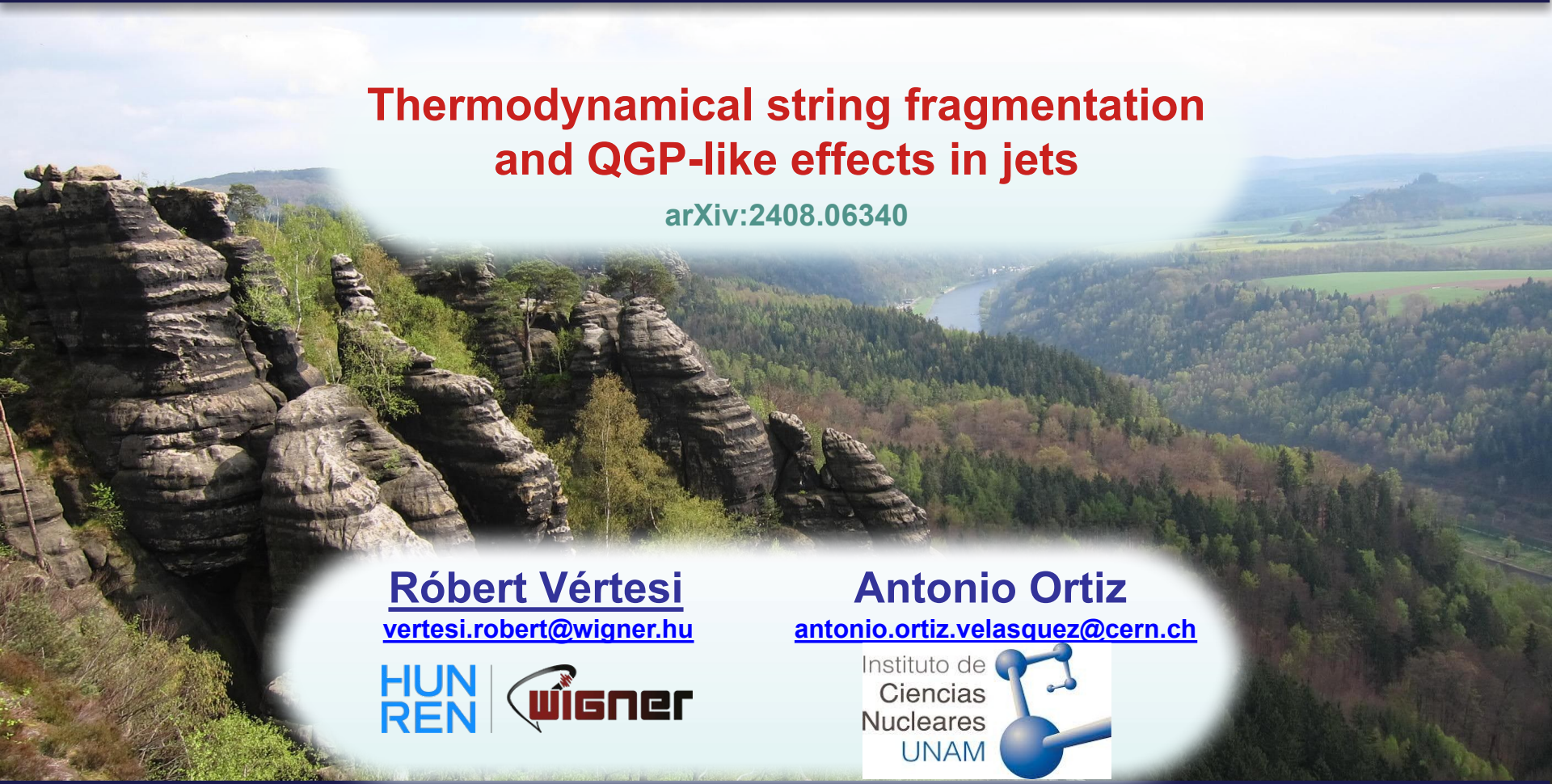
Thermodynamical string fragmentation and QGP-like effects in jets

arXiv:2408.06340



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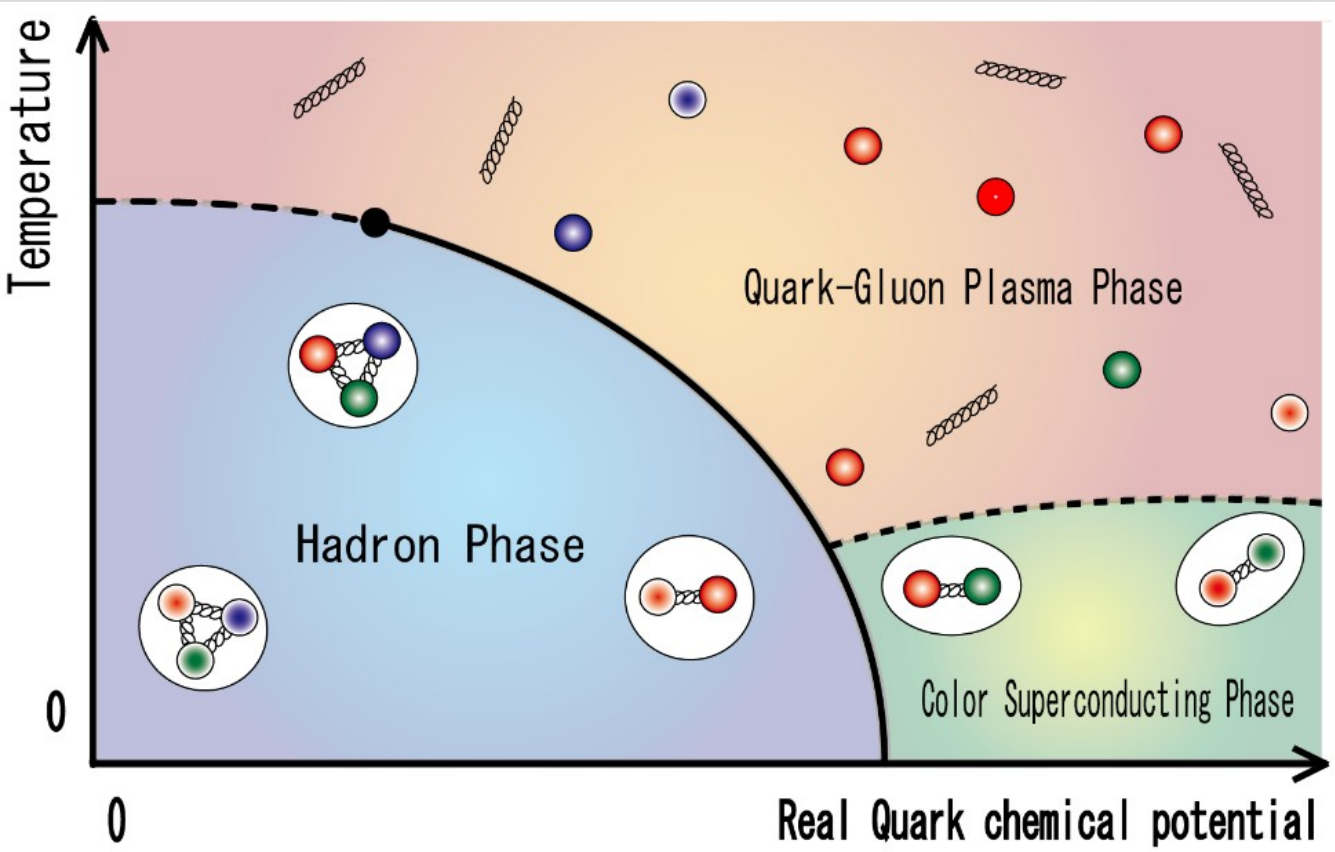
The phase diagram of QCD



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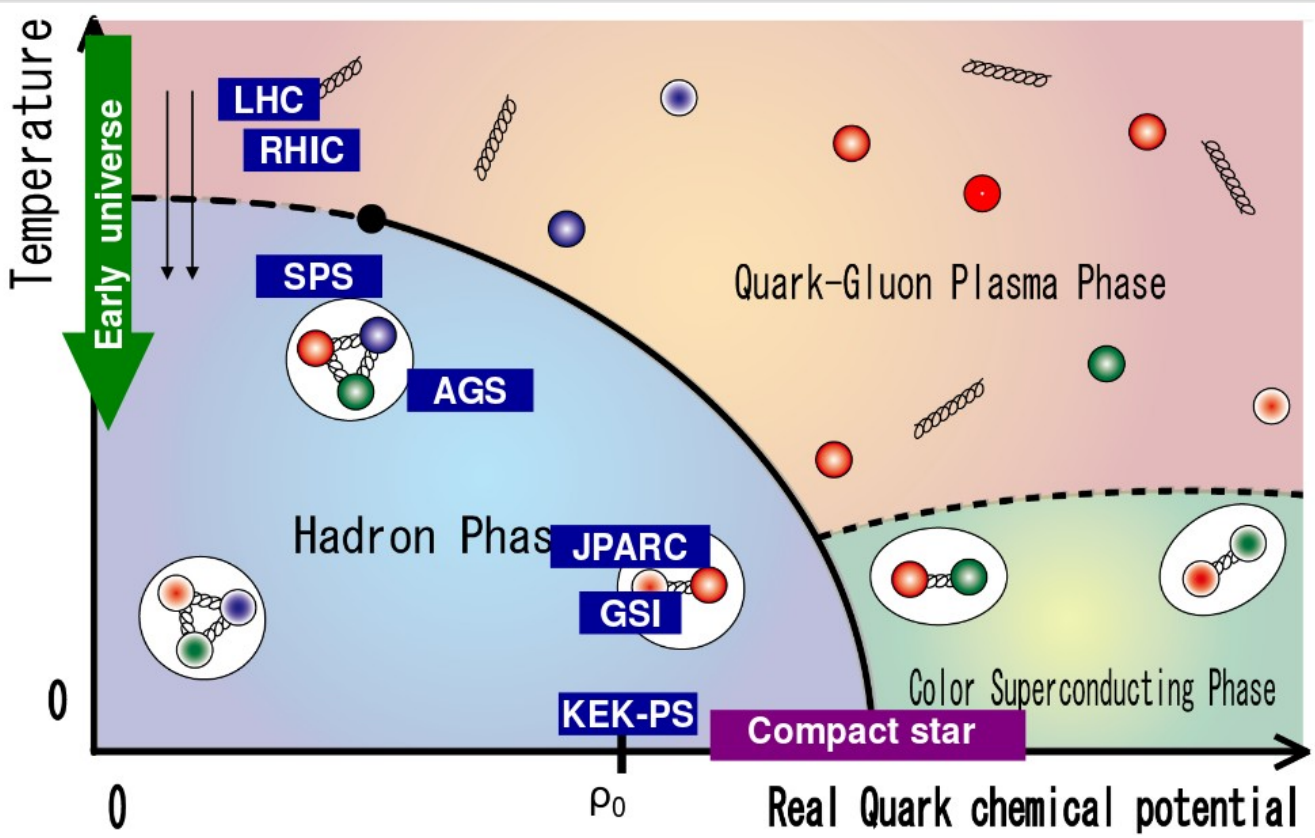
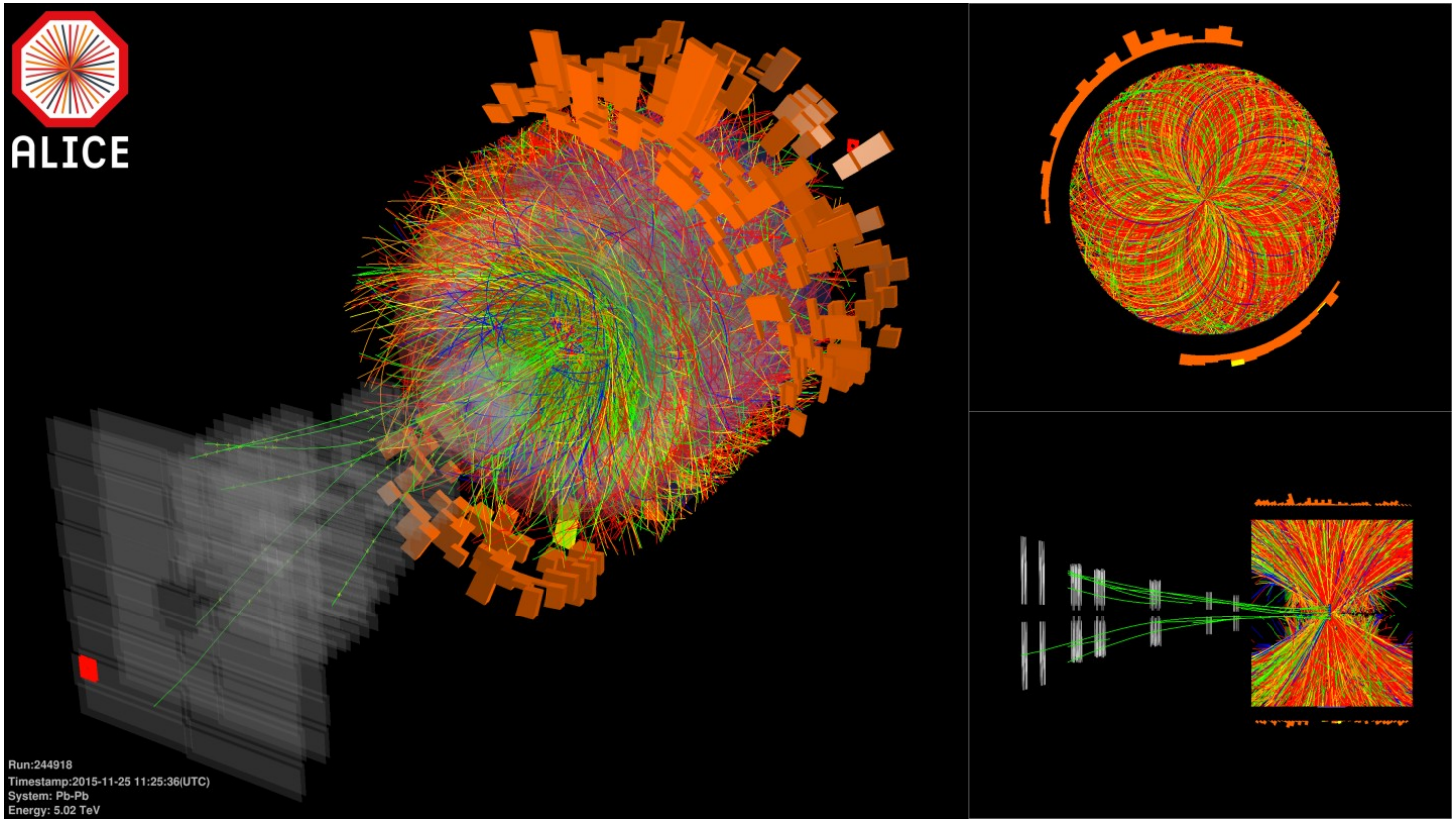


Modern day accelerators: recreate the Quark Gluon Plasma

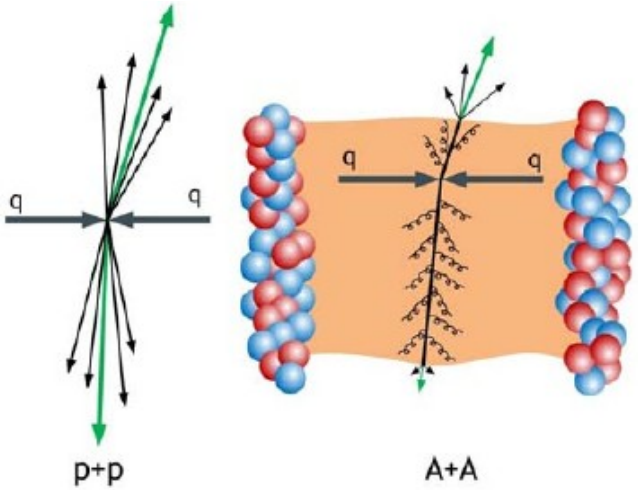
Reconstructed heavy-ion collision



ALICE@LHC central $\sqrt{s_{NN}}$=5.02 TeV Pb+Pb collision

Probing the QGP

- **"Hard" processes**
  - few, high-momentum particles
  - early production in well-known pQCD processes
  - high permeability
  - **Tomography of the sQGP, modification in the medium**



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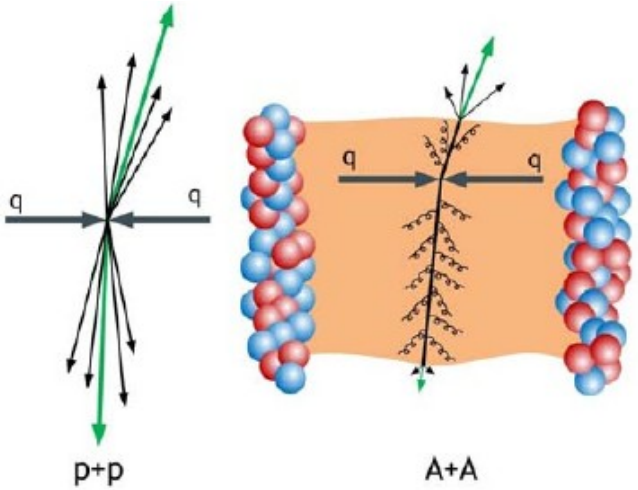

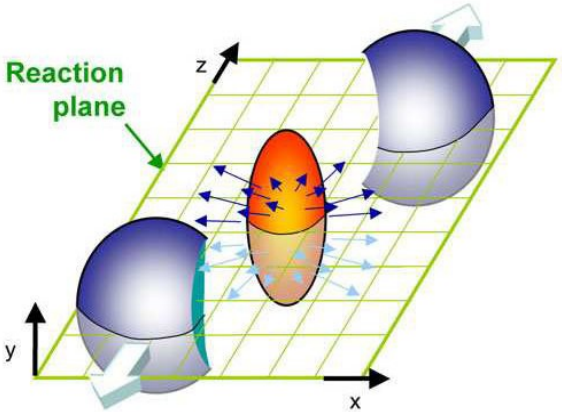

- **"Soft" processes**
  - Many, low-momentum particles
  - From the later stages
  - **Thermal behavior**
  - **Collective dynamics ("flow")**

Small collision systems

- **High-multiplicity pp collisions:** similar signatures to those observed in heavy-ion collisions where the formation of a quark-gluon plasma (QGP) is expected:

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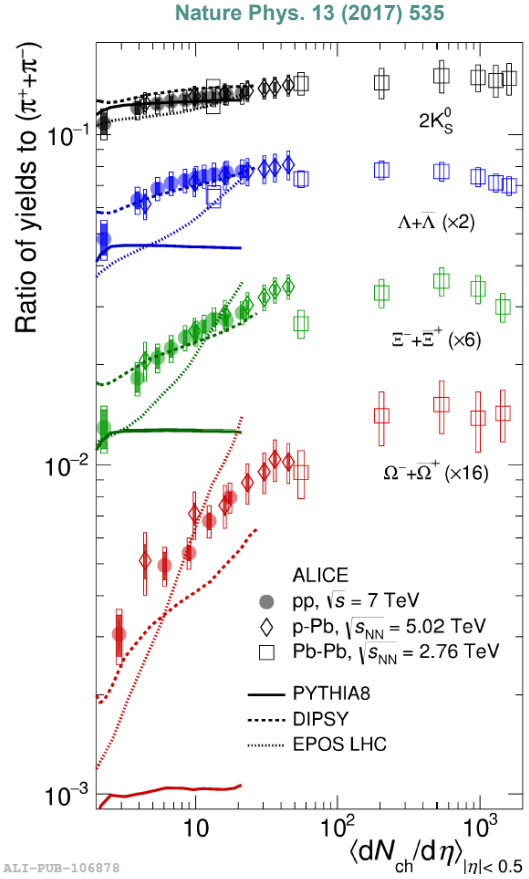

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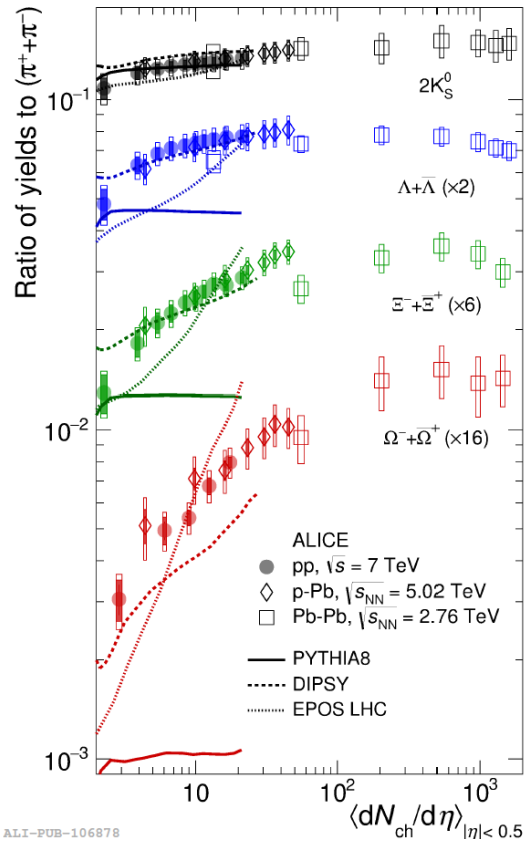
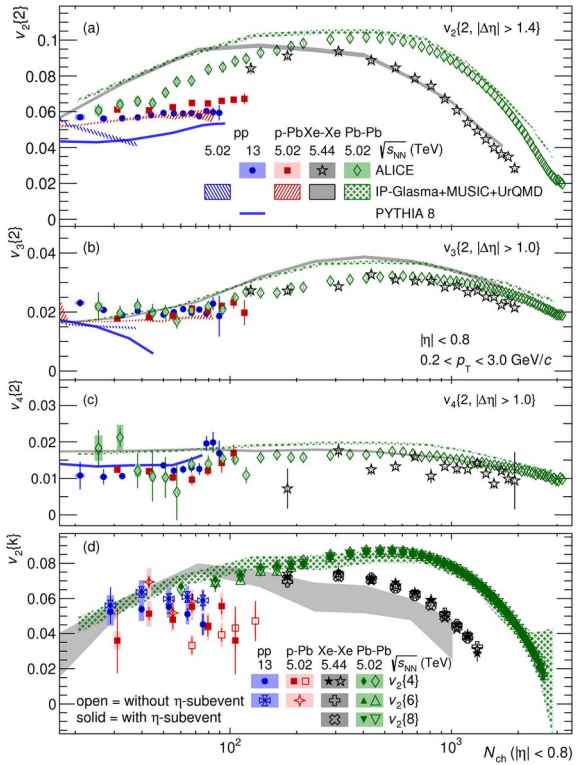
Nature Phys. 13 (2017) 535



Phys. Rev. Lett. 123 (2019) 142301



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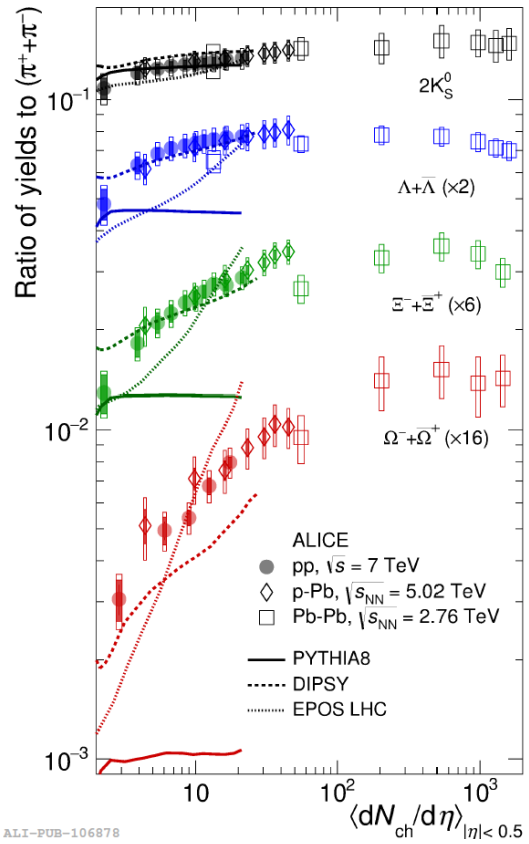
- **Strangeness enhancement**
- Long-range multiparticle correlations, "**flow**"
- **Is there a quark-gluon plasma in pp collisions?**
- Or are vacuum-QCD effects responsible for this behavior

Nature Phys. 13 (2017) 535



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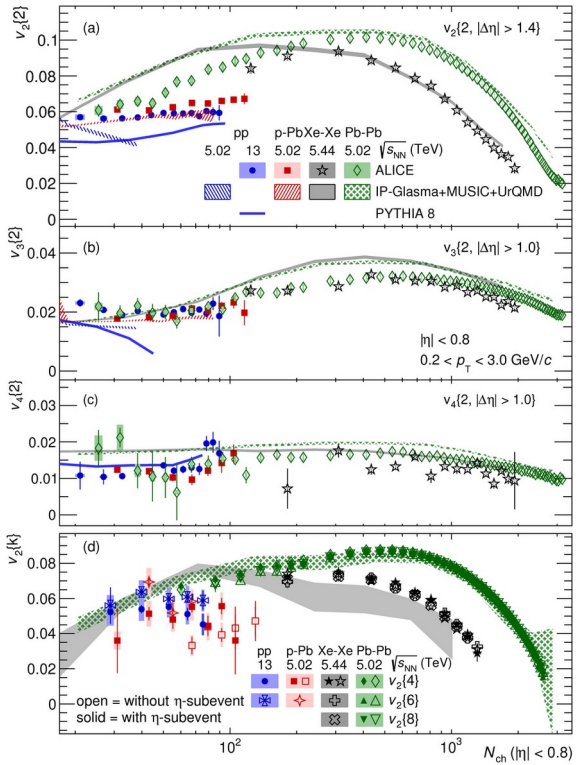
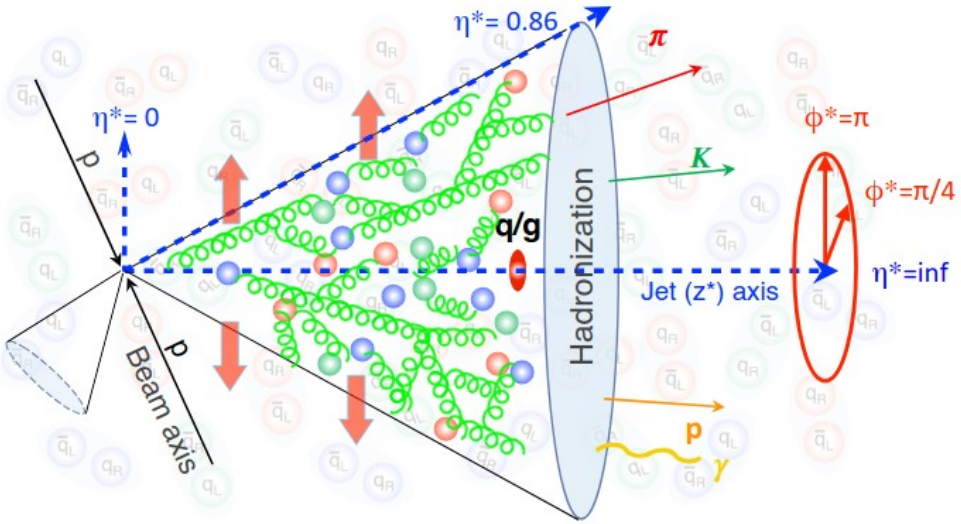


Collective system from a single parton?

- 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

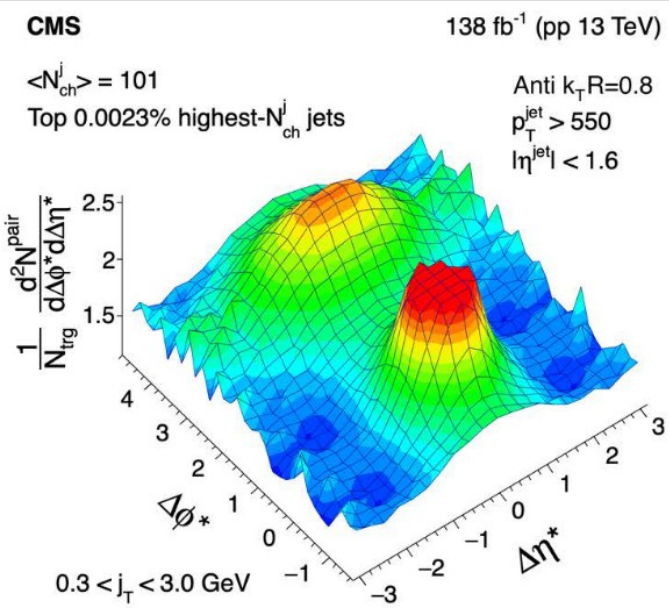
A. Baty et al., Phys.Rev.C 107 (2023) 6, 064908



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*

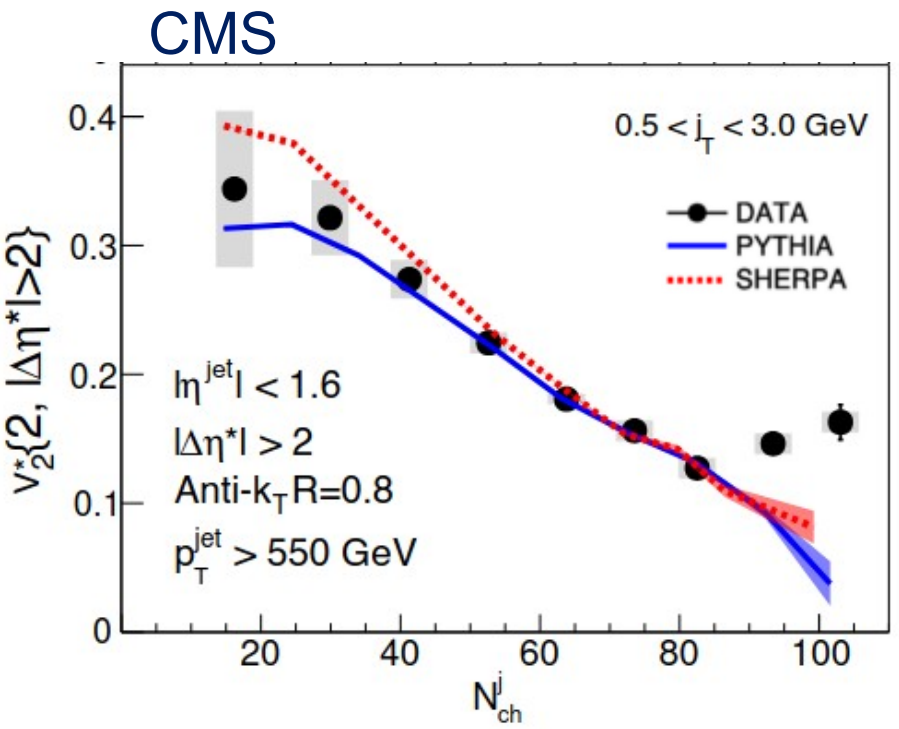
CMS angular correlations in the jet frame



- CMS measured angular correlations, to deduce intra-jet azimuthal anisotropy (v_2*, elliptic flow)
- **Phys.Rev.Lett.133(2024)14,142301**

CMS angular correlations in the jet frame

- Substantial v_2^* is seen
- For low and medium jet multiplicity (N^j_{ch}), the trend is well understood by models



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

CMS angular correlations in the jet frame

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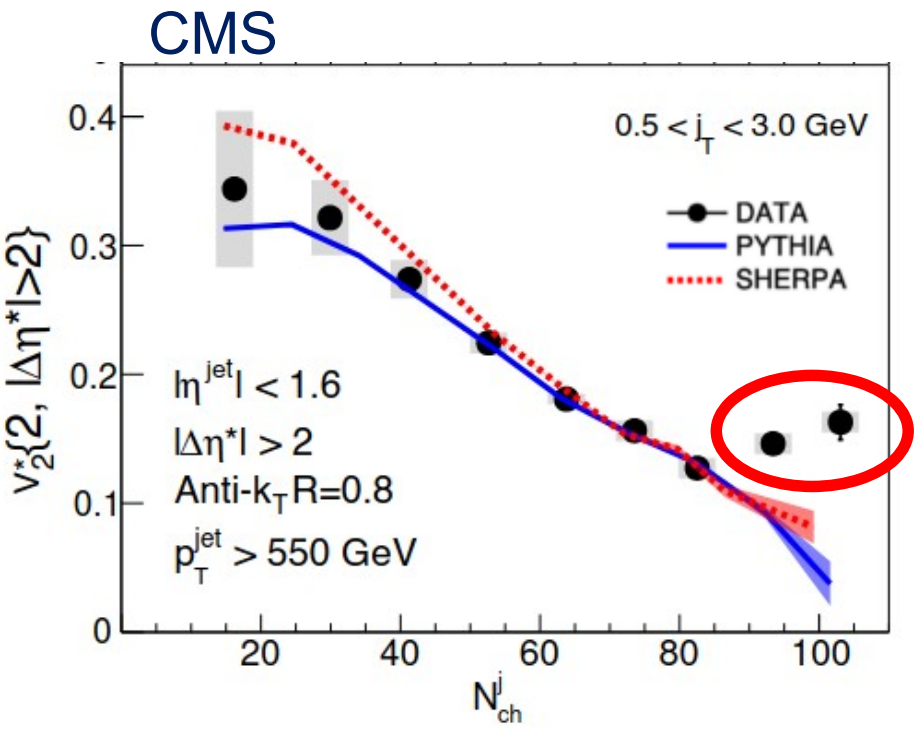
- A high-N^j_{ch} increase is present compared to predictions



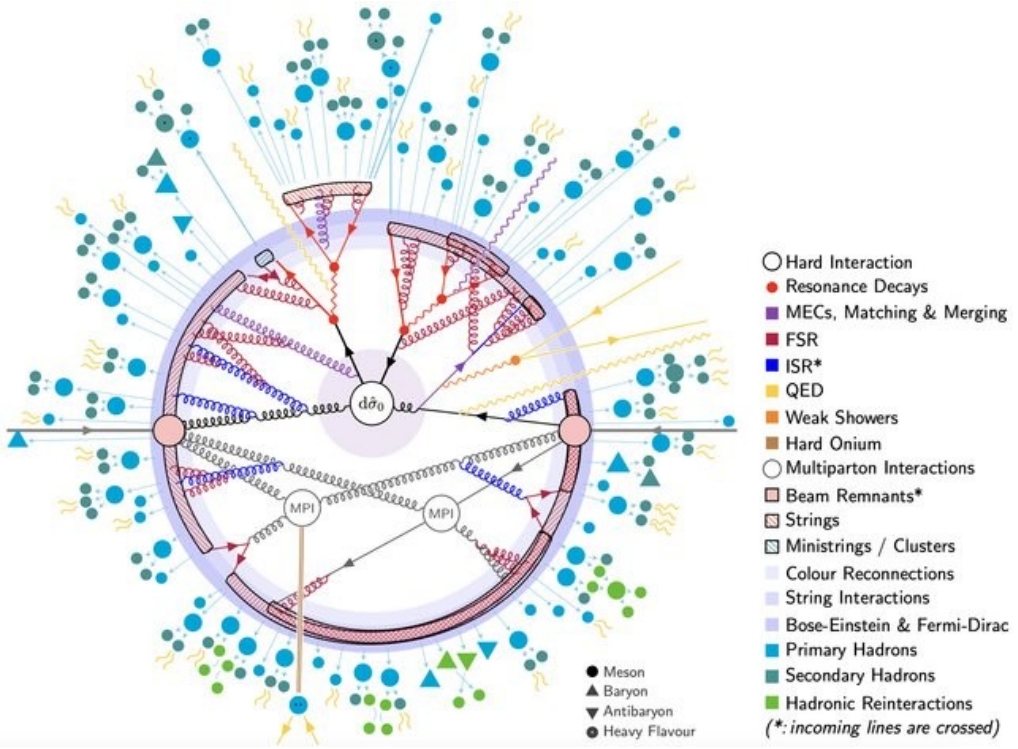
Phys.Rev.Lett.133(2024)14,142301

PYTHIA 8

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

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

Comput.Phys.Commun. 191 (2015) 159-177



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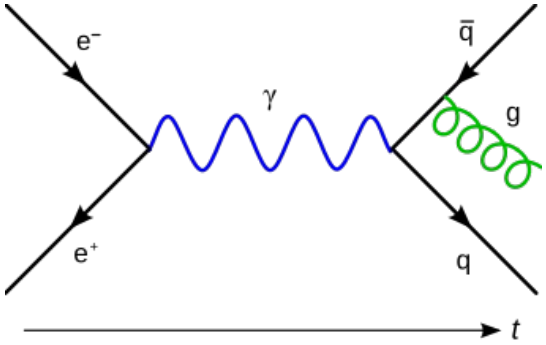

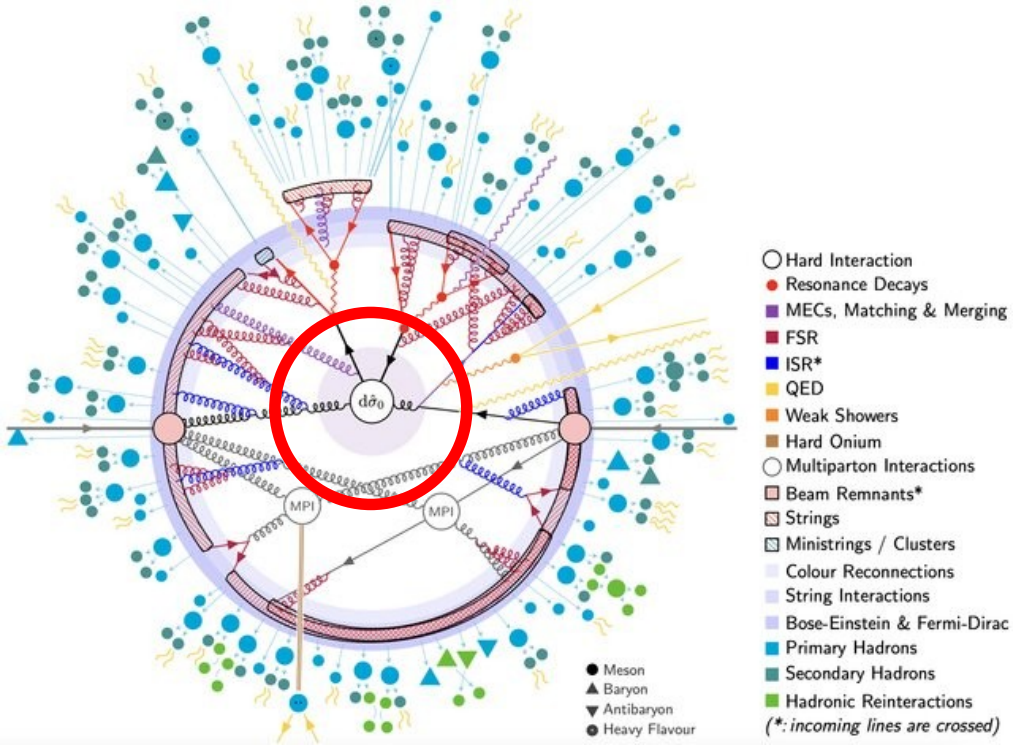

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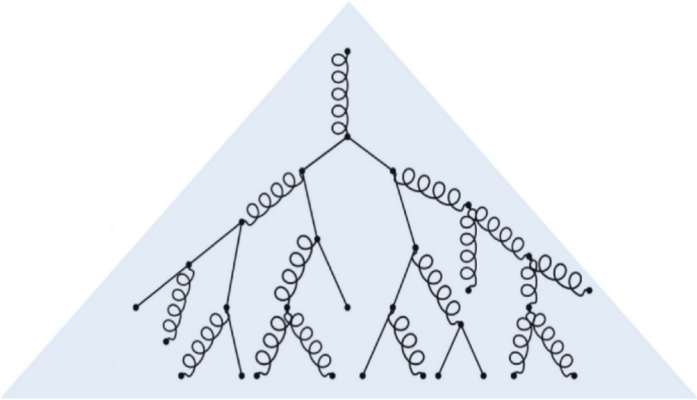

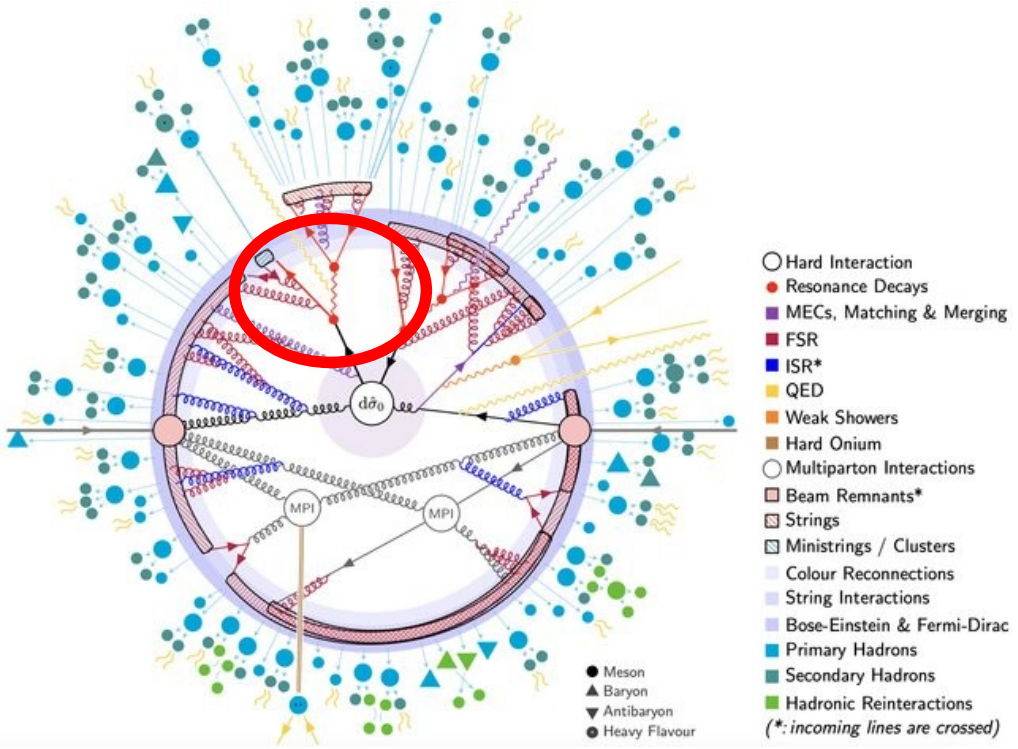

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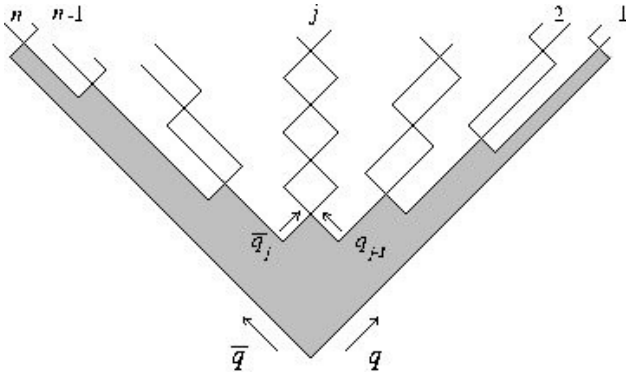

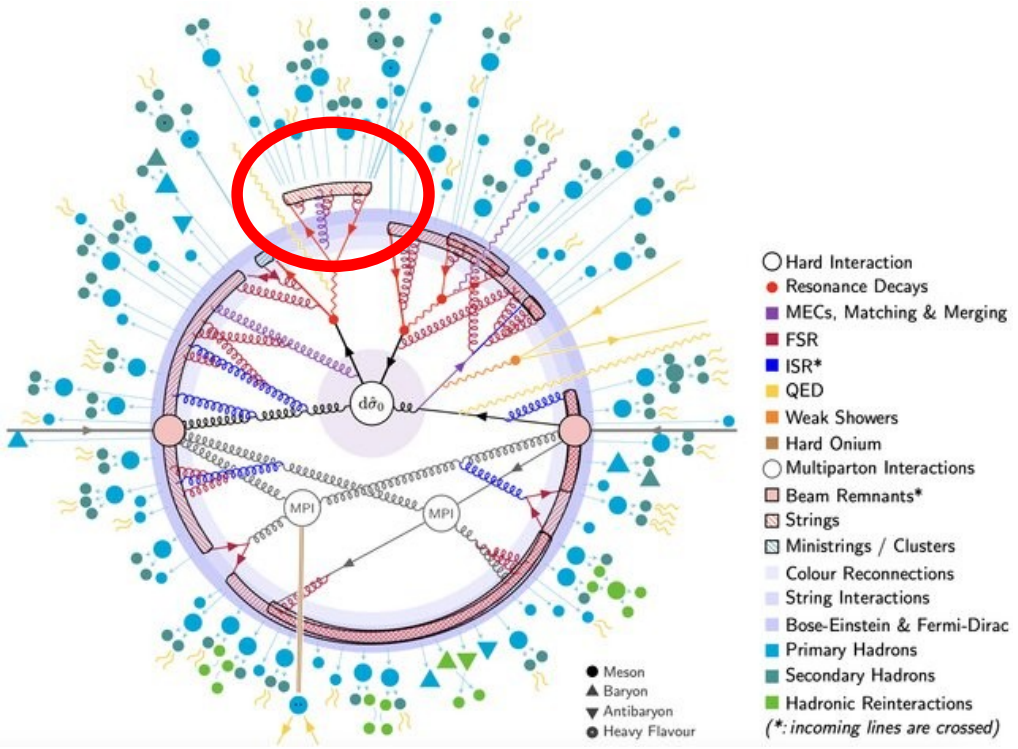

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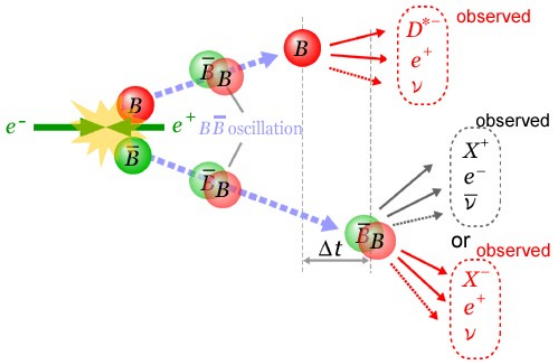

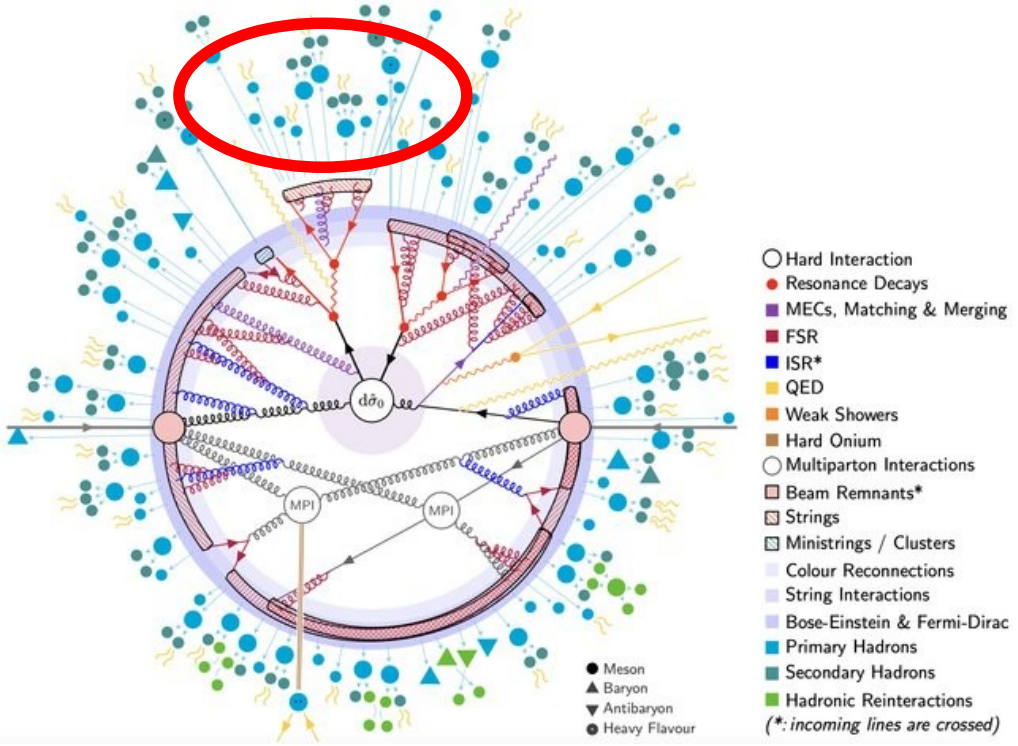

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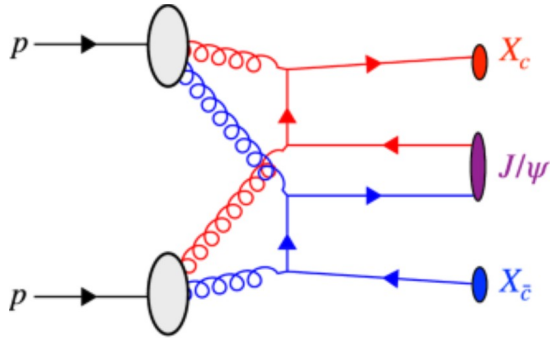
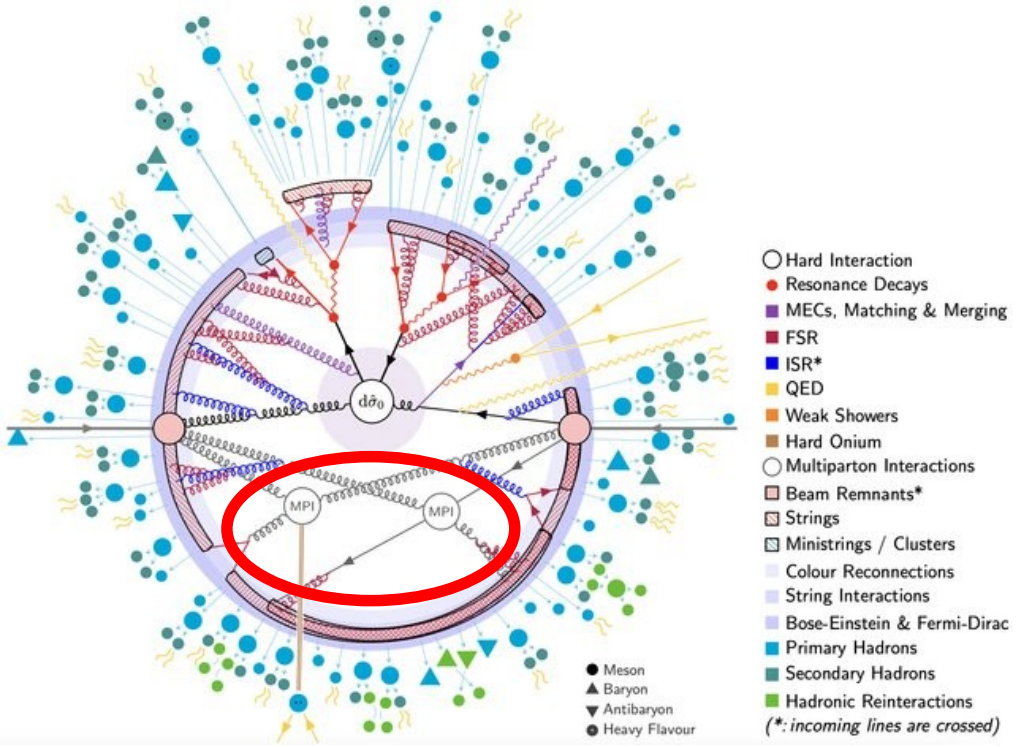
+ Multi-parton interactions





PYTHIA: Hadronization

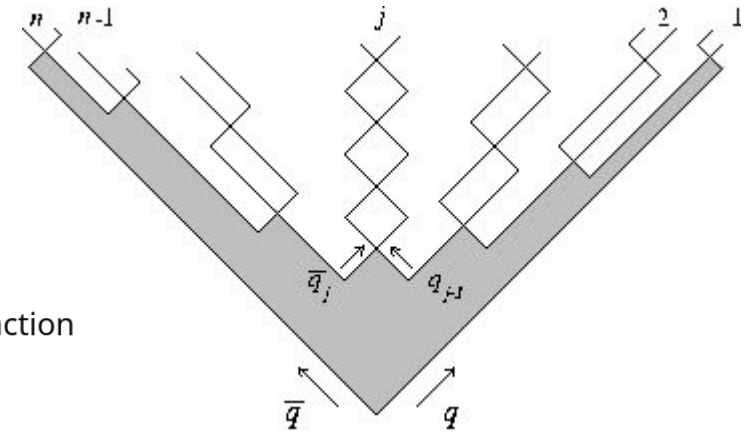
- Lund fragmentation
  - Color field between quarks: flux tube
  - Breaking with quantum tunnelling into a chain of hadrons

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

z: Light-cone momentum fraction

m_T: Transverse mass

a, b: Tuning parameters



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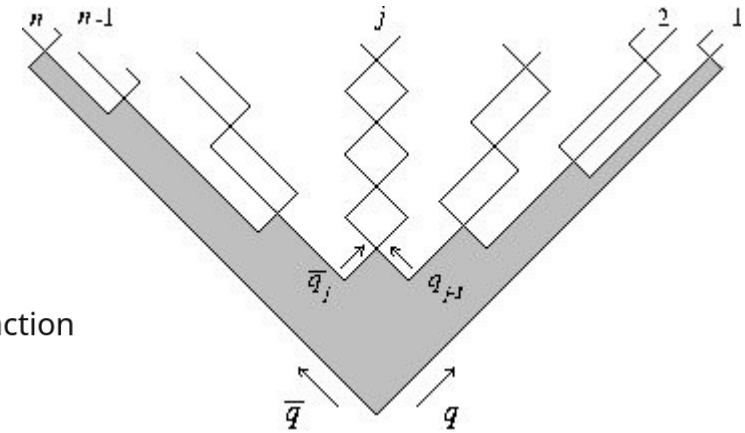


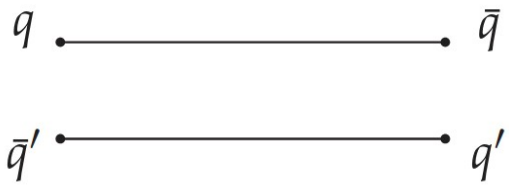
- Thermodynamical string fragmentation
  - Hadrons produced with Boltzmann-like probability
  - Mimics thermalized hadron production

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

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



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  - Minimizes overall color string length λ

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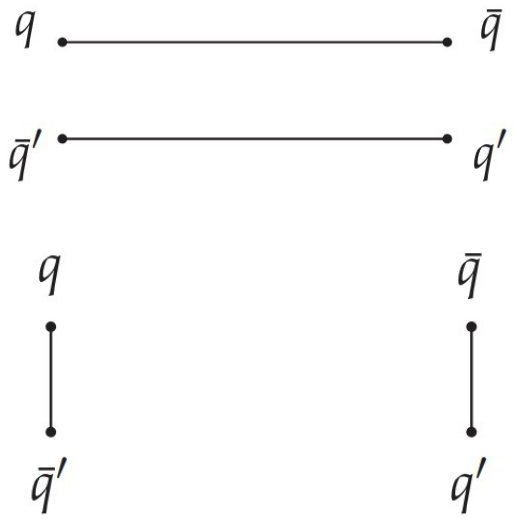

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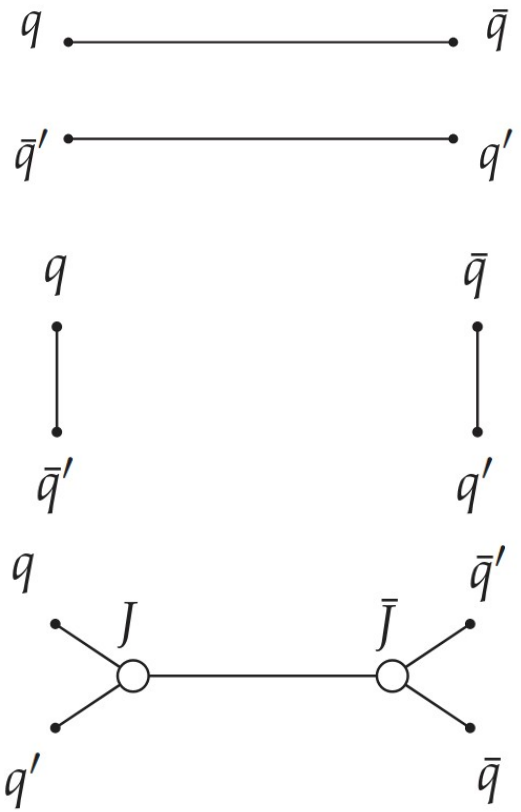
1) MPI-based model
  - tests possibilities within range r

2) QCD-based CR scheme
(beyond leading color approximation)
  - Tests all possibilities allowed by $SU(3)_{color}$
  - Color junctions enhance baryon production
  - JHEP 08 (2015) 003



Simulations: models

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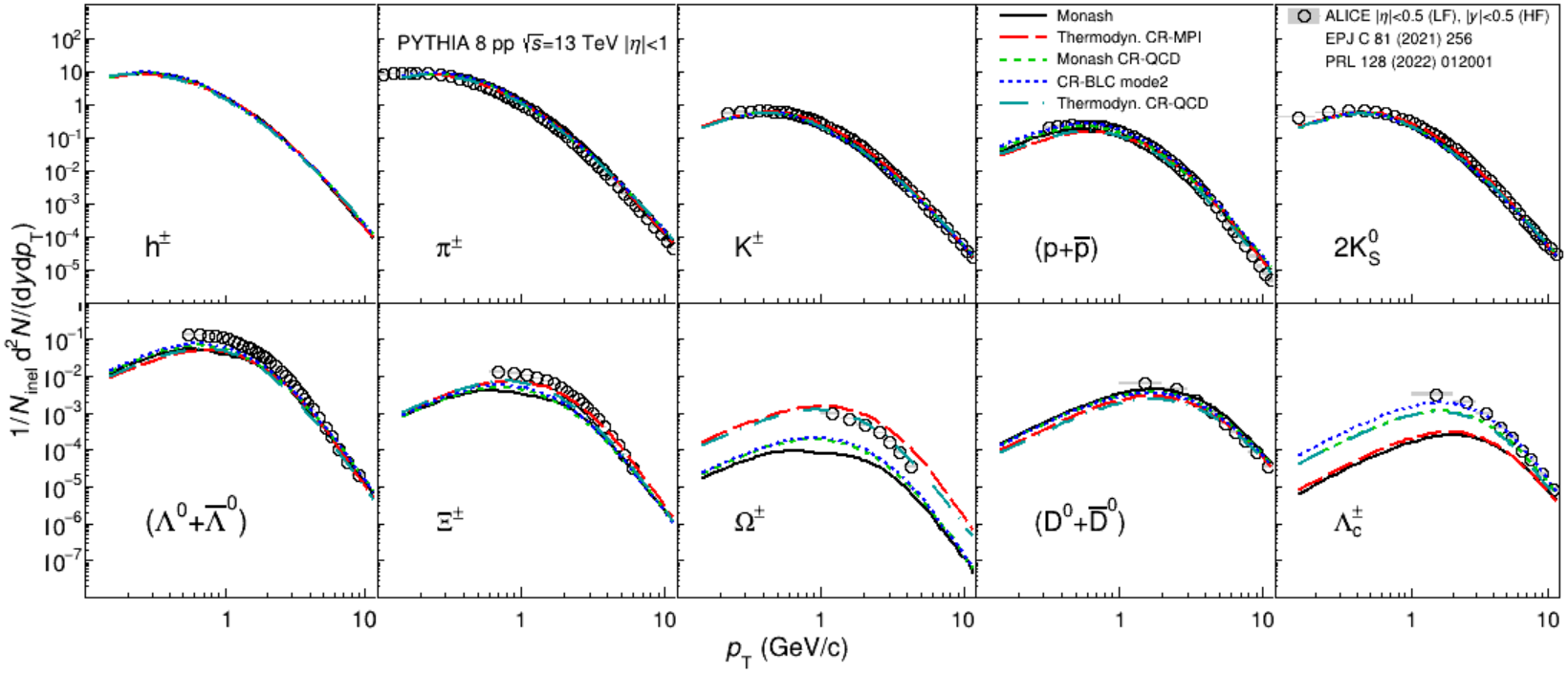
- Further model settings were explored
  - QCD-scheme color reconnection with default settings (CR-QCD), as well as CR-BLC mode 2 that is tuned to describe heavy-flavor baryon sector: allow for color string junctions
  - Thermodynamical string fragmentation
    with and without close packing
    (more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

Simulations: validation on minimum-bias data



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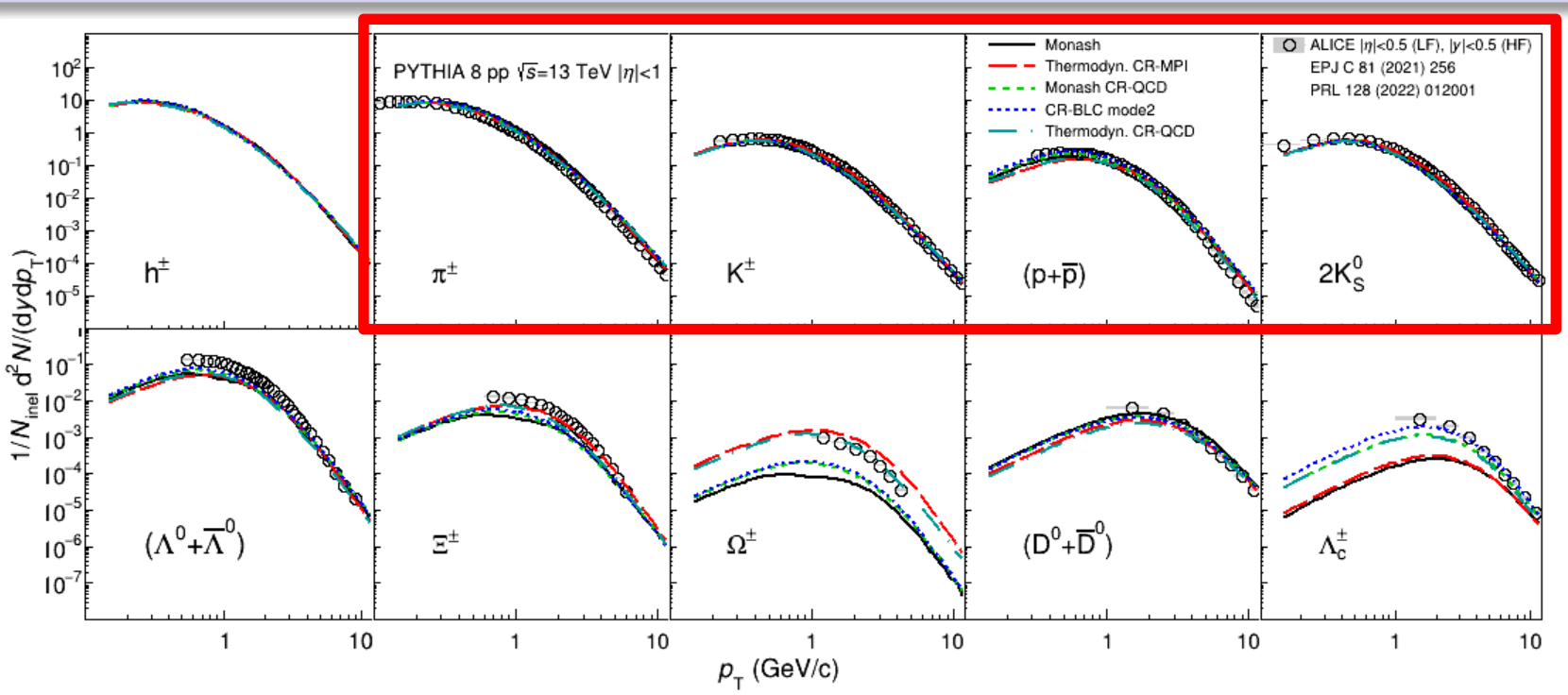

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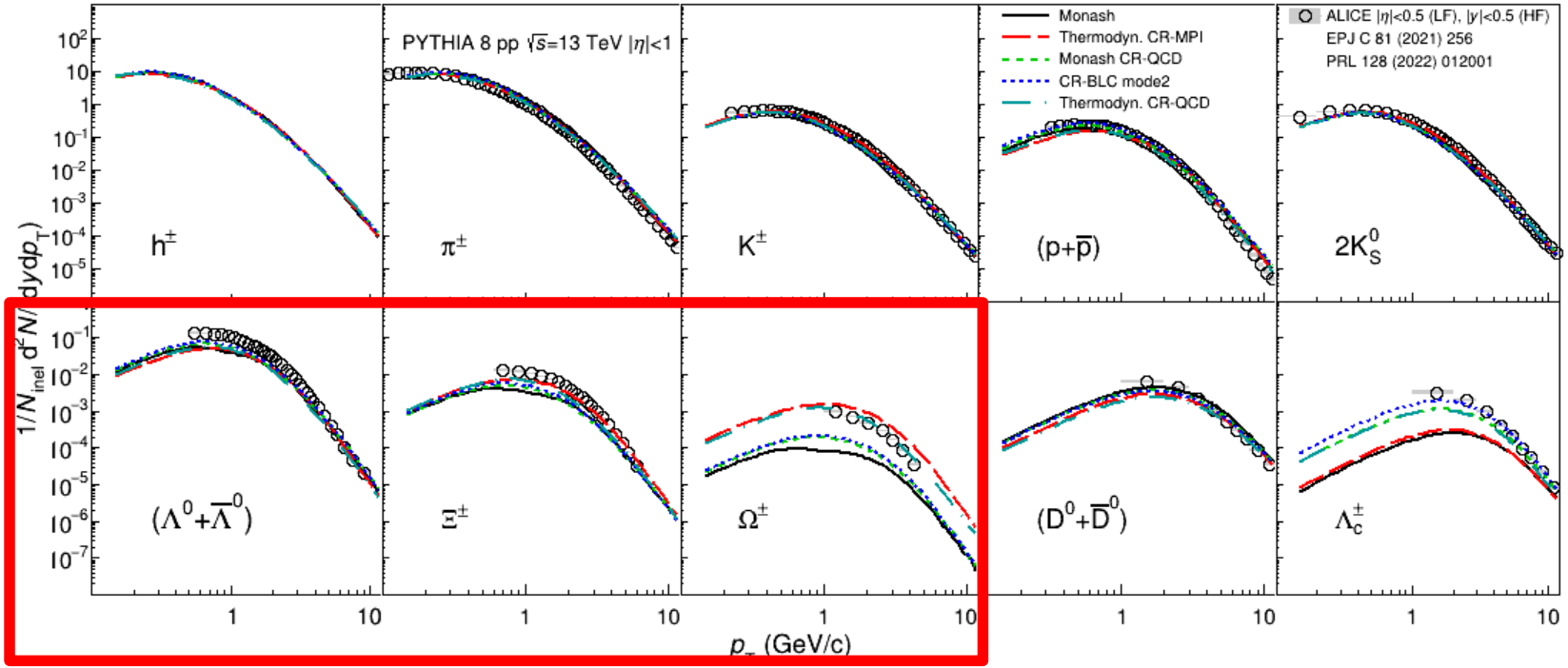

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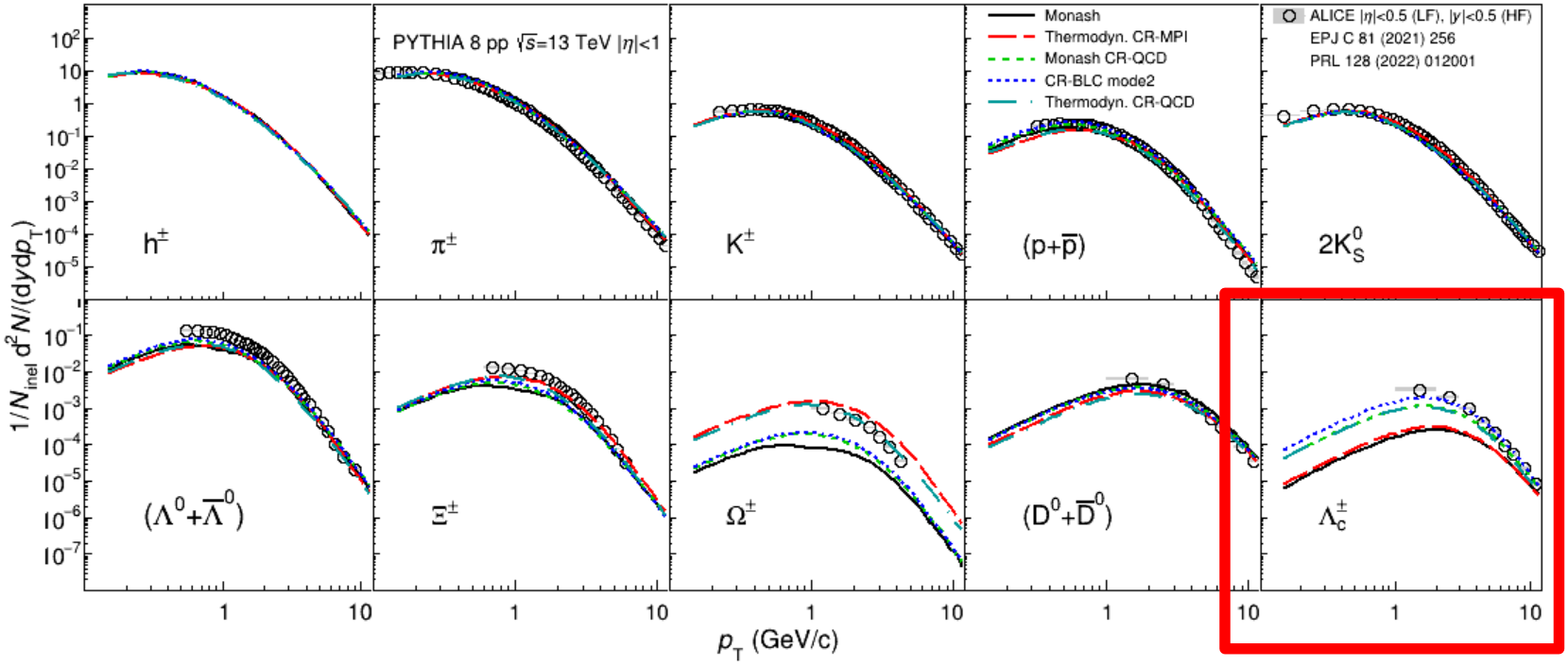

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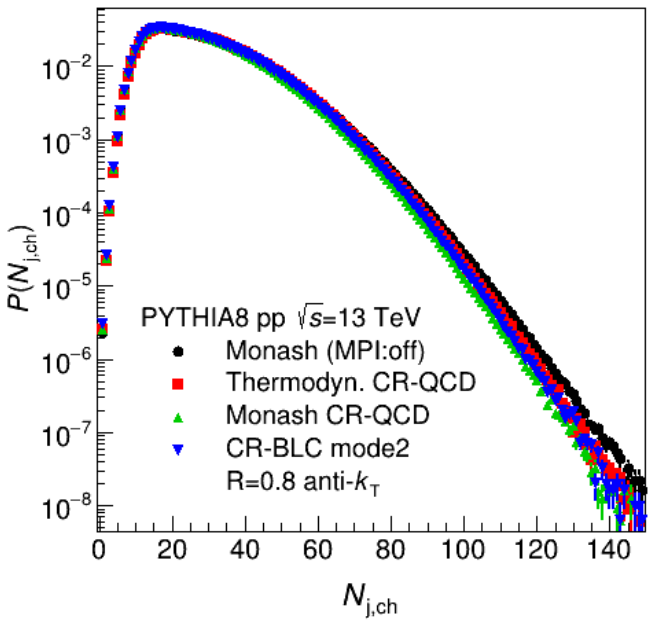
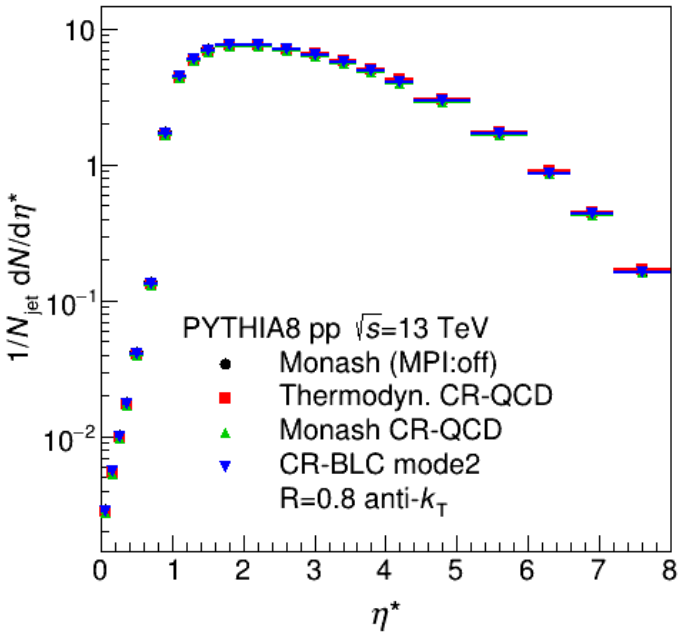
- Charmed hadrons are best described by the CR-BLC tune

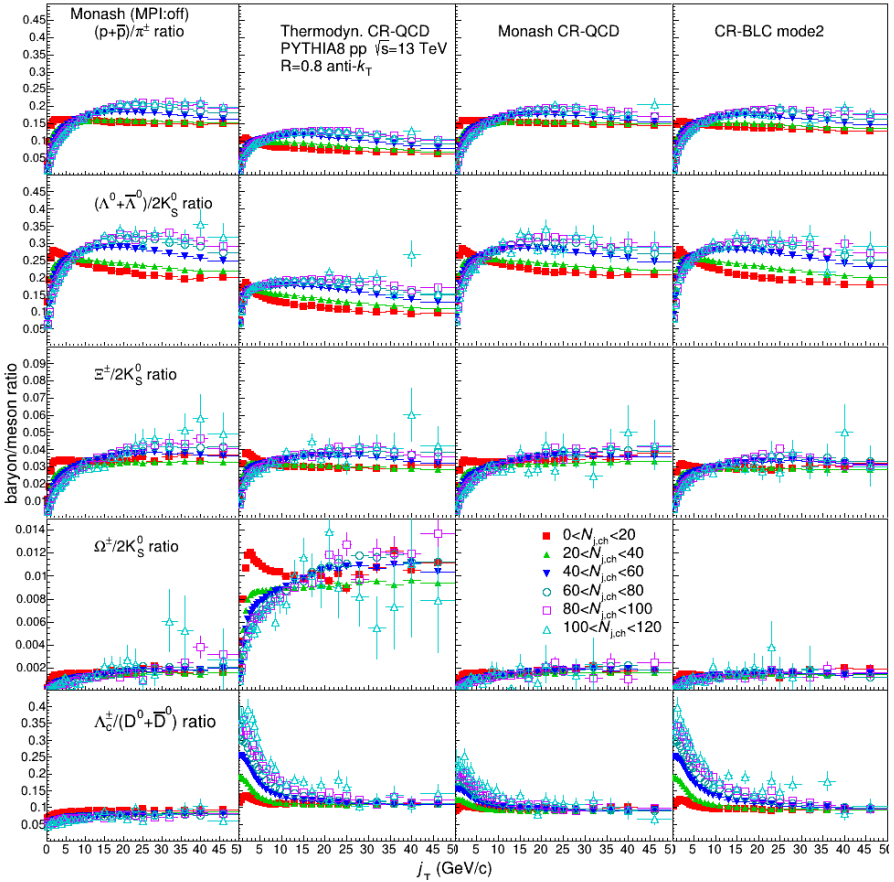
Simulations: jet reconstruction





- Jet reconstruction: anti-k_T algorithm and R=0.8, p_T^{jet} > 550 GeV/c
  - Jet multiplicities and η* distributions are relatively uneffected by the choice of model

Results: baryon-meson ratios vs. j_T



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

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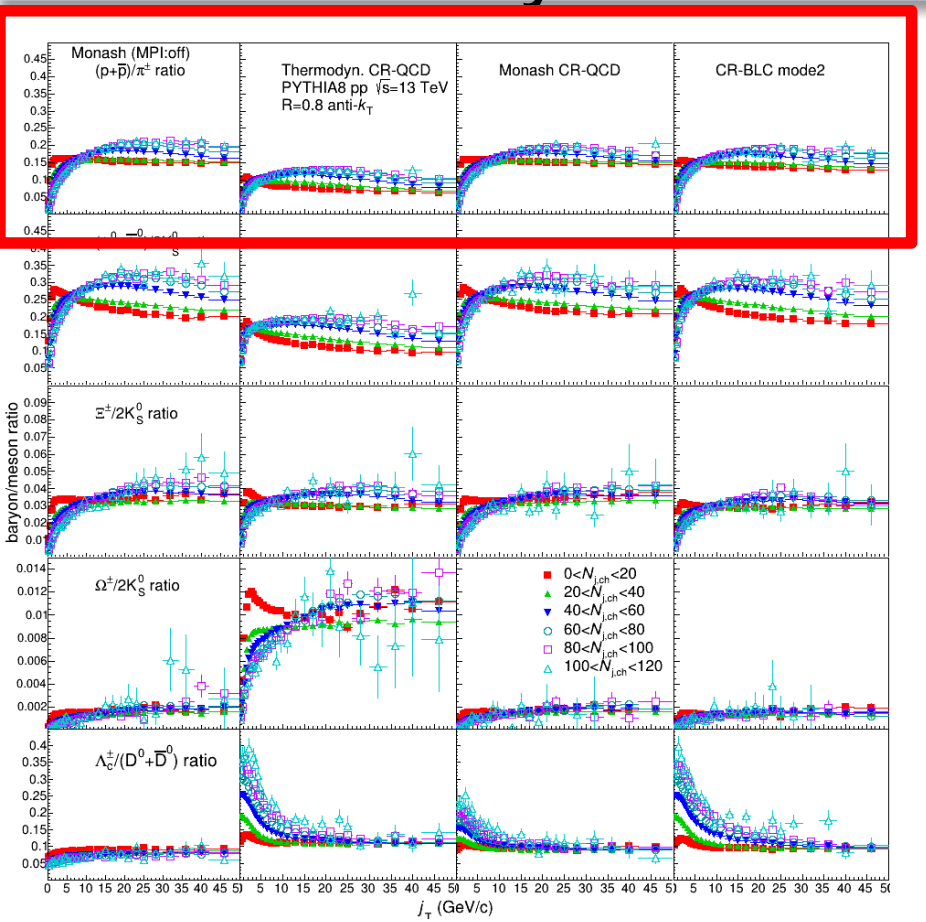

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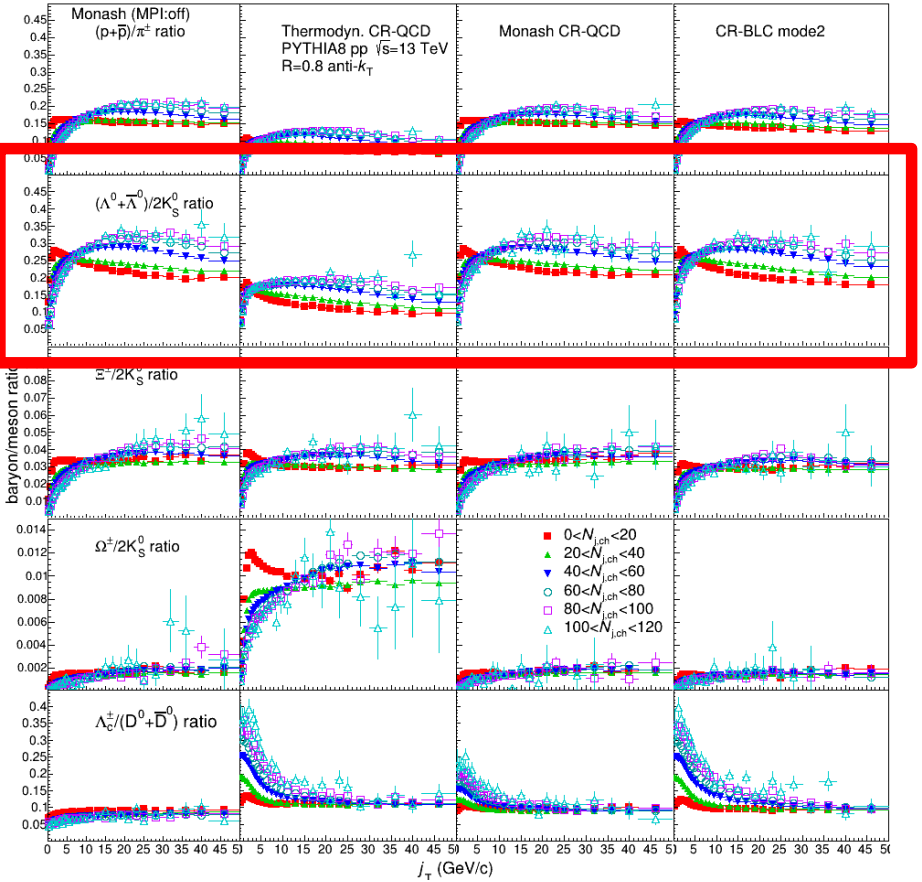

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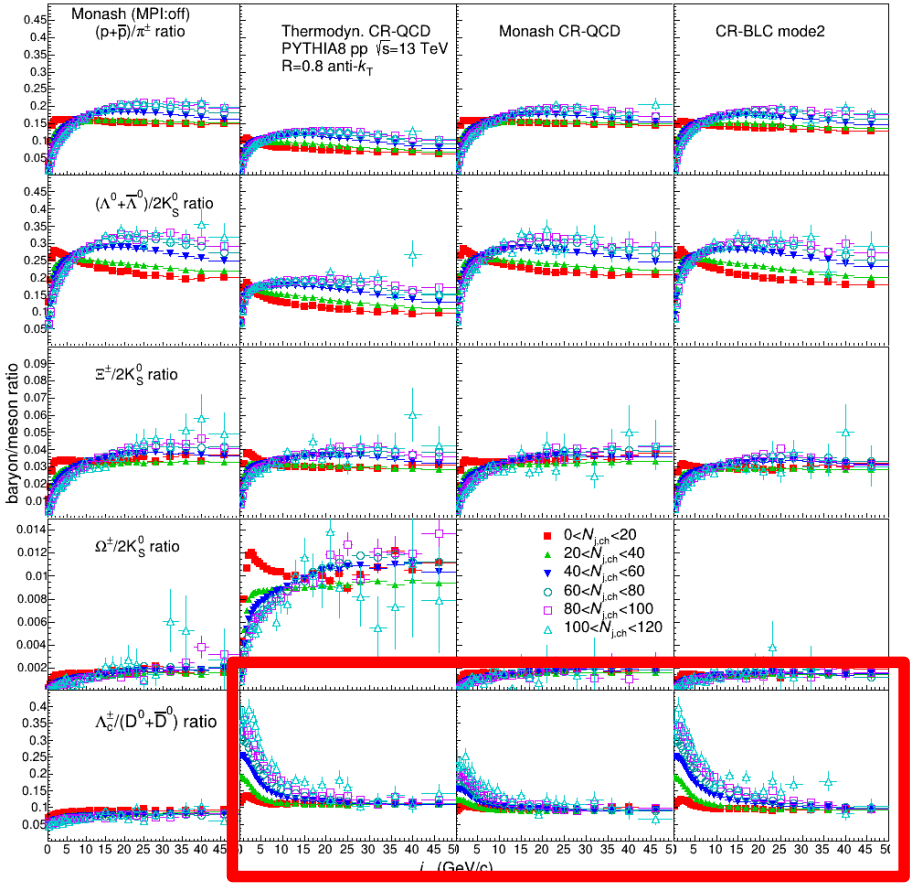

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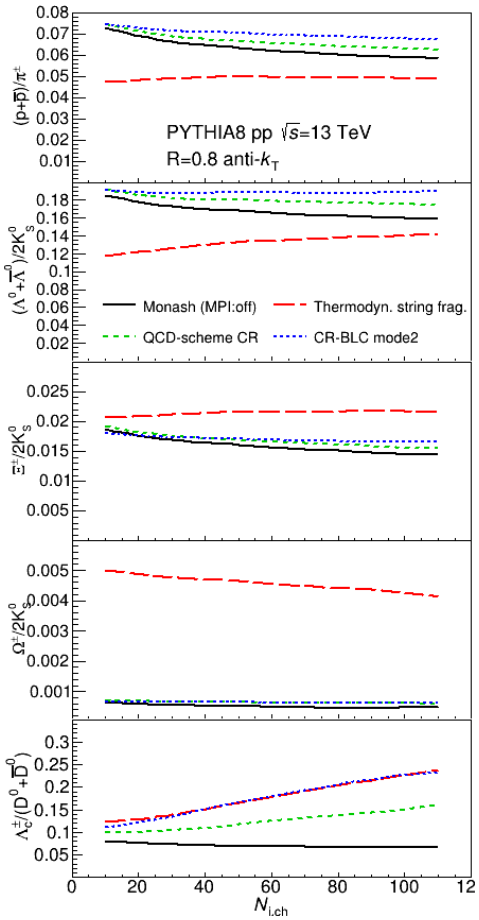
- Λ^0/K_S^0: grouping into low-N^j_{ch} and high-N^j_{ch} curves
- Λ_c^+/D^0: if color junctions are allowed, a characteristic low-j_T enhancement is present that gets stronger with multiplicity; this is similar to p_T-dependent enhancement of charmed baryons in minimum-bias data

ALICE, Phys. Rev. C 107, 064901

Results: baryon-meson ratios vs. $N_{j,ch}$

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



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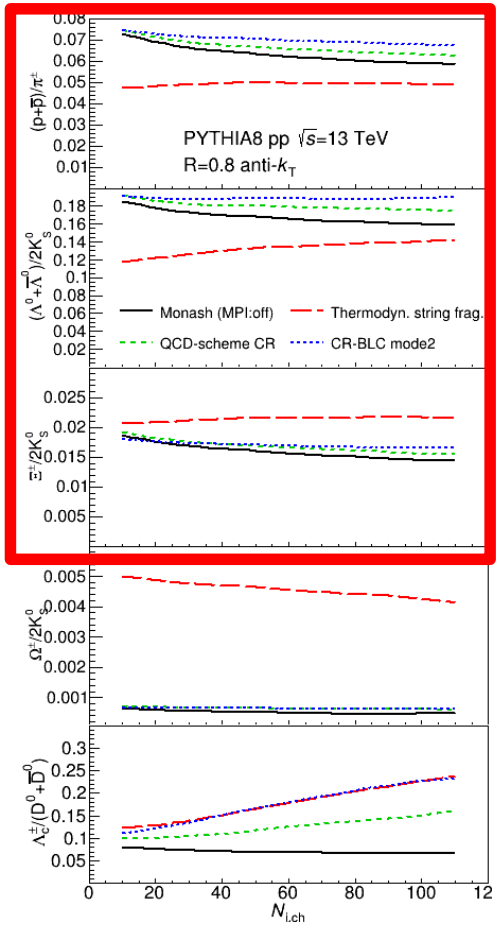

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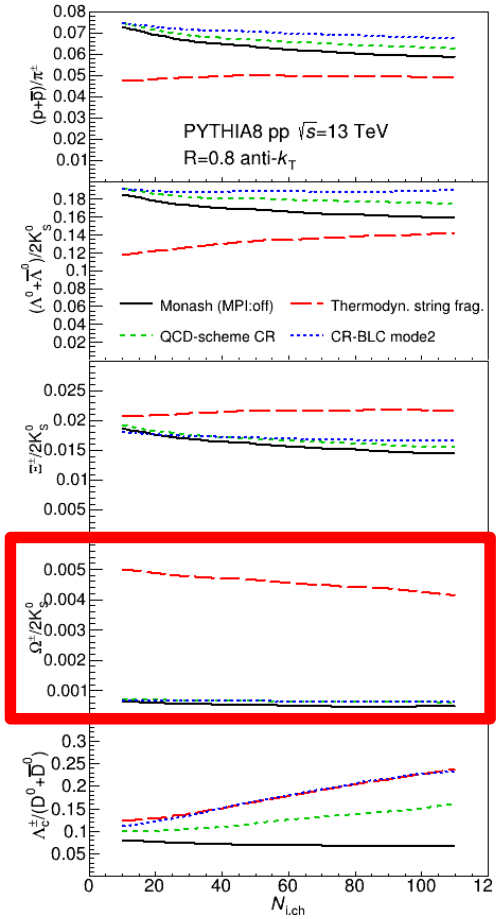

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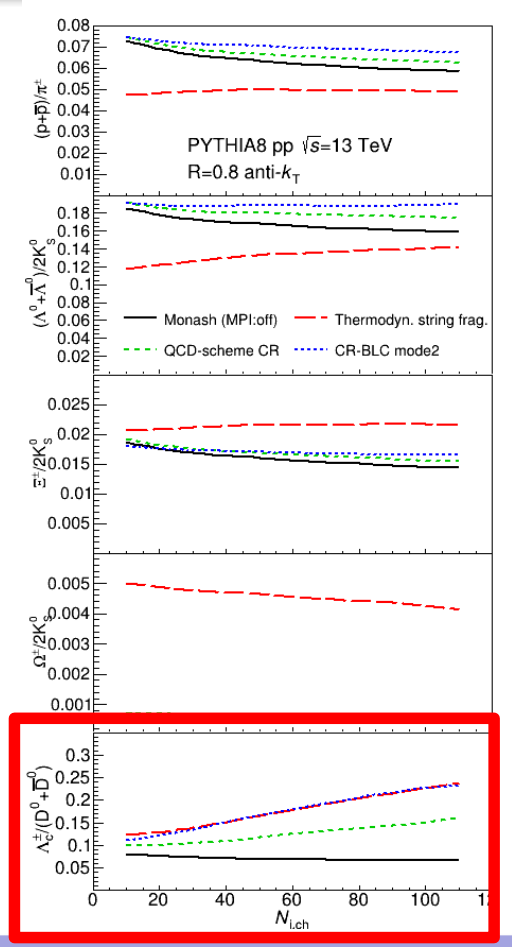

Results: effect of close packing on B/M vs. $N_{j,ch}$

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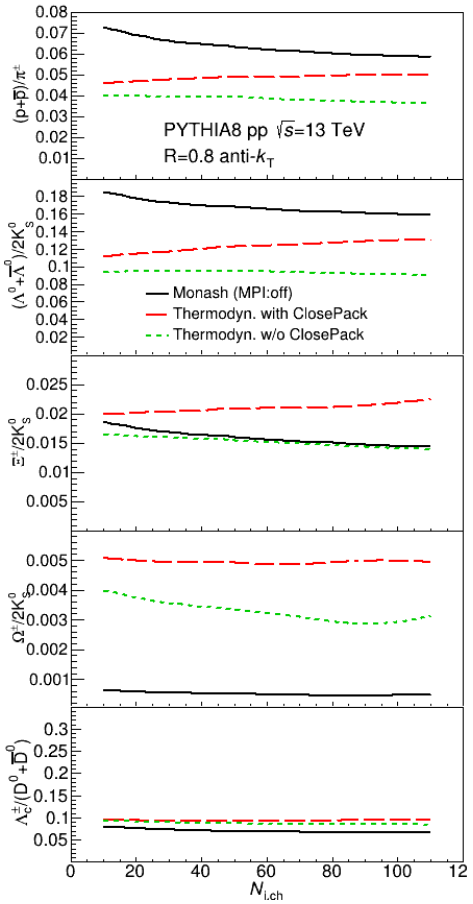
- No color junctions allowed

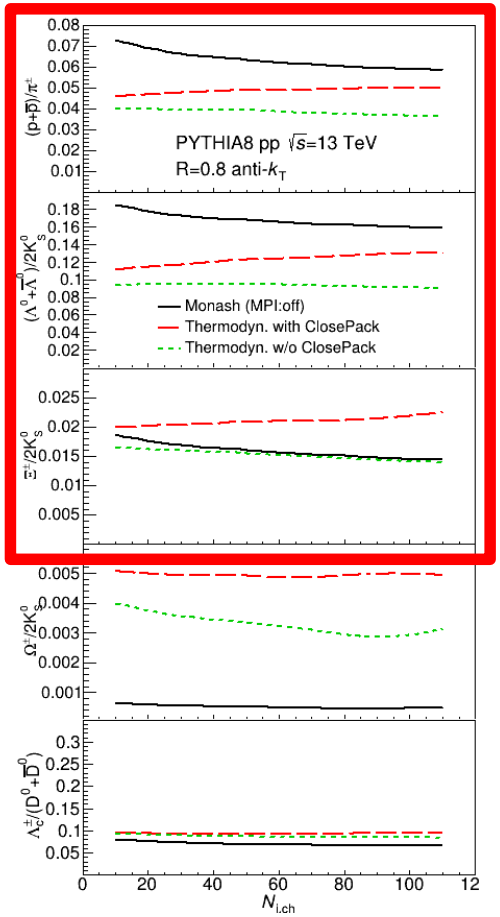


Results: effect of close packing on B/M vs. $N_{j,ch}$

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

- No color junctions allowed
- Increasing trend can be partly attributed to close packing of color strings

  (Close packing: more constrained placing of partons before break-up into hadrons)



Conclusions

Structures in j_T

- The proton-to-pion and the Λ^0/K_S^0 ratios show low-high multiplicity grouping trend for j_T>5 GeV/c, possibly reflecting the flavor of the jet-initiating parton.
- The Λ^0/K_S^0 and $\Xi^{\pm}/K_S^0$ ratios show a bump structure reminiscent of the radial flow-like effects observed in the p_T spectra as a function of the inclusive charged particle multiplicity

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Thermodynamical string fragmentation with close packing

- Continuous increase of the p/π, Λ^0/K_S^0 and Ξ/K_S^0 ratios with increasing N^j_{ch}. Effect gets reduced with the increase of the s-quark content, probably because of phase-space constraints
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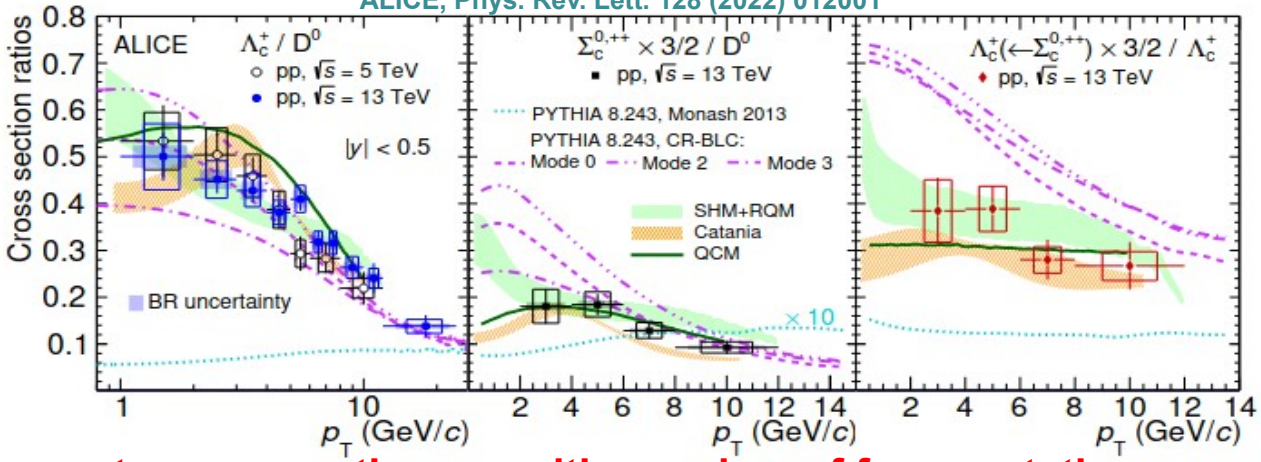
Heavy flavor with QCD-scheme CR

- Λ_c^+/D^0 shows an increase at low j_T with increasing N^j_{ch} for the Lund string fragmentation model. The effect is similar to the multiplicity-dependent Λ_c^+/D^0 as a function p_T reported by ALICE.


Thank you!

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

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