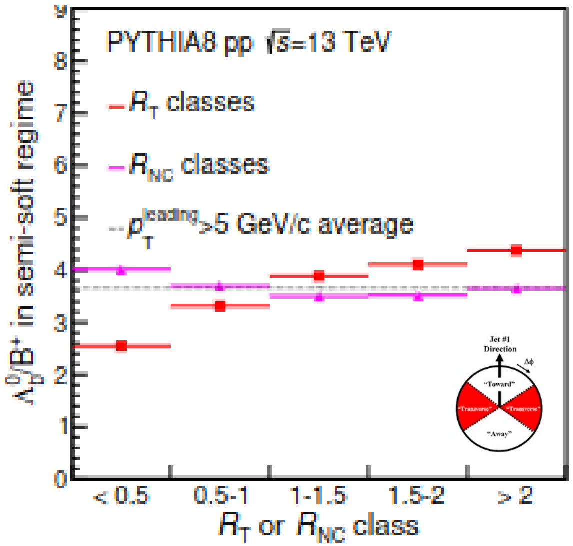
- There is a **low p_T enhancement** connected to the **charm content**
- There is a **high p_T enhancement** connected to the **strange content** (above that of the charm enhancement)

Beauty R_T / R_{NC}

Int.J.Mod.Phys.A 40 (2025) 21, 2542005







- The charm result repeats for beauty: Λ_b^0/B^+ rises with R_T, is essentially flat in R_NC below ~6 GeV/c.
- Confirms the UE-not-jet origin across flavors.

Model dependence and known limitations

- **CR-BLC modes**: mode 2 reproduces $\Lambda c^+/D^0$; mode 0 gives slightly less enhancement; mode 3 overestimates the UE
- **Charm vs beauty**: $\Lambda c^+/D^0$ best by **CR-BLC mode 2**, $\Lambda b^0/B^+$ by **CR-QCD** — no single tune describes both; CR-BLC overshoots low-p_T LHCb beauty by ~2×
- N_{MPI} is not an observable — used only as the model's internal UE proxy; physical classifiers (R_T, ρ) are what's measurable.
- Simulation multiplicity classes **don't map exactly** onto the experimental ones (e.g. ALICE forward V0A/V0C η ranges differ from N_{fw}

Christiansen–Skands 1505.01681
Altmann–Skands 2404.12040