Baryon enhancement in jets

[1] Phys.Rev.D 112 (2025) 3, 036009
[2] arXiv:2604.23189 (2026)

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Baryon enhancement in small systems

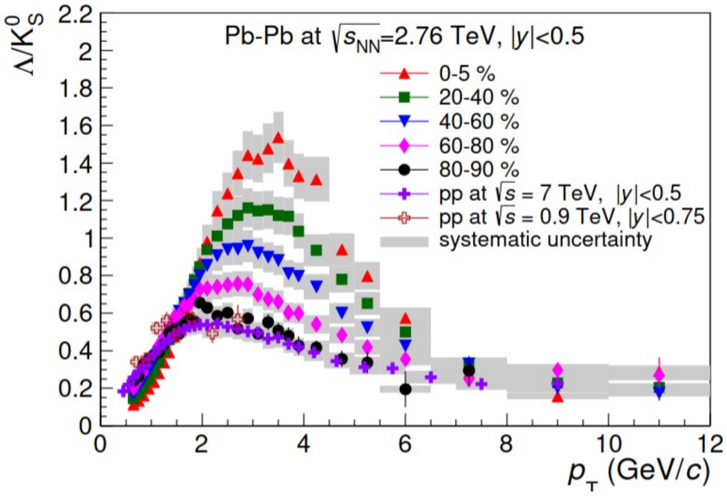
- Heavy-ion benchmark: Baryon/meson enhancement at intermediate p_T
  - Standard QGP picture: radial flow + recombination
- Surprise: same qualitative B/M enhancement in **small systems** (high-multiplicity pp, p-Pb).
- Two open narratives:

1) **Collective:** mini-QGP, hydro + recombination

2) **Microscopic:** vacuum QCD effects such as multiparton interactions, color junctions, string density effects

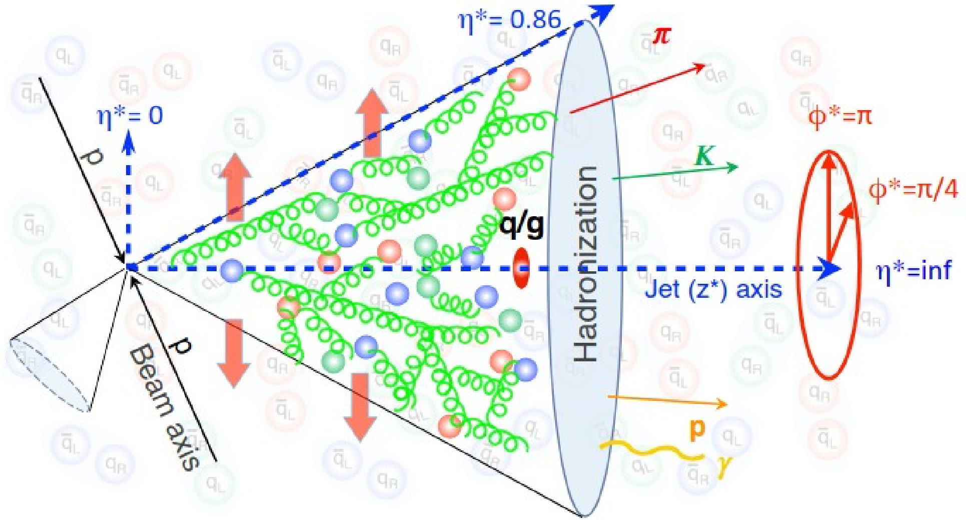
- This talk: a controlled, **non-collective** baseline using PYTHIA, focused *inside hard jets*

Phys.Rev.Lett. 111 (2013) 222301



Collective system from a single parton?

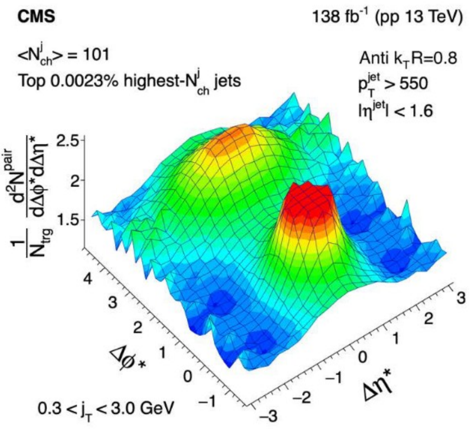
- Small collision systems exhibit collectivity
- Is there similar collectivity in a single jet?
- Idea: in the jet frame the particle shower is similar to bulk physics
  A. Baty et al., Phys.Rev.C 107 (2023) 6, 064908



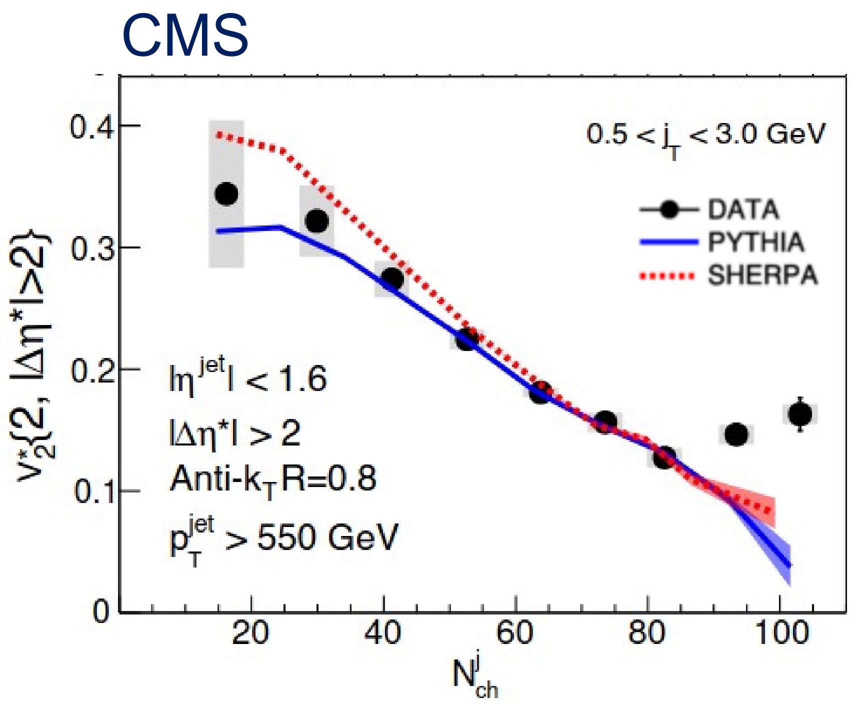
Jet frame (j_T,Φ*,η*)
- j_T perpendicular to jet axis (z*)
- Φ* is the azimuth around z*
- η* represents the angle with z*

CMS angular correlations in the jet frame

- CMS: substantial elliptical flow in the jet system v_2^* is seen



- Low and medium jet multiplicity (N^j_{ch}) trend is well understood by models



Phys.Rev.Lett.133(2024)14,142301

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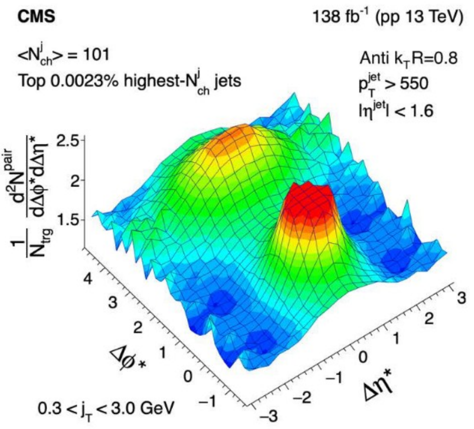
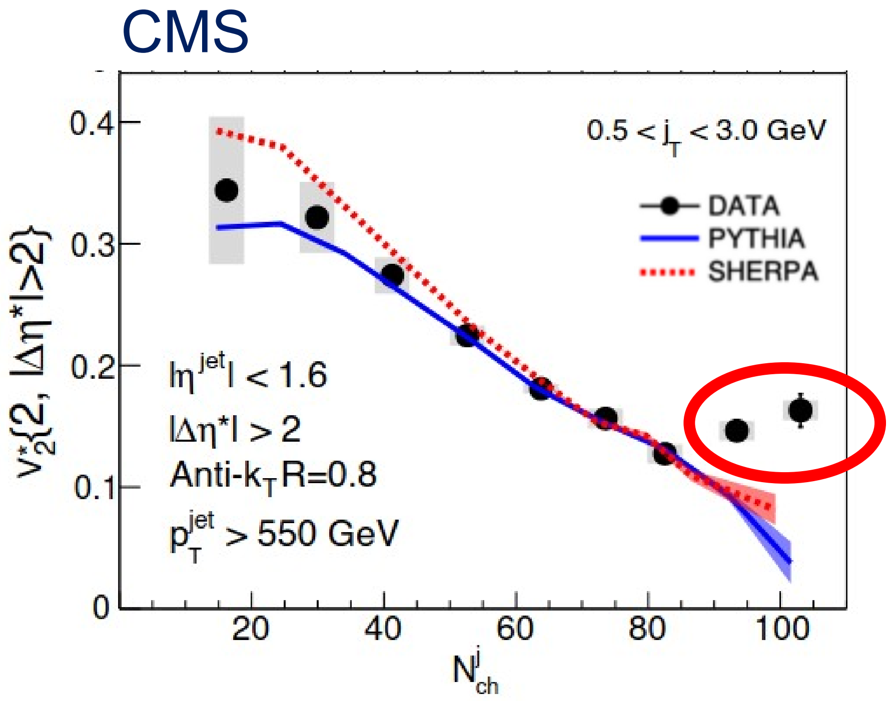


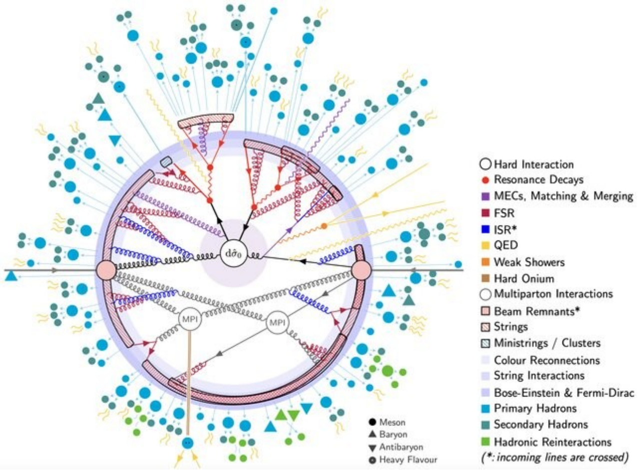


- Low and medium jet multiplicity (N^j_{ch}) trend is well understood by models
- A high-N^j_{ch} increase is present compared to predictions

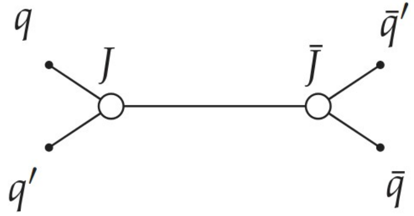
Phys.Rev.Lett.133(2024)14,142301

Simulations: models

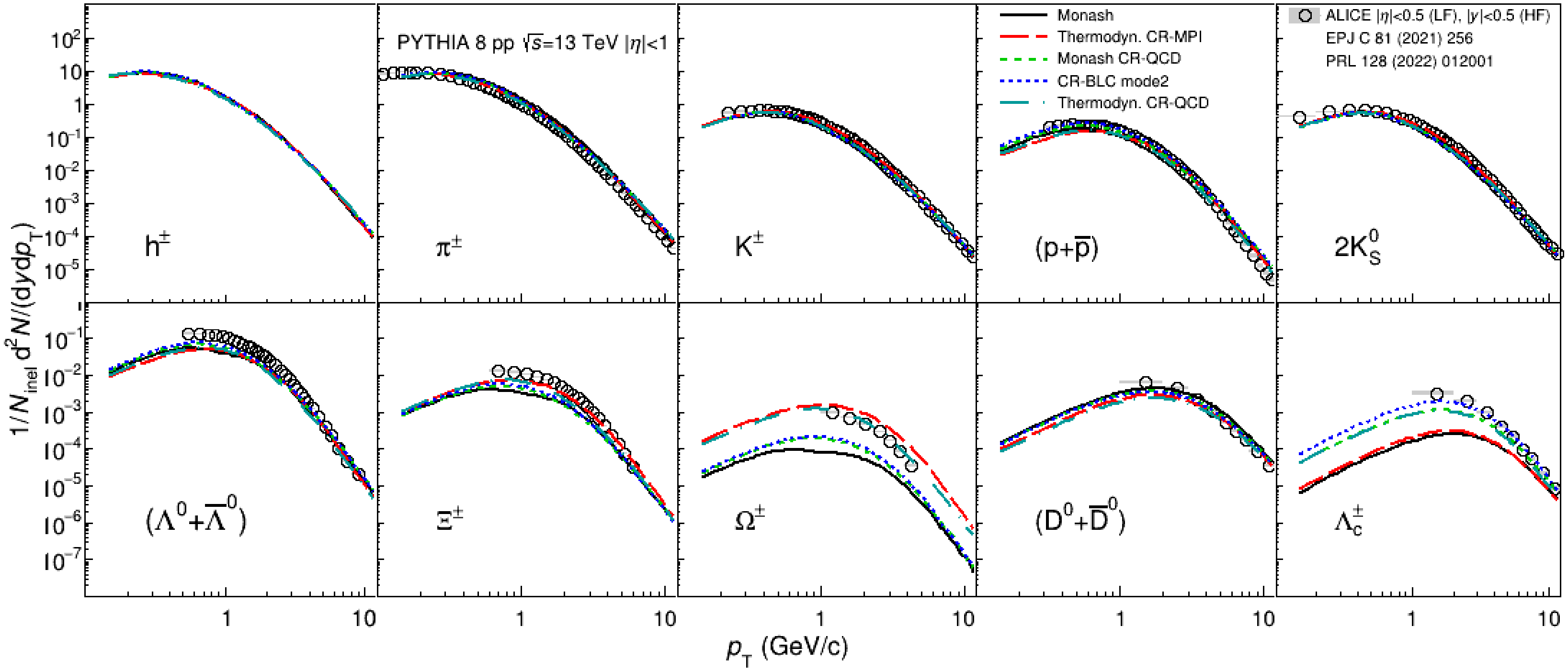
- **PYTHIA 8** was used to explore signatures of collectivity within jets
  - Multi-parton interactions (MPI) off to suppress the underlying event
  - Monash tune: established from early LHC data, successfully describes many observables, includes Lund fragmentation



- Further model settings were explored
  - QCD-scheme color reconnection with default settings (CR-QCD), as well as CR-BLC mode 2 that is tuned to describe heavy-flavor baryon sector: allow for color string junctions
  - Thermodynamical string fragmentation with and without close packing (more constrained placing of partons before break-up into hadrons)



Simulations: validation on minimum-bias data



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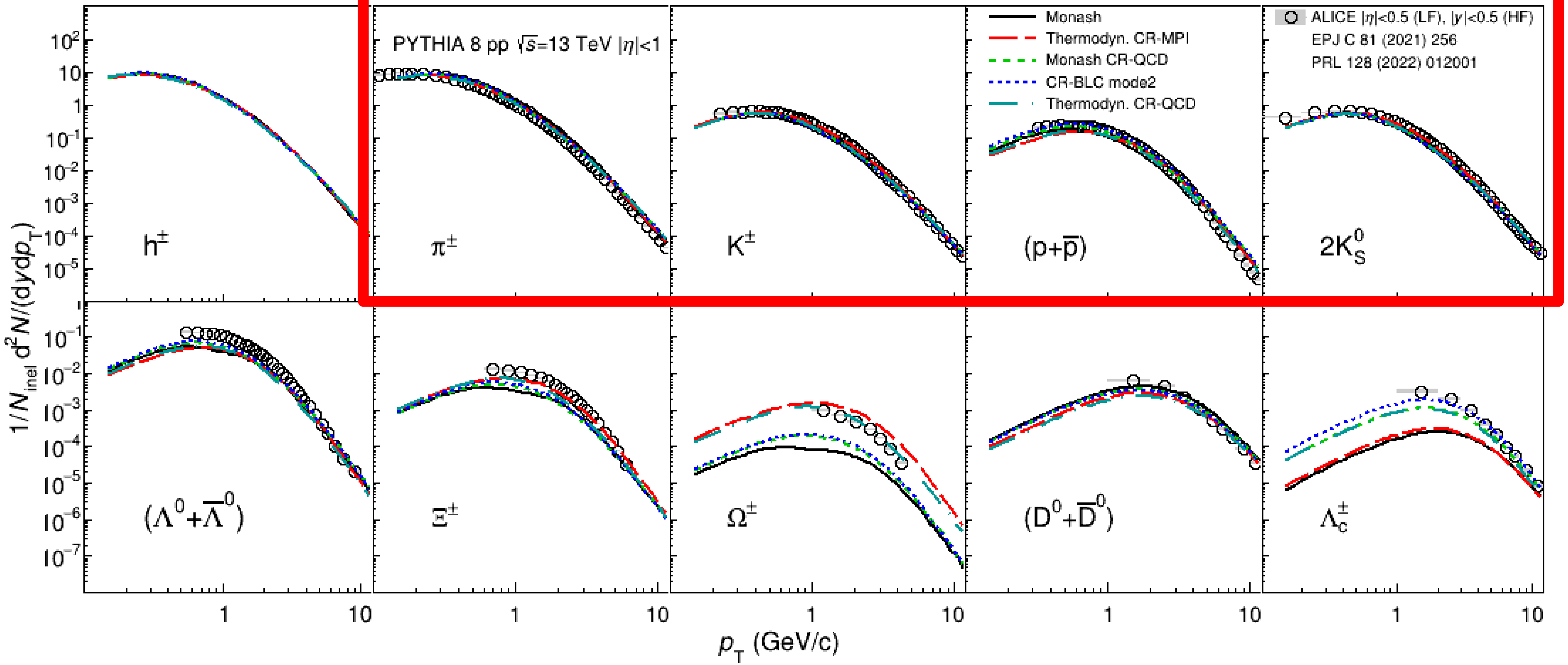

- Light particle yields are generally well-described by the Monash tune

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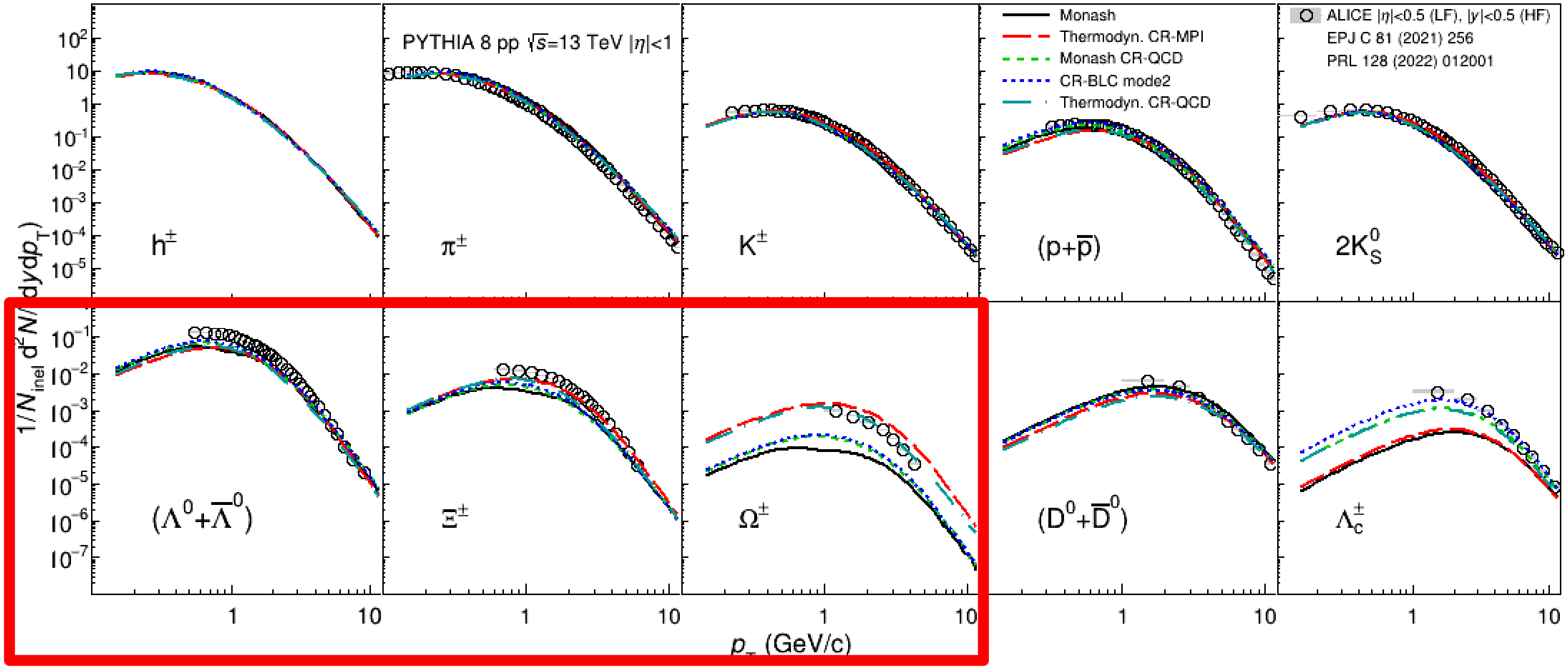

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- Strange baryons are better described by thermodynamical fragmentation with close packing

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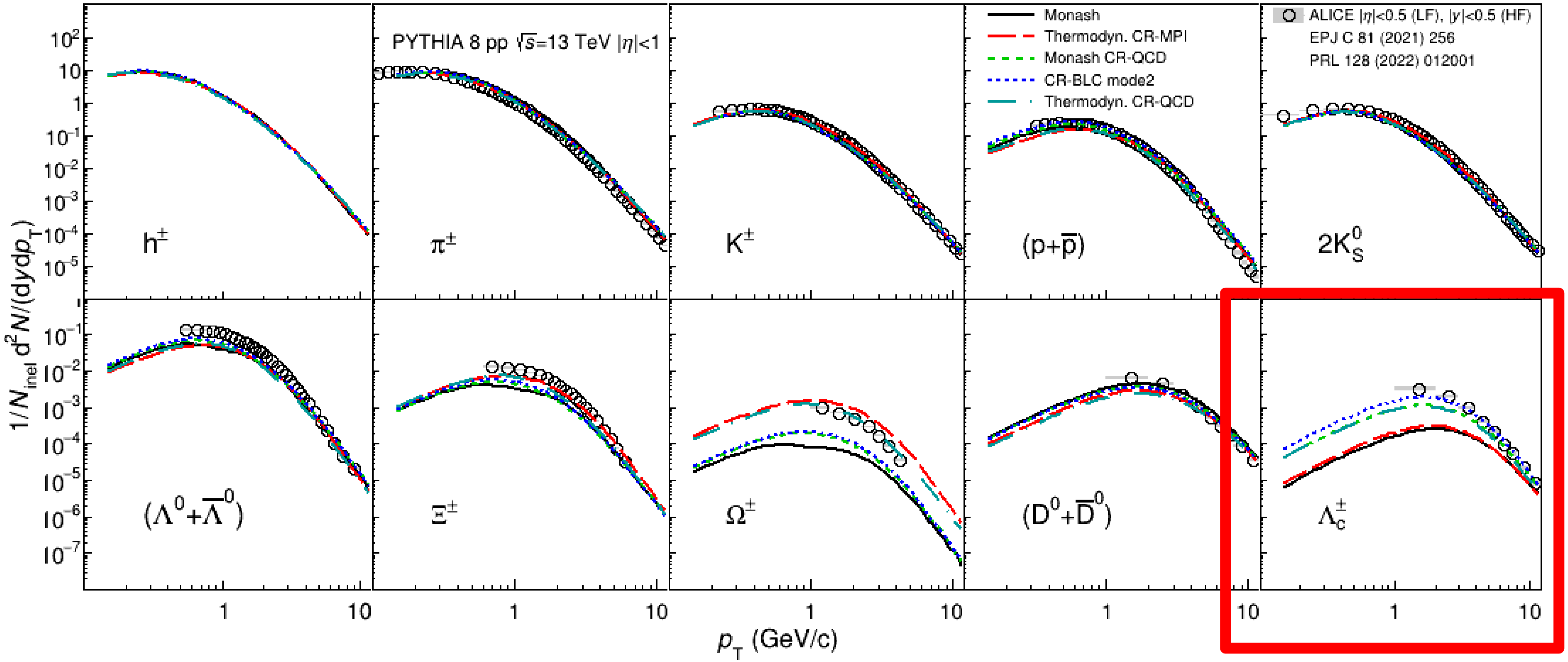
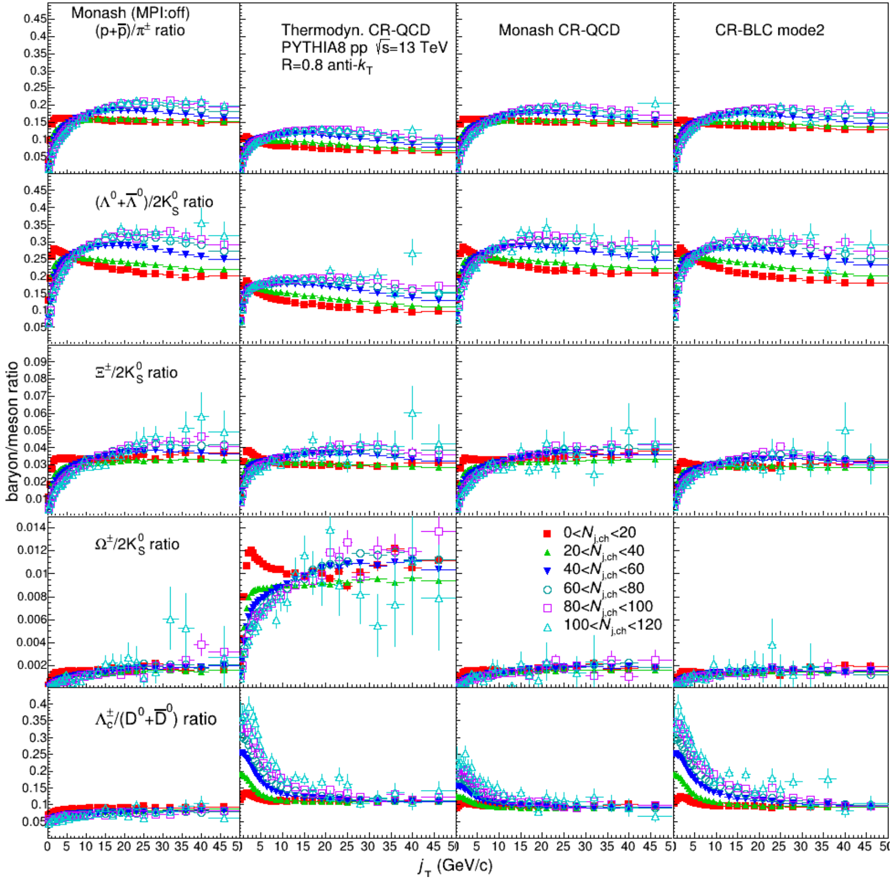


- Light particle yields are generally well-described by the Monash tune
- Strange baryons are better described by thermodynamical fragmentation with close packing
- Charmed hadrons are best described by the CR-BLC tune (color junctions)

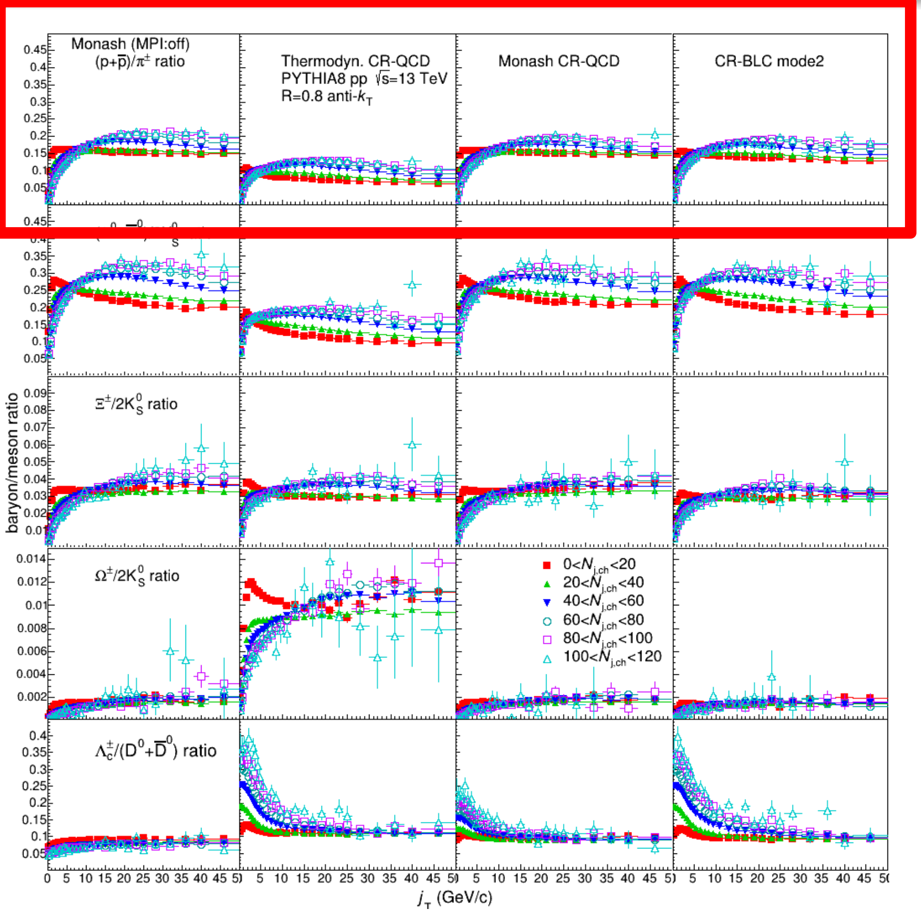
High-p_T jets: baryon-meson ratios vs. j_T



Jet reconstruction: anti-k_T algorithm and R=0.8, p_T^{jet} > 550 GeV/c (CMS setup)

Baryon-meson ratios as a function of j_T, different N^j_{ch} ranges

High-p_T jets: baryon-meson ratios vs. j_T



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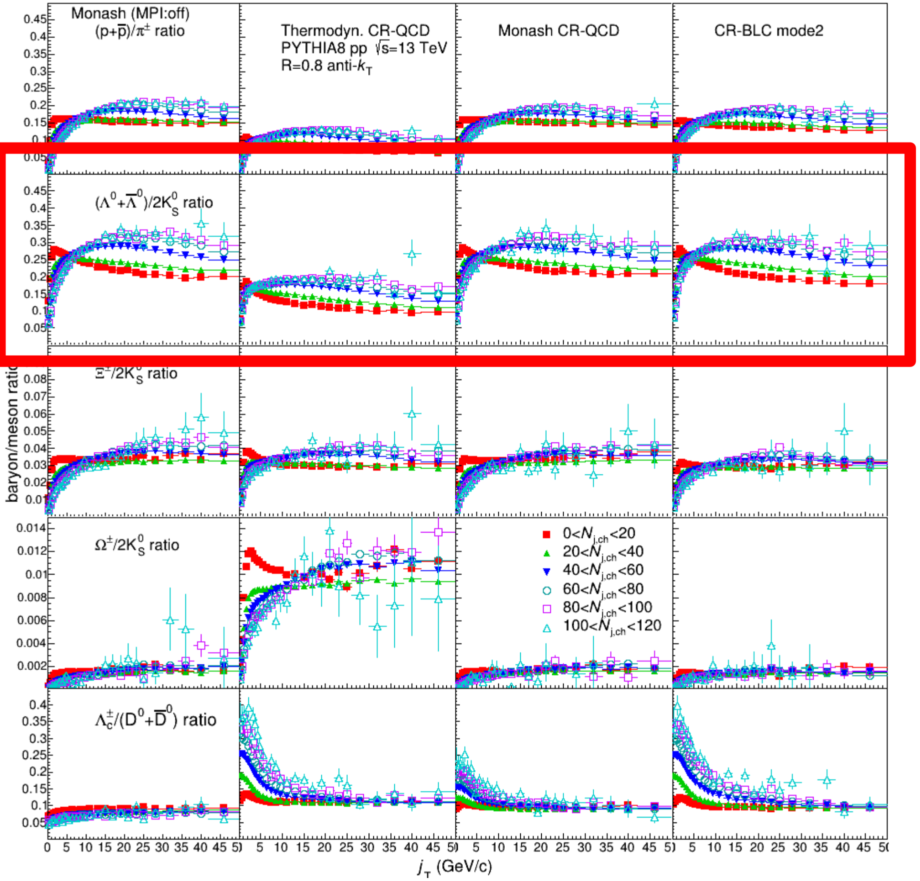

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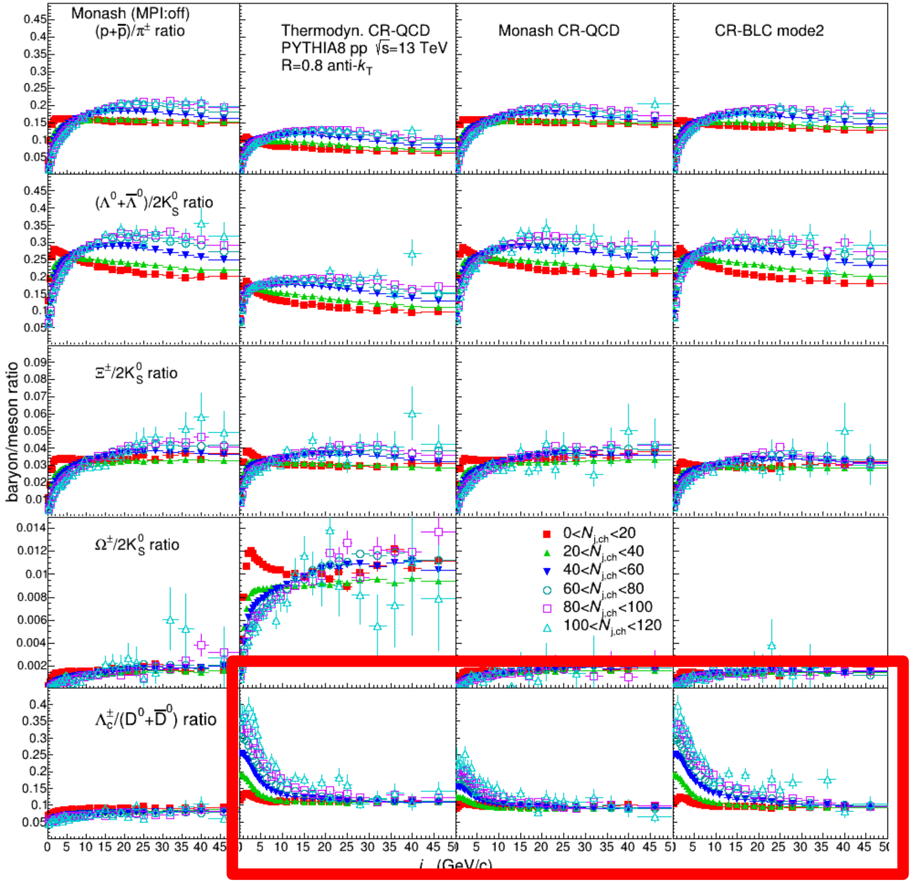

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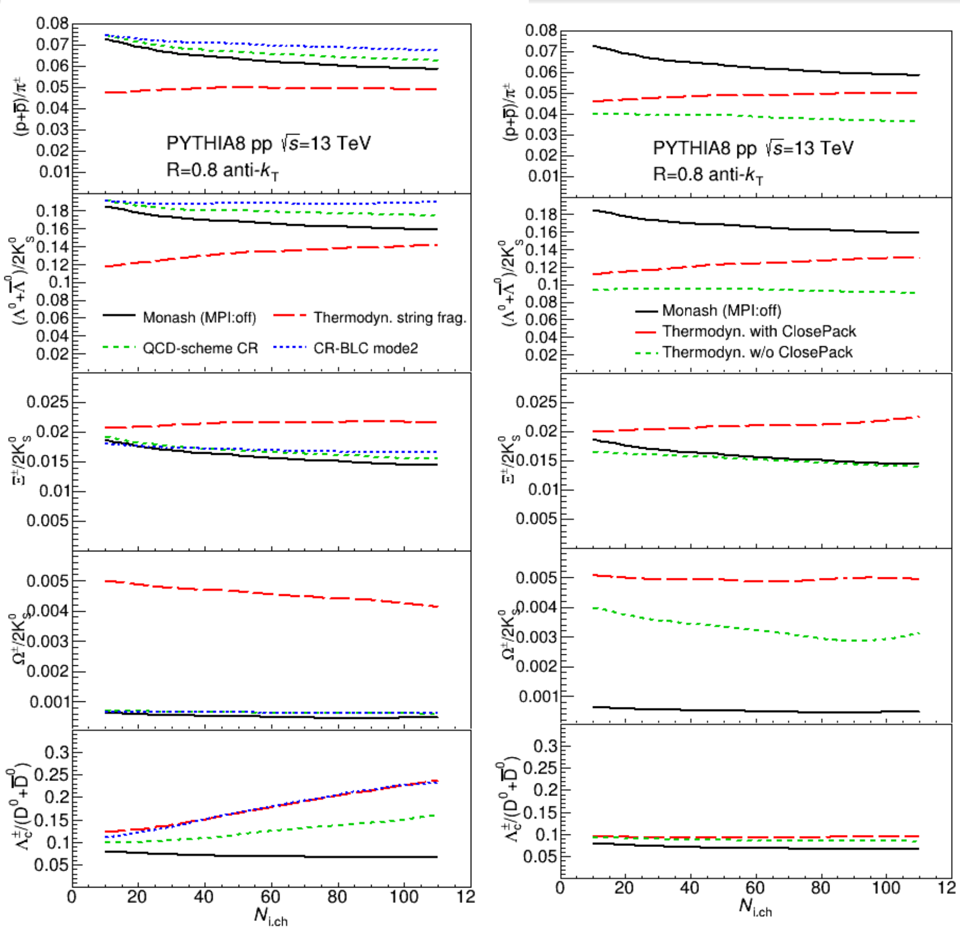
Baryon-meson ratios as a function of j_T, different N^j_{ch} ranges

- In the light-flavor sector, trends are similar for all models
- Λ^0/K_S^0: grouping into low-N^j_{ch} and high-N^j_{ch} curves
- Λ_c^+/D^0: if color junctions are allowed, a characteristic low-j_T enhancement is present that gets stronger with multiplicity; this is similar to p_T-dependent enhancement of charmed baryons in minimum-bias data

ALICE, Phys. Rev. C 107, 064901

High-p_T jets: baryon-meson ratios vs. $N_{j,ch}$

j_T-integrated baryon-to-meson ratios as a function of $N_{j,ch}$, different models



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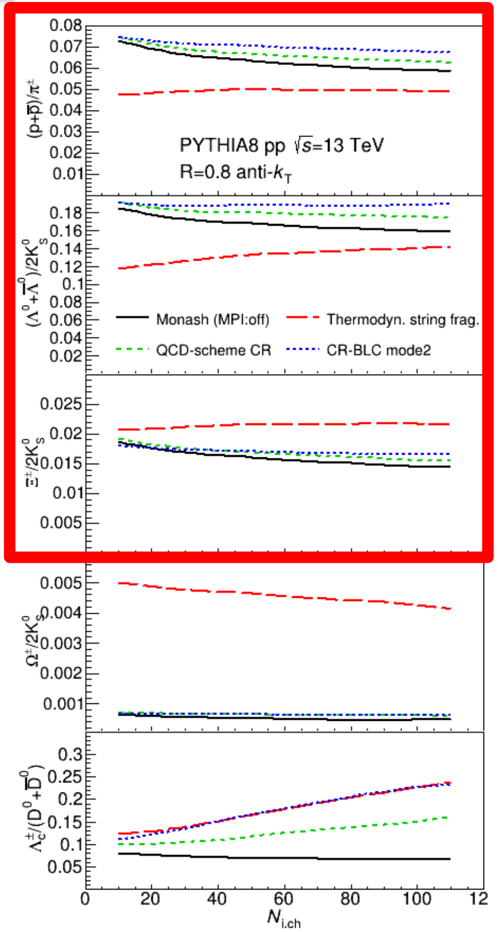
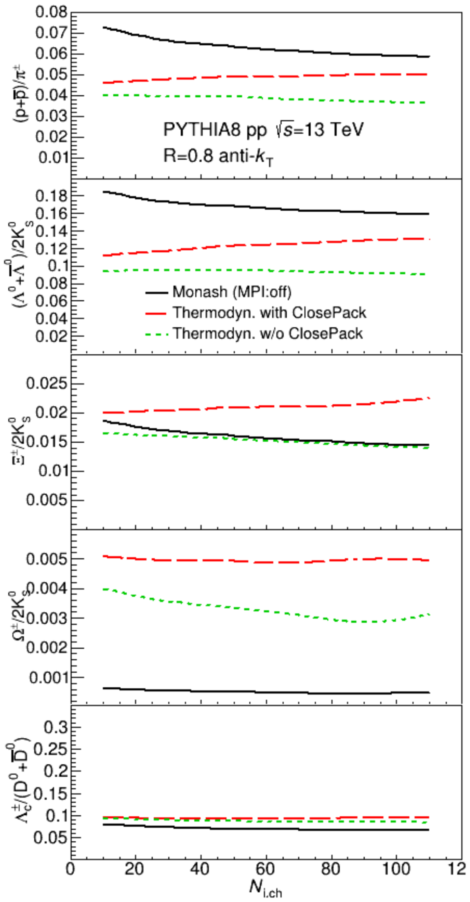
- Thermodyn. fragmentation rises with $N_{j,ch}$ (Lund stays flat) → relative baryon enhancement





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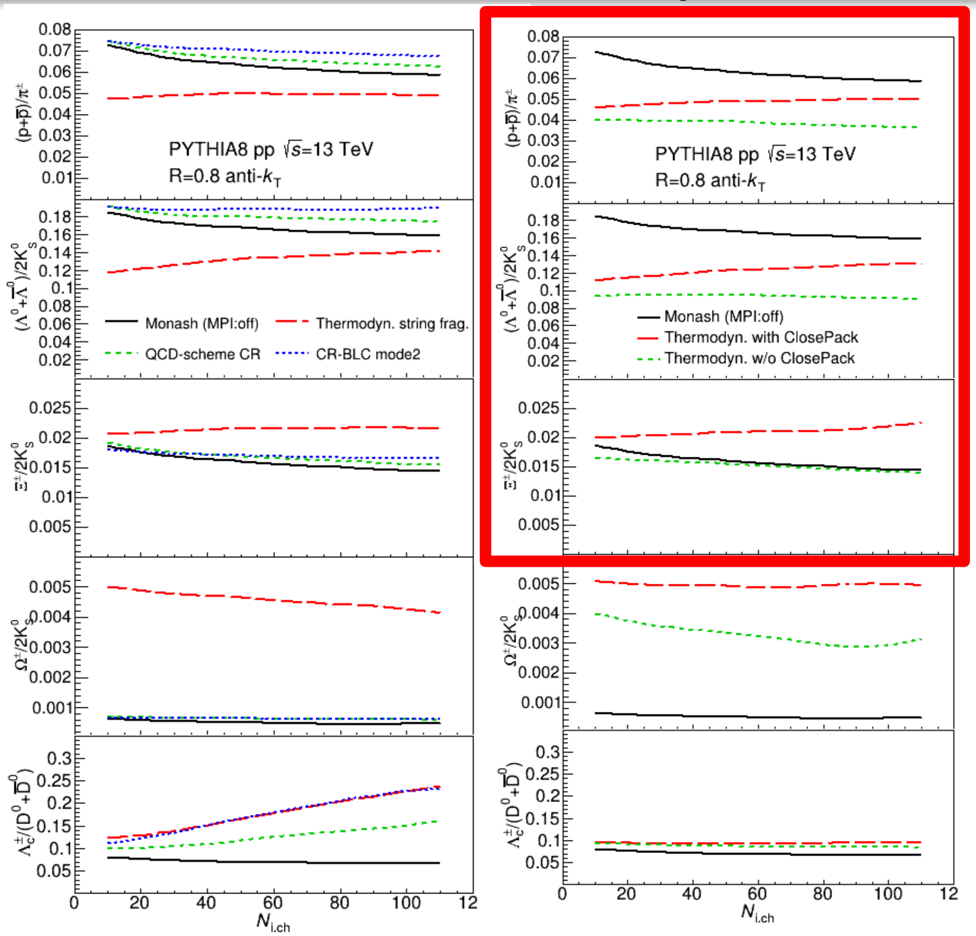
- Rise is partly close-packing-driven (Thermodyn. with vs without ClosePack)



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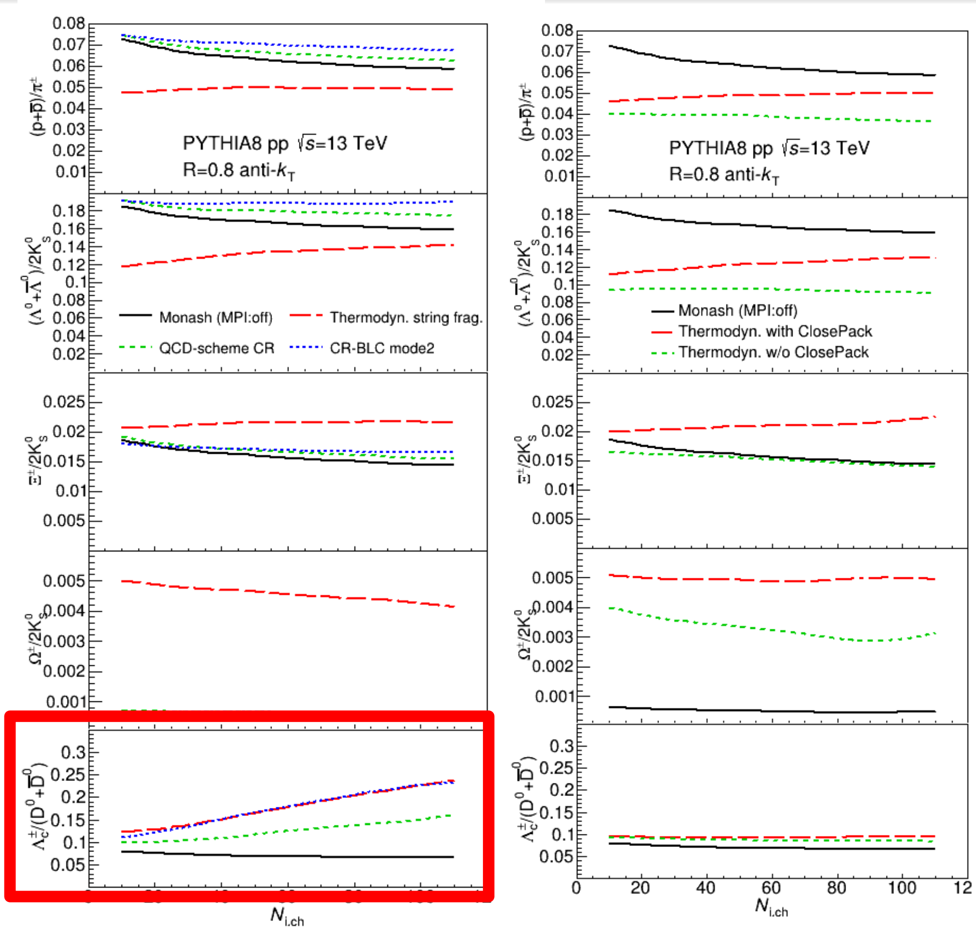
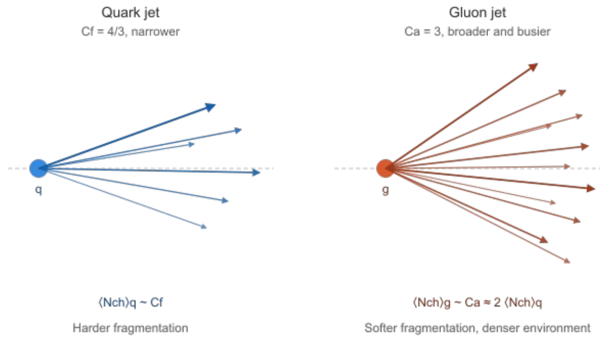
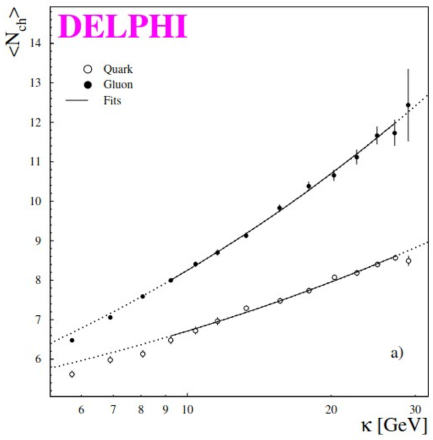
- Rise is partly close-packing-driven (Thermodyn. with vs without ClosePack)
- Junction-allowing tunes drive the enhancement in Λ_c^+/D^0



Quark and gluon jets

- **Quark and gluon jets are physically different**
  - Multiplicity: $\langle N_{ch}\rangle_g \sim C_A/C_F \langle N_{ch}\rangle_q$
    $\rightarrow$ Gluon jets carry ~2x more particles
  - Angular profile: g-jets are **broader** (more soft radiation, larger angularity)
  - Fragmentation function: g-jets are **softer** in *z*, populate high-*z* less.
  - Color flow: g-jets are between two color partners $\rightarrow$ richer junction / denser string environment

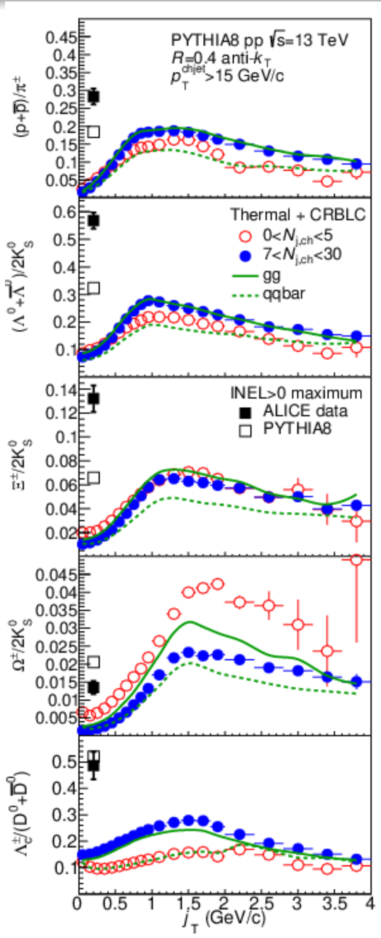




Phys.Lett.B 449 (1999) 383-400

Intermediate p_T^{jet}: B/M ratios vs. j_T

- B/M ratios vs j_T in the Thermodyn. + CR-BLC model
  ALICE acceptance, capabilities ($15<p_T^{ch,jet}<30$ GeV/c)
  Two $N_{j,ch}$ ranges



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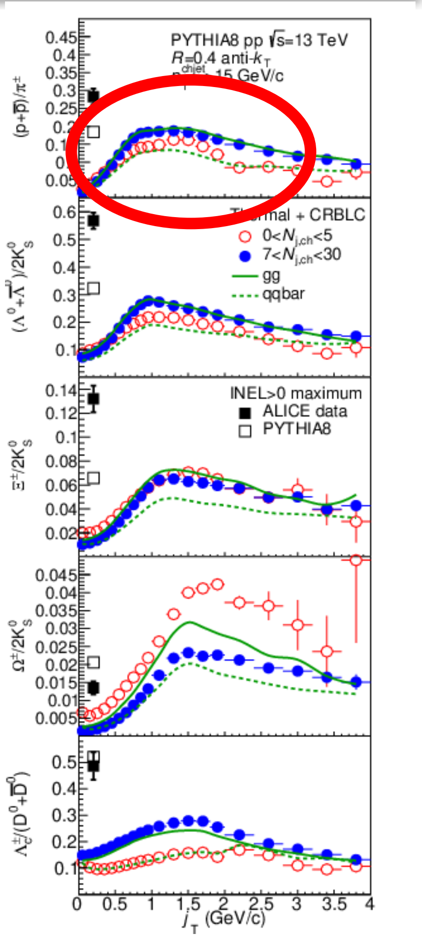
  - **Bump structure**, similar to minimum bias data vs. p_T



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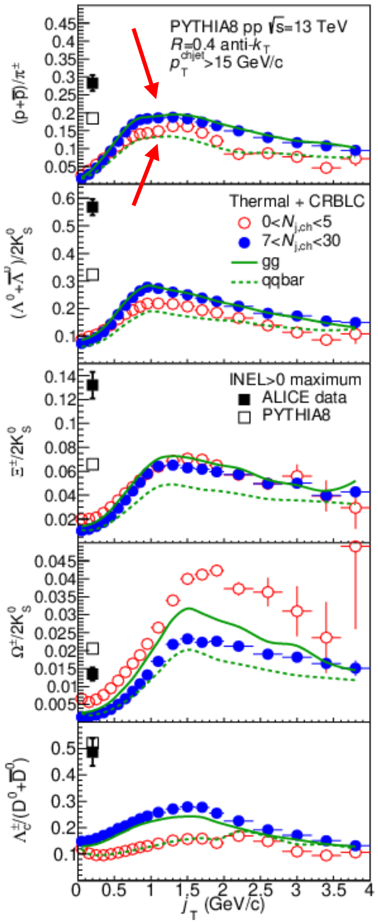
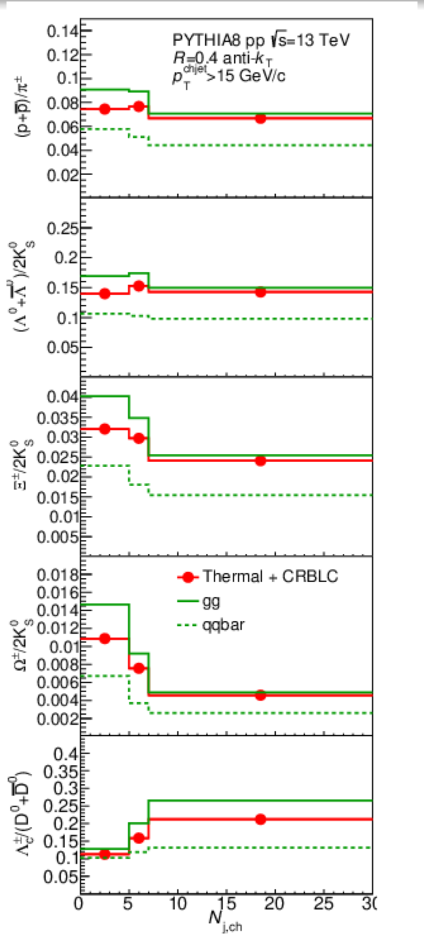
  Two $N_{j,ch}$ ranges
  - **Bump structure**, similar to minimum bias data vs. p_T
- Same observables, now decomposed by jet-initiating parton flavor
  - Gluon jets carry systematically larger B/M than quark jets at all j_T
  - Gluon jets ~ high N_{jch} and quark jets ~ low N_{jch}
  - (except for multi-strange hadrons where phase-space constraints can be at play)

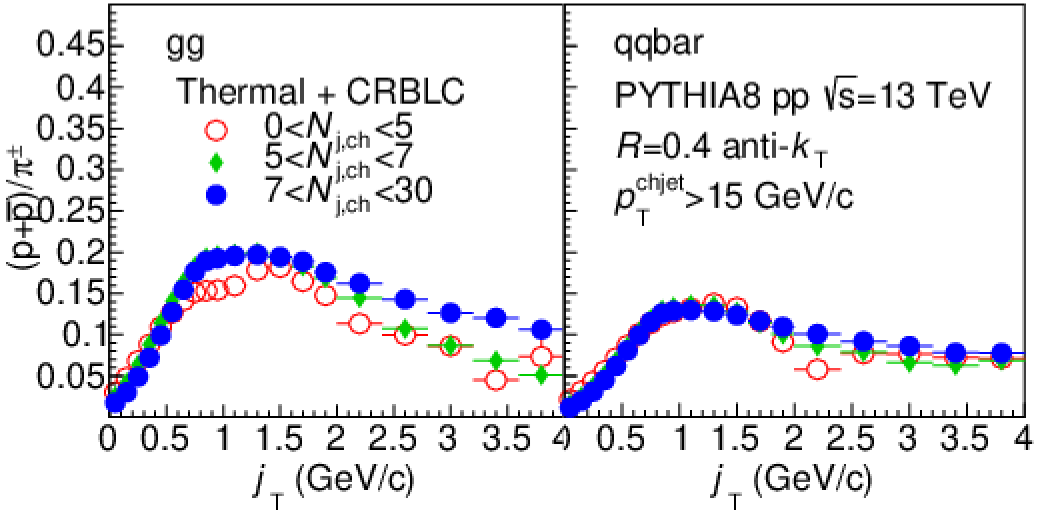


Intermediate p_T^{jet}: B/M ratios vs. N_{jch}

- Quark-jet and gluon-jet B/M ratios are only mildly $N_{j,ch}$-dependent within each sub-sample
- The q/g fraction appears to shift strongly with $N_{j,ch}$: low $N_{j,ch}$ → quark-dominated, high $N_{j,ch}$ → gluon-dominated
- The inclusive multiplicity dependence is in good part a q-jet → g-jet sample-mixture effect



B/M vs j_T split by initiating parton: gg vs q$\bar{q}$



- **Gluon jets**: clear $N_{j,ch}$ ordering of the bump amplitude — low-$N_{j,ch}$ and high-$N_{j,ch}$ curves separate.
- **Quark jets**: curves collapse — almost no $N_{j,ch}$ dependence.

→ The $N_{j,ch}$ dependence of the inclusive bump is carried by the gluon-jet sub-sample.

- Consistent with more activity along the jet axis → richer junction / denser string environment, which lives in gluon jets

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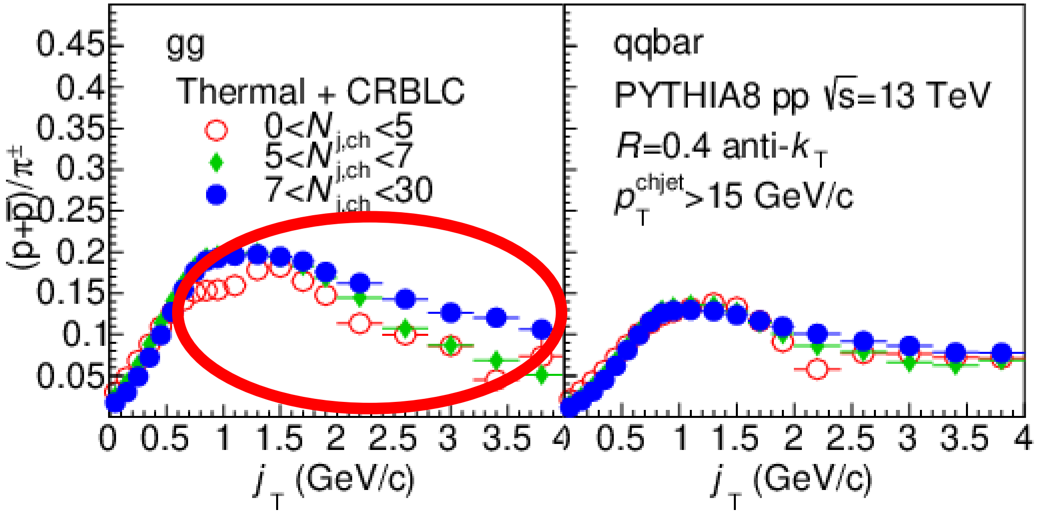

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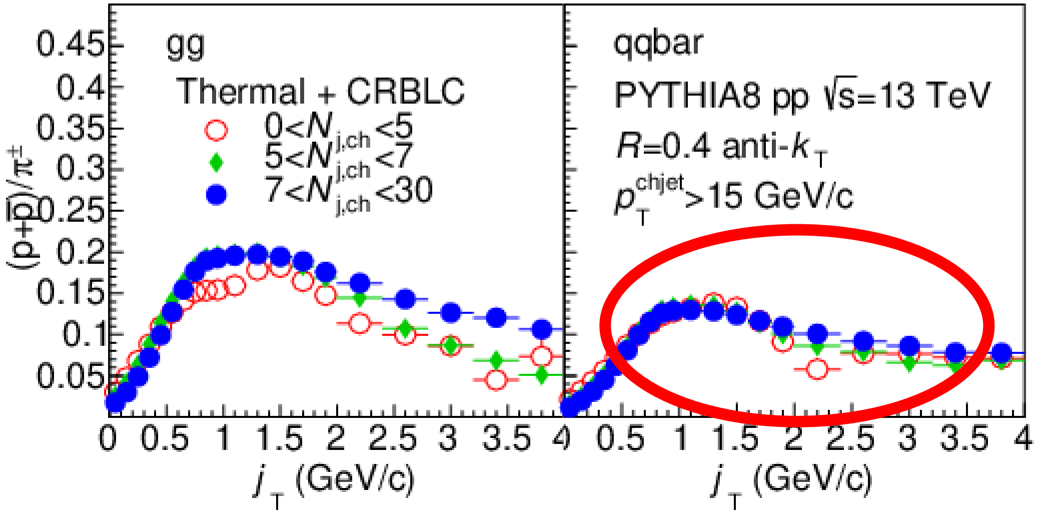

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Summary of results

Observations for high-p_T jets

- p/π, Λ^0/K^0_S, $\Xi^{\pm}/K^0_S$ in hard pp jets show a bump structure vs j_T and a rise vs $N_{j,ch}$ — reminiscent of the radial-flow-like patterns seen vs. event multiplicity, but produced without flow or MPI
- The thermodynamical fragmentation model with close packing reproduces the rise
- junction-allowing tunes drive Λ_c^+/D^0 at low j_T, matching ALICE p_T-dependent pattern in minimum bias

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Decomposing the multiplicity dependence

- B/M ratios decomposed into quark-initiated ($q\bar{q}$) and gluon-initiated (gg) jet sub-samples for the first time in this framework.
- Within each sub-sample, the B/M ratios are nearly $N_{j,ch}$-independent.
- The inclusive multiplicity dependence is dominantly a q-jet → g-jet sample-mixture effect along $N_{j,ch}$
- The $N_{j,ch}$ ordering of the bump structure in j_T is in the gluon-jet sub-sample; quark-jet curves collapse
- Note: Same B/M ratios vs longitudinal $z_{||}^{ch}$ are essentially $N_{j,ch}$-independent → multiplicity structure lives in the transverse direction (j_T)

Implications: jet flavor or collectivity?

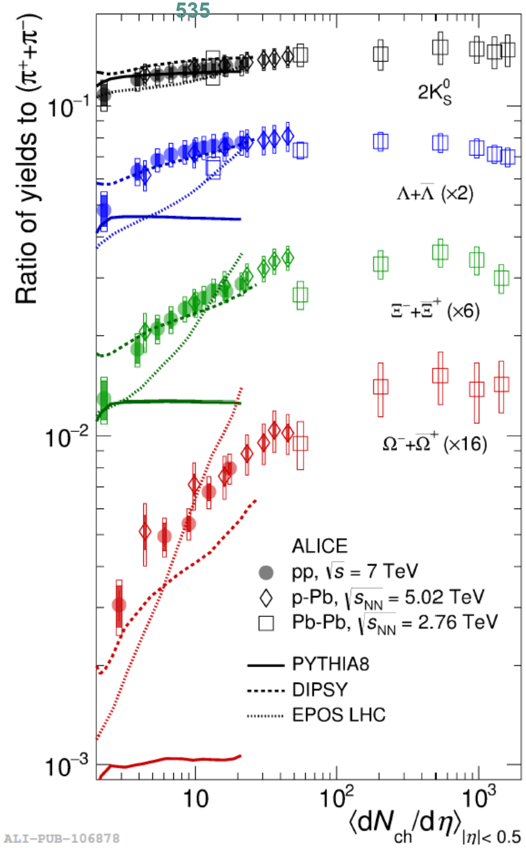
- $N_{j,ch}$-dependent **baryon enhancement** in hard pp jets is reproduced by PYTHIA **without any collective ingredient** — driven by junction/string density physics and a changing q/g jet mixture
- → Multiplicity-dependent B/M enhancement is not a unique signature of collectivity in small systems
- The same **q/g sample-mixture** mechanism can **bias correlation observables**:
  - Quark and gluon jets differ in $\langle N_{j,ch} \rangle$, angular profile, balance, intra-jet azimuthal correlations
  - Higher $N_{j,ch}$ bins are gluon-jet-enriched → multiplicity-dependent intra-jet correlation observables carry a built-in q→g bias
- Proposed **experimental test**:
  - Measure B/M vs. $N_{j,ch}$ in separately tagged quark-jet (γ+jet, dijet) and gluon-jet samples
  - First step on the experimental side: ALICE jets with ID hadrons vs. j_T at $15 < p_T^{ch,jet} < 30$ GeV/c
  - The same q/g-tagged strategy applies to other intra-jet correlation observables such as v_2^*


Thank you!

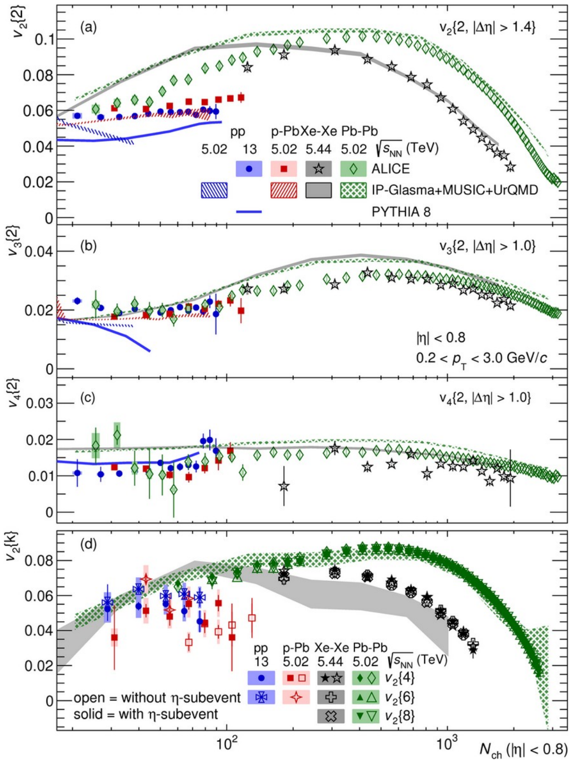
Collectivity in small collision systems

- **Azimuthal anisotropy:** considered a tell-tale signature of the QGP
- **High-multiplicity pp collisions:** similar signatures to those observed in heavy-ion collisions
  - **Strangeness enhancement**
  - Long-range multiparticle correlations, "**flow**"
- **Is there a quark-gluon plasma in pp collisions?**
- Or are vacuum-QCD effects responsible for this behavior

Nature Phys. 13 (2017) 535



Phys. Rev. Lett. 123 (2019) 142301

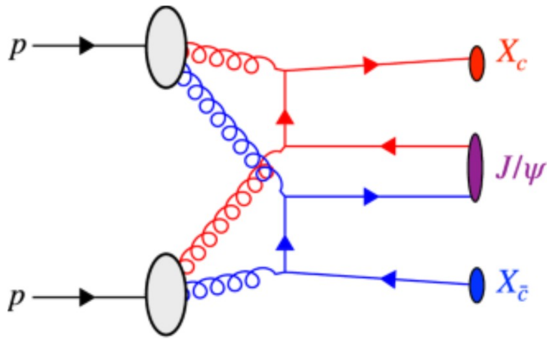


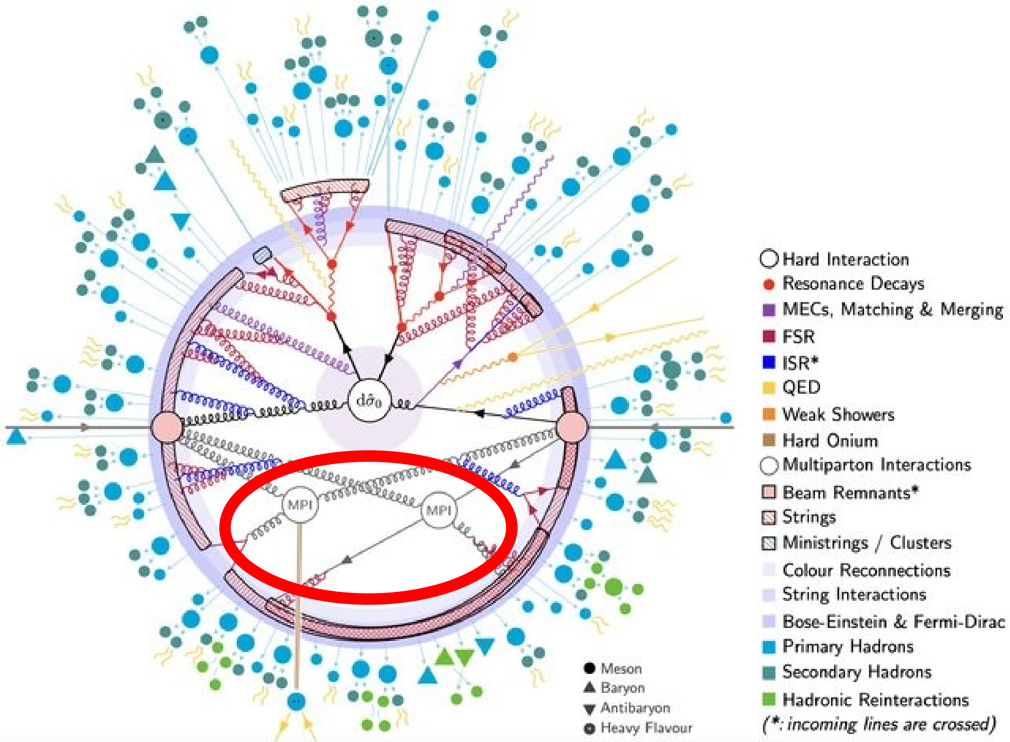
PYTHIA 8

- A MC event generator, simulating the full evolution of the collision

1) Hard process
2) Parton shower
3) Hadronization
4) Decays

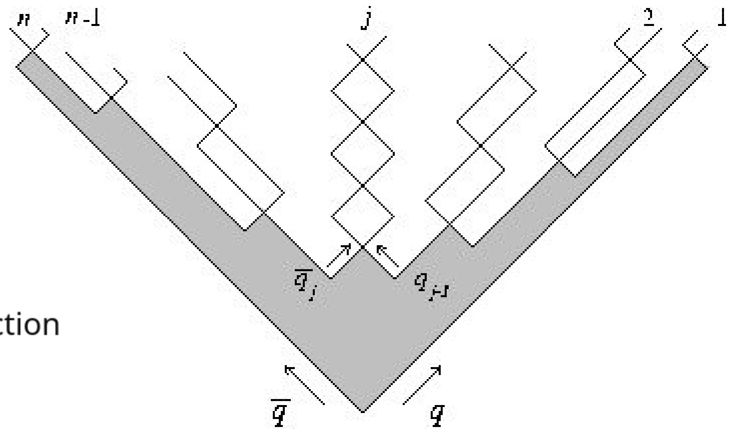
+ Multi-parton interactions





PYTHIA: Hadronization

- **Lund fragmentation**
  - Color field between quarks: flux tube
  - Breaking with quantum tunnelling into a chain of hadrons



$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{bm_T^2}{z}\right)$$

z: Light-cone momentum fraction

m_T: Transverse mass

a, b: Tuning parameters

- **Thermodynamical string fragmentation**
  - Hadrons produced with Boltzmann-like probability
  - Mimics thermalized hadron production

$$P(E) \propto \exp\left(-\frac{E}{T}\right)$$

T: "Temperature" parameter (~170 MeV typical)

PYTHIA: Color reconnection

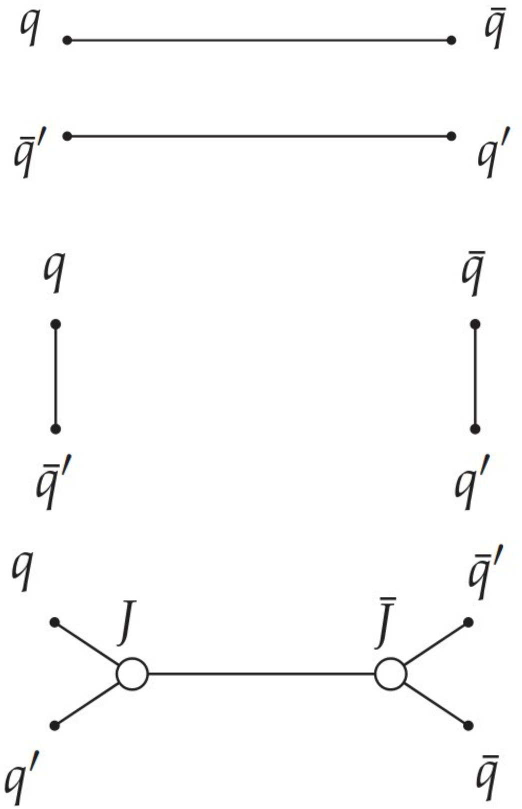
- Color flow is not traced during hadronization
  - Different color connections may be possible between a set of quarks

- “Afterburner” step: color reconnection
  - Minimizes overall color string length λ

1) MPI-based model
  - tests possibilities within range r

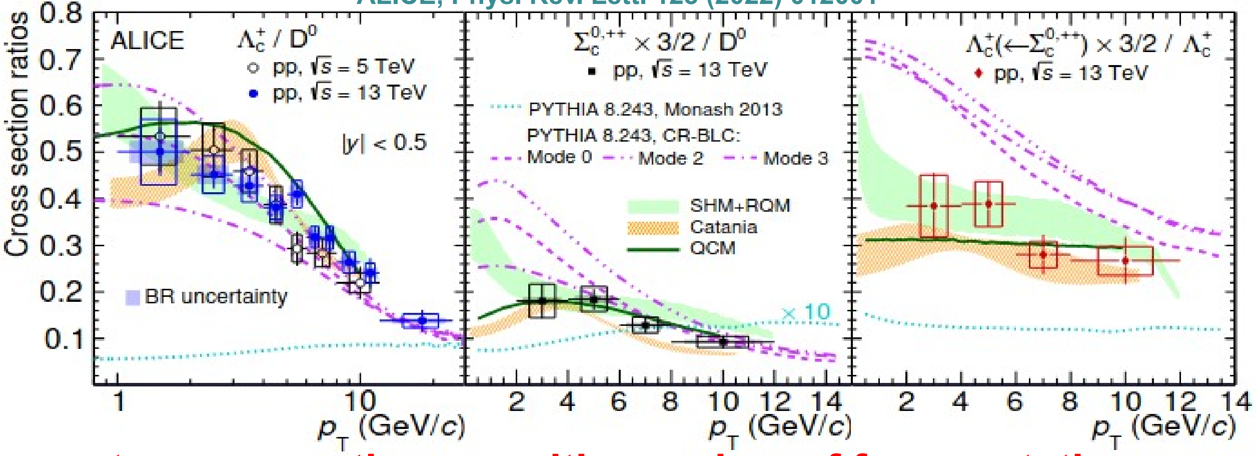
2) **QCD-based CR scheme**
(beyond leading color approximation)
  - Tests all possibilities allowed by $SU(3)_{\mathrm{color}}$
  - Color junctions enhance baryon production

  - JHEP 08 (2015) 003



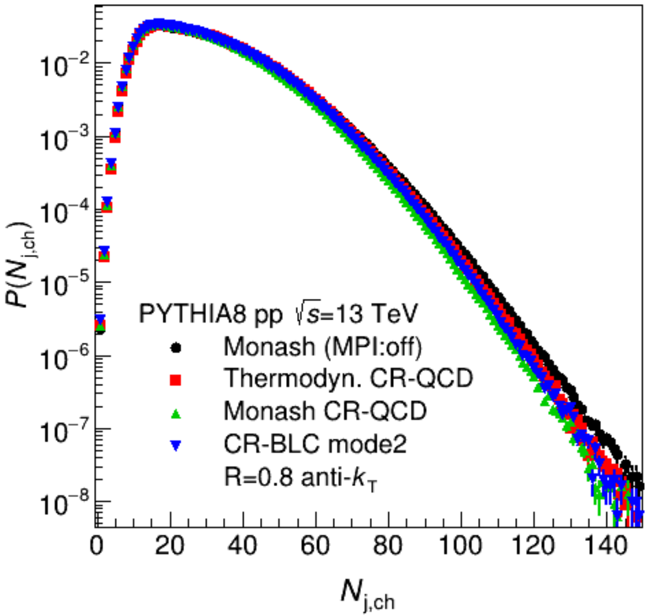
Charm baryon enhancement

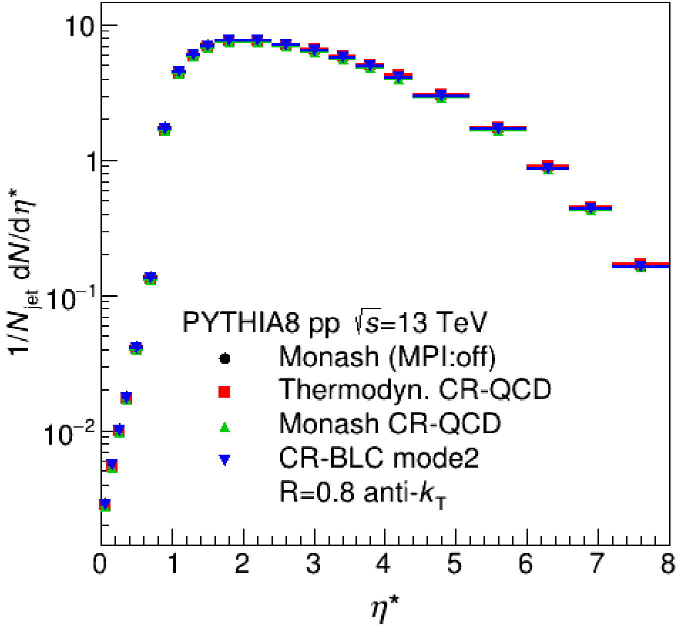
ALICE, Phys. Rev. Lett. 128 (2022) 012001



- **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!**
- **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

High-p_T jets: jet reconstruction



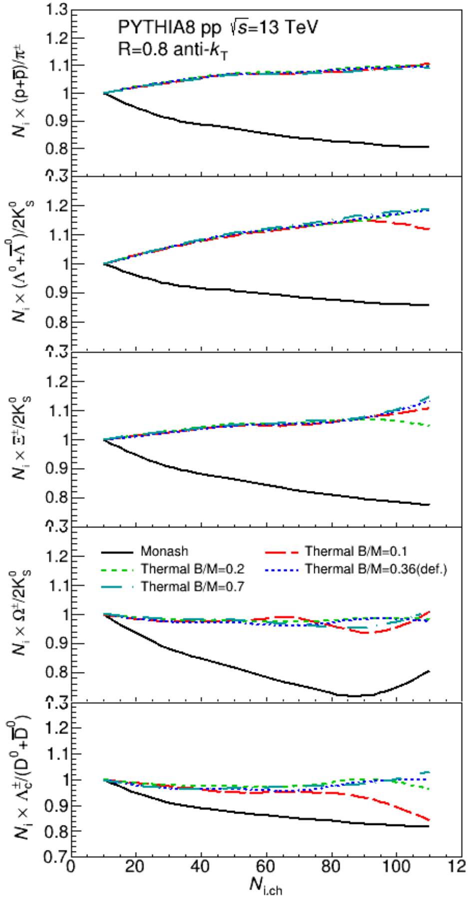


- Jet reconstruction: anti-k_T algorithm and R=0.8, p_T^{jet} > 550 GeV/c (CMS)
  - Multi-parton interactions (MPI) off to suppress the underlying event
  - Jet multiplicities and η* distributions are relatively uneffected by the choice of model

Results: double ratios

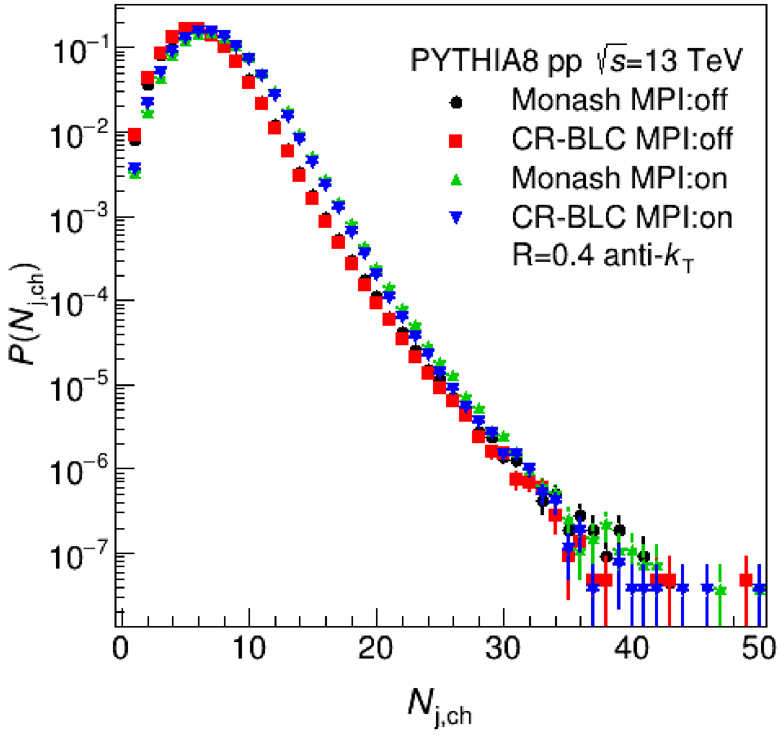
Normalized j_T-integrated baryon-to-meson ratios as a function of N^j_{ch} for different models

- Varied input B/M ratios
- Ratios normalized to the first point
- Trends for all the B/M ratios are the same, just the normalization changes
- Input B/M ratios do not have a direct effect on multiplicity-dependent baryon numbers



Jets in ALICE

- Focus on ALICE HF-jets
  - Charged jets 15 < $p_T^{ch,jet}$ < 30 GeV
  - (matches current D^0, Λ_c^+ jets)
  - Jet reconstruction: Anti-k_T R=0.4
- MPI makes a difference!
  - Underlying event has a clear role in this energy regime



Fragmentation function

- B/M ratios, as a function of $z_{||}^{ch}$ (longitudinal momentum fraction along the jet axis), in three $N^{j,ch}$ ranges, Thermodyn.+CR-BLC.

- Light-flavor B/M (p/π, Λ^0/K^0_S): essentially N_j,ch-independent at all z — different from what jT shows
→ The multiplicity-dependent B/M structure is in the transverse-to-jet direction (j_T), not in the longitudinal sharing Consistent with a fragmentation-/string-density-driven origin rather than a longitudinal hardening

- Multi-strange (Ξ/K^0_S, Ω/K^0_S): mild $N_{j,ch}$ dependence at intermediate-to-high z.

- Heavy flavor (Λ_c^0/D□): clear $N_{j,ch}$ dependence; the model trend reproduces the ALICE in-jet measurement within uncertainties.