ALICE explores strangeness and nucleosynthesis in hadronic collisions

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ALICE

INFN
Istituto Nazionale di Fisica Nucleare

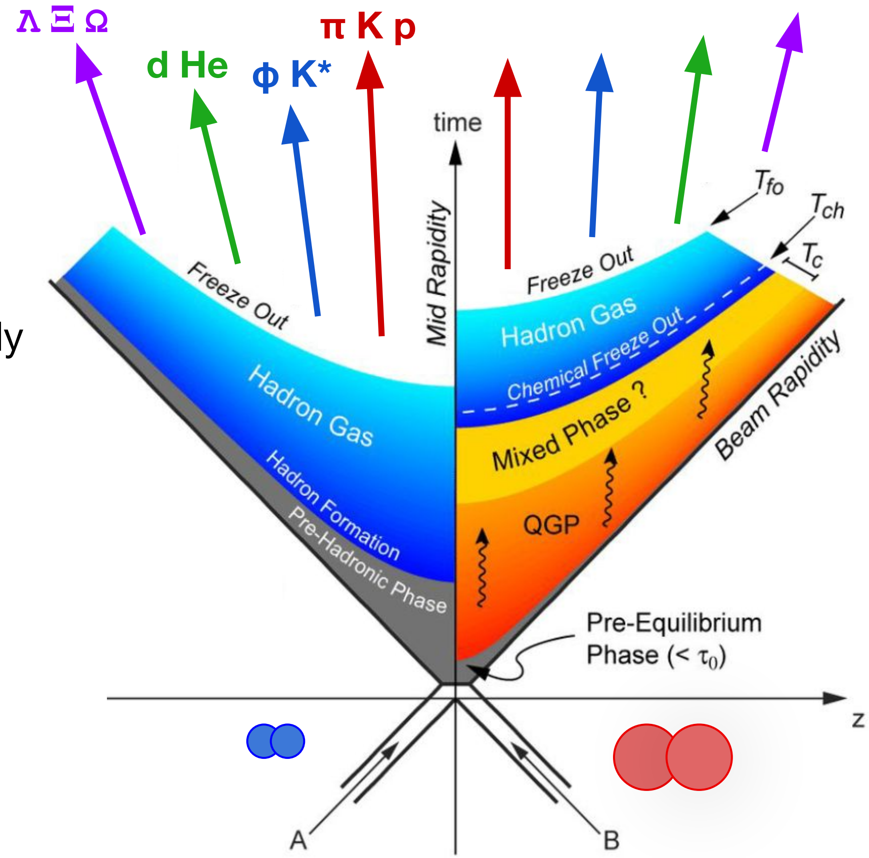
CosmicAntiNuclei

Light flavour production in hadronic collisions

Light flavor (u, d, s) quarks **thermally produced** in the QGP → soft probes are key to study the properties of the medium

Large interest also in **small systems** (pp, pA) not only as a reference to AA

- different **system sizes** are sensitive to different production mechanisms
- striking similarities observed **between small and large systems**

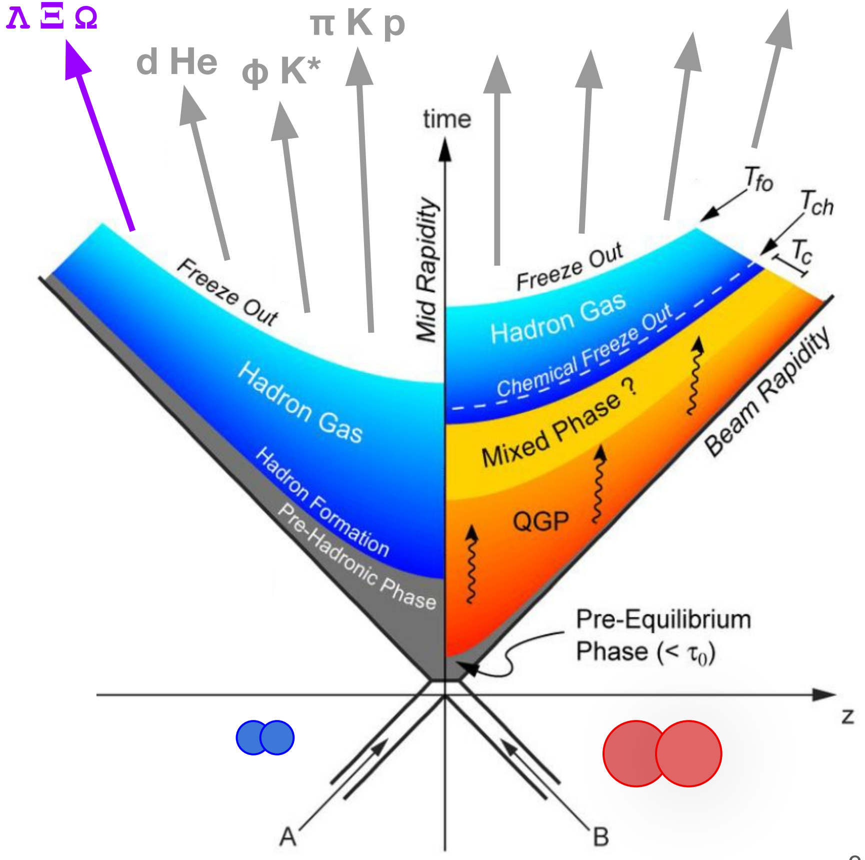


Light flavour production in hadronic collisions

Strangeness production:

Strangeness enhancement in AA is historically considered a signature of QGP formation, with Minimum-Bias pp as reference

Striking **similarities** observed **between small and large systems** as a function of multiplicity



Light flavour production in hadronic collisions

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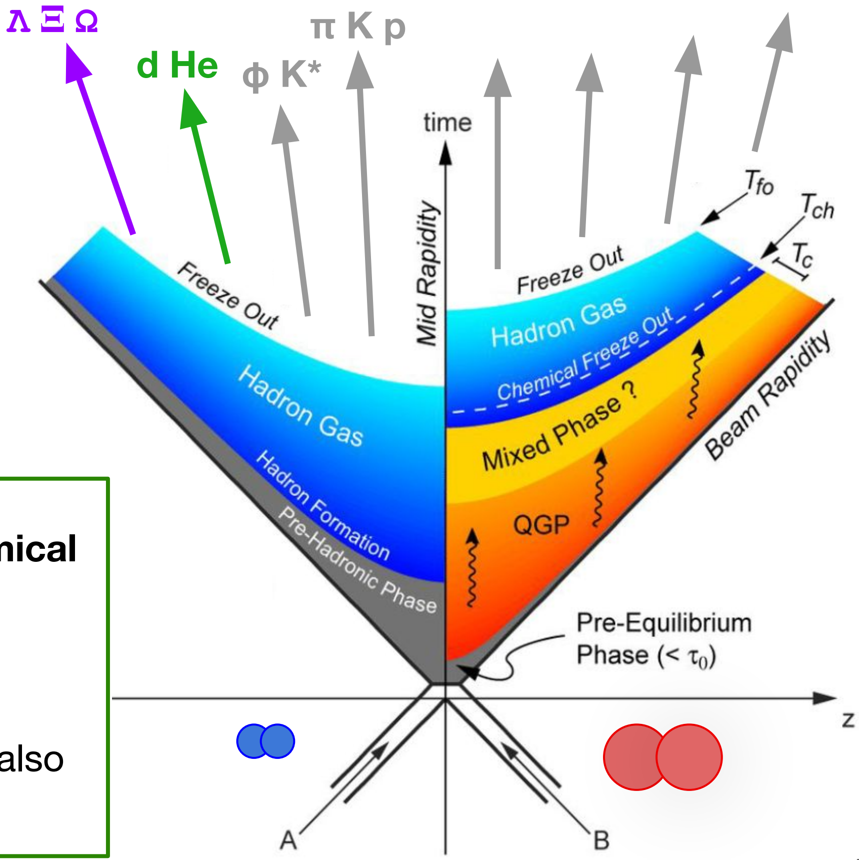
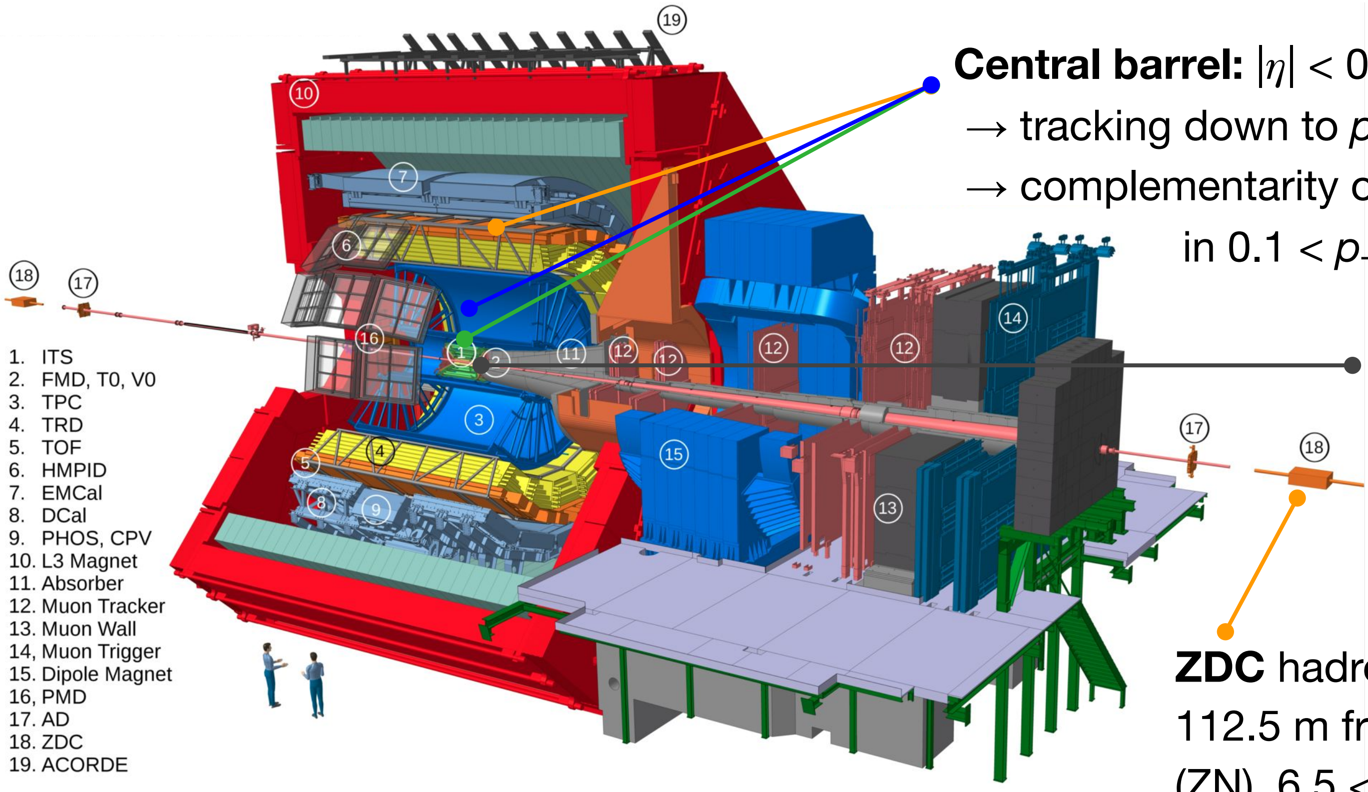
(Anti)nuclei production:

Constrain the **properties** of the system in AA at the **chemical freeze-out** (T, μ_B) and understand **nucleosynthesis mechanisms** in high-energy collisions

The production of antinuclei measured at accelerators is also crucial input in **astrophysical searches for Dark Matter**



The ALICE detector in Run 1 and 2



Central barrel: $|\eta| < 0.9$, B = 0.5 T

→ tracking down to p_T ~ 100 MeV/c

→ complementarity of several PID techniques in $0.1 < p_T < 30$ GeV/c

V0 detectors: triggering, multiplicity

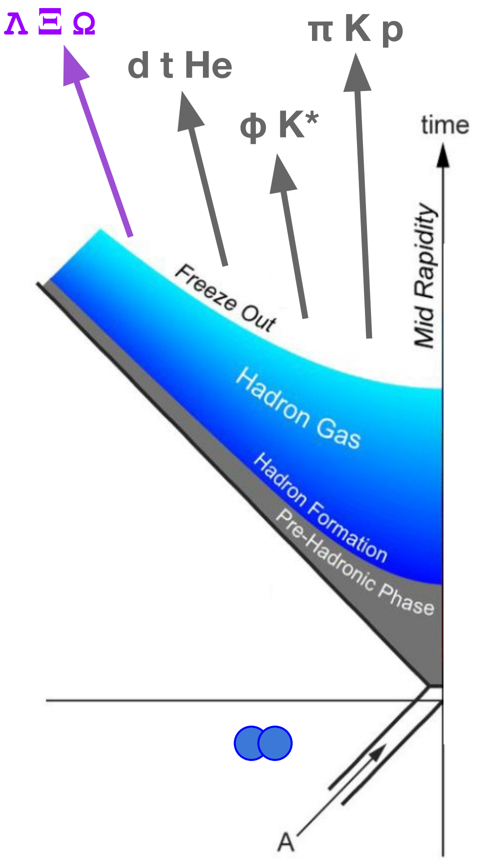
$2.8 < \eta < 5.1$ (V0A)

$-3.7 < \eta < -1.7$ (V0C)

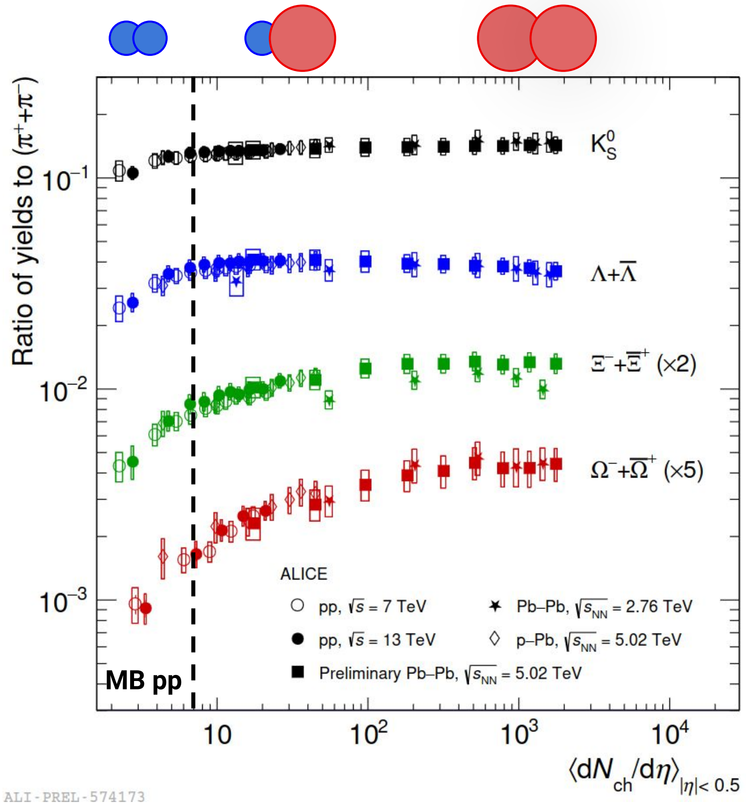
ZDC hadronic calorimeters, 112.5 m from the IP $|\eta| > 8.8$ (ZN), $6.5 < |\eta| < 7.4$ (ZP*)

*considering LHC beam optics ZP acceptance for protons is $7.0 < |\eta| < 8.7$

Strangeness production in pp collisions at the LHC



Strangeness production across collision systems



Continuous evolution of strange hadron yield ratios to pions **with the charged-particle multiplicity** observed at the LHC, smoothly connecting different systems and energies

Strangeness production **increases with** particle **multiplicity**, saturating for central Pb–Pb

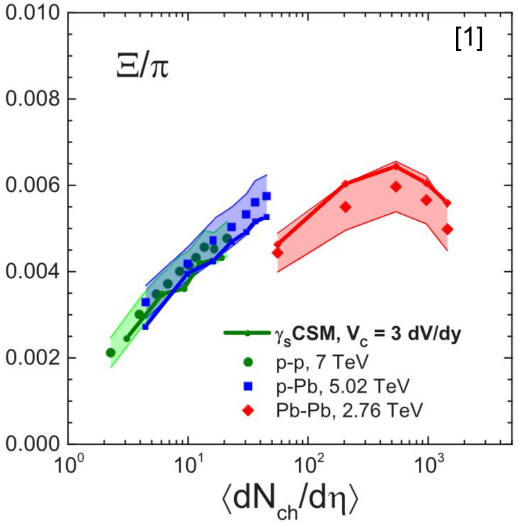
Strange content **hierarchy**:

$$|S_{\Omega^\pm}| > |S_{\Xi^\pm}| > |S_\Lambda| \approx |S_{K^0_S}|$$

Modelling strange hadron production

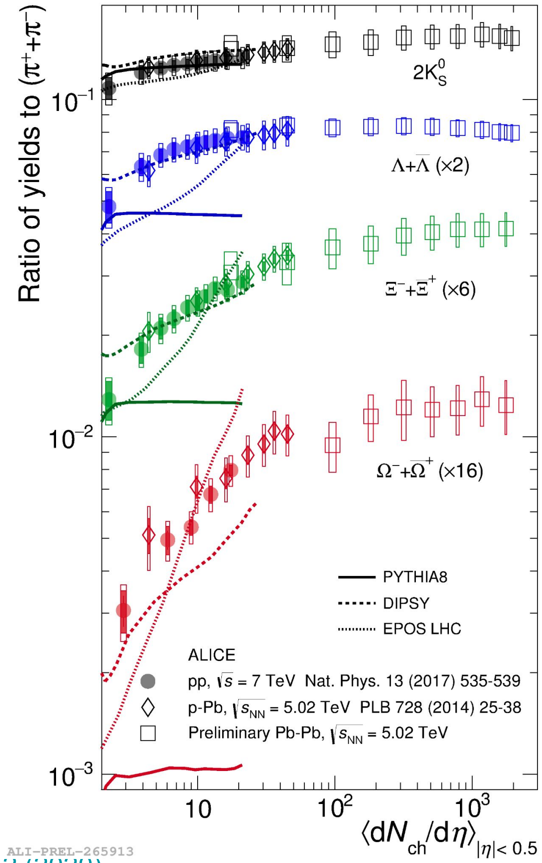
Several approaches attempt to describe strangeness hadronization in small systems:

- **canonical suppression + running of γ_S** in statistical hadronization models (CSM) [1]



- **string/rope hadronization** models including colour reconnection (CR) effects (PYTHIA/DIPSY) [2]

- two-component (**core-corona**) models (EPOS) [3]



[1] Phys. Rev. C 100, 054906 (2019) [2] Phys. Rev. D 100, 074023 (2019) [3] Phys. Rev. C 101, 024912 (2020)

Multi-differential analysis by ALICE

Several ALICE new results from **multi-differential analyses** to explore strangeness production in small collision systems

- Study strangeness production as a function of **new observables**, sensitive to different collision properties:
  - **Effective energy** → This talk!
  - Transverse **spherocity** → JHEP 05 (2024) 184

- Explore strangeness production **in- and out-of-jets** with different techniques → JHEP 07 (2023) 136, arxiv:2405.14511 , arxiv:2405.19855

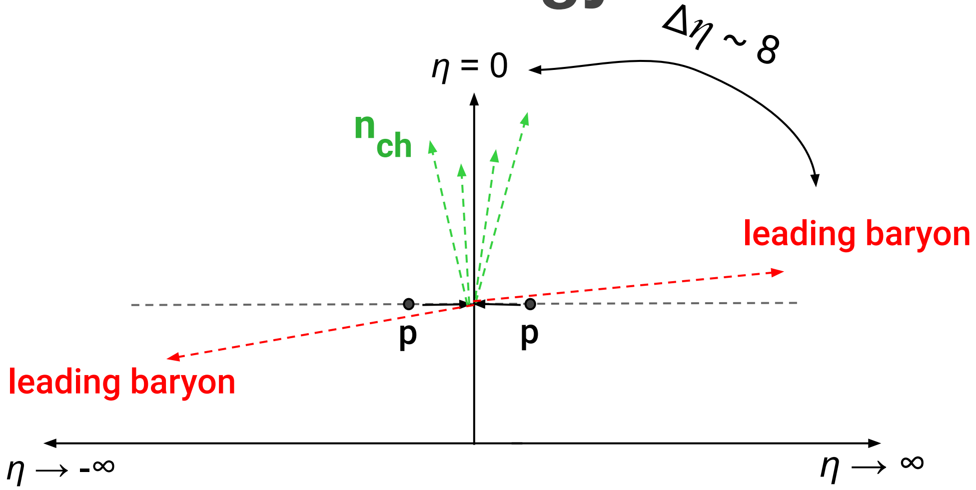
- Investigate **multiple strange hadron production in high multiplicity events** → This talk!

The concept of effective energy

Two-dimensional analysis as a function of**:**

- Charged-multiplicity at midrapidity
  proxy for local effects,
  e.g. jet production

- Leading energy
  proxy for global effects, e.g. the
  initial effective energy in the collision



$$E_{\text{eff}} = \sqrt{s} - E_{\text{leading}}$$ → First studied at the CERN ISR in the 80's [1,2]

Independent proxies given the large η separation

[1] M. Basile et al., Phys. Lett. B 95 (1980) 311
[2] A. Akindinov et al., EPJ C 50 (2007) 341–352

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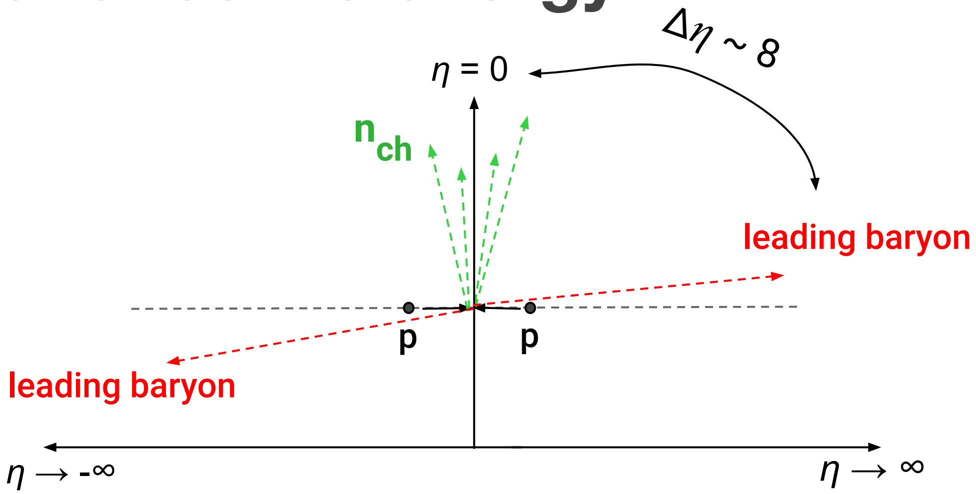

What is the interplay of global and local effects for strange hadron production?

[1] M. Basile et al., Phys. Lett. B 95 (1980) 311
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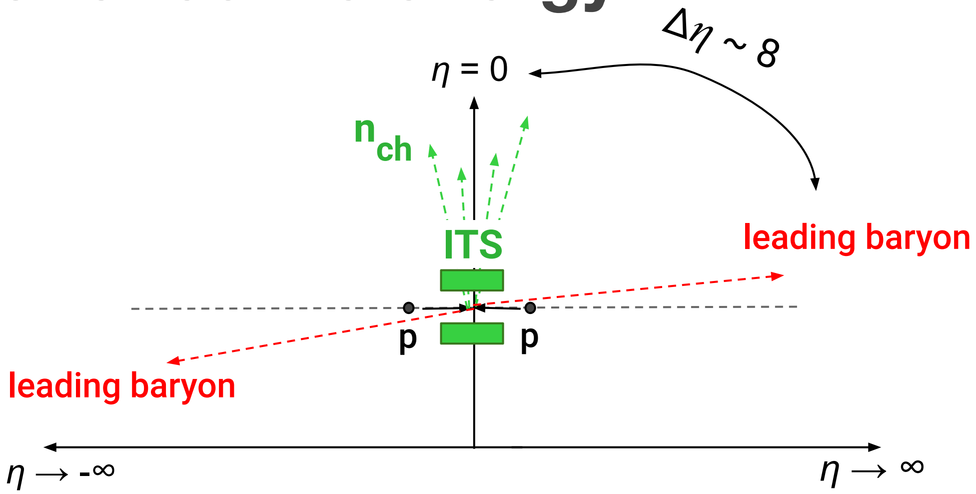

ALICE can measure:

- midrapidity multiplicity (**SPD**)

The concept of effective energy

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$$E_{\text{eff}} = \sqrt{s} - E_{\text{leading}} \simeq \sqrt{s} - E_{\text{ZDC}}$$

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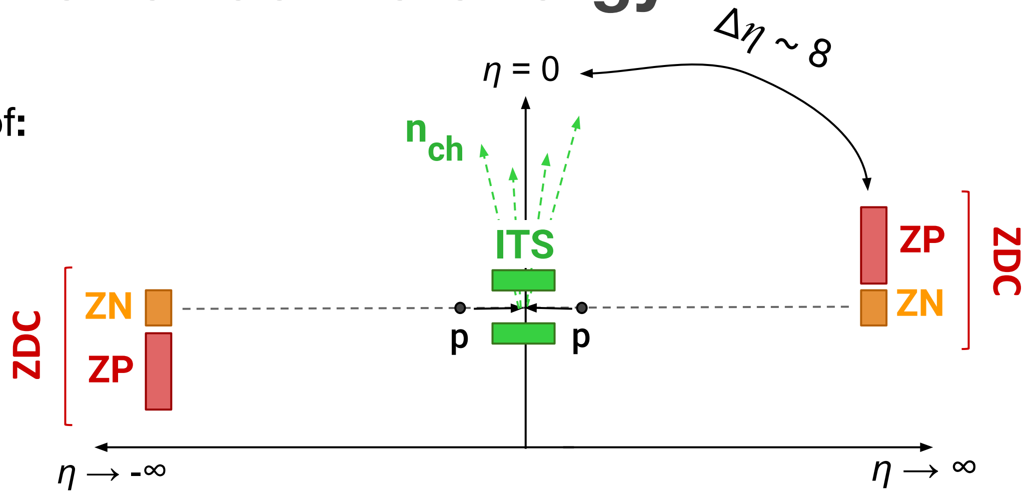

ALICE can measure:

- midrapidity multiplicity (**SPD**)
- leading energy (**ZDC**)

The concept of effective energy

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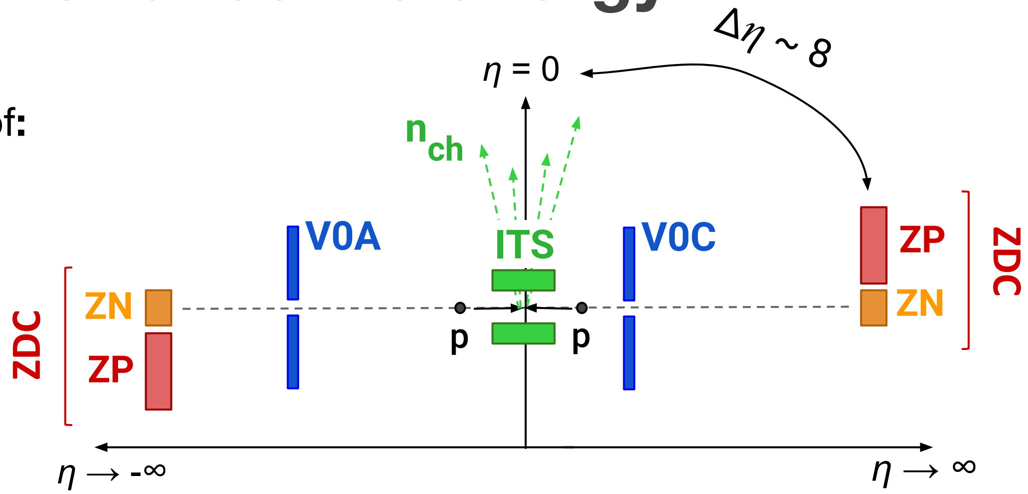


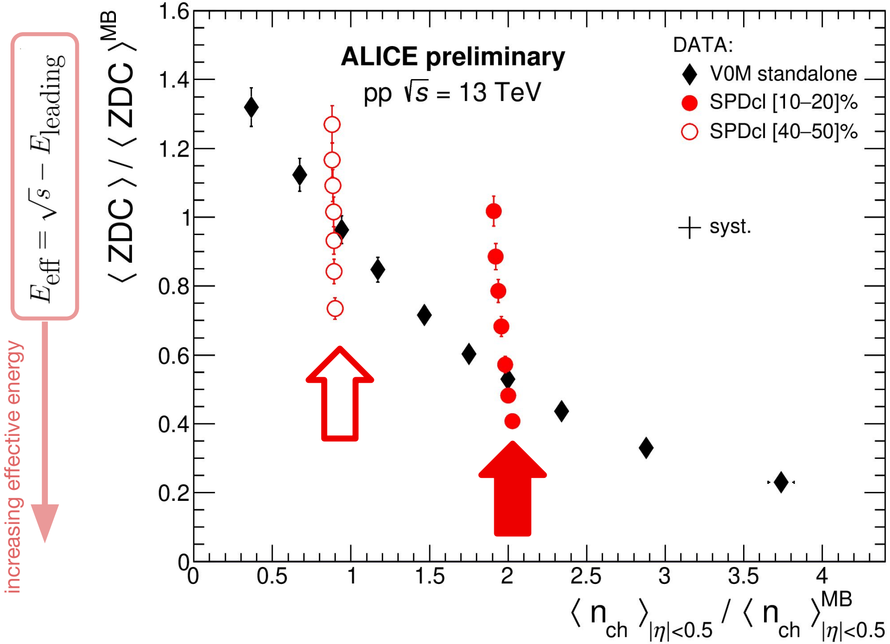
ALICE can measure:

- midrapidity multiplicity (**SPD**)
- leading energy (**ZDC**)
- forward multiplicity (**V0M** = V0A+V0C)

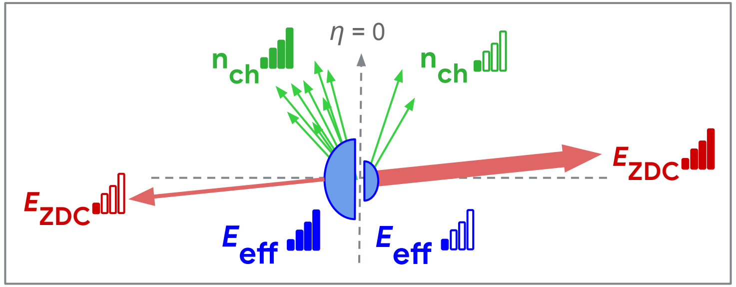
Event classes with a differential approach

The leading energy decreases with increasing particle multiplicity produced at midrapidity [1]

New multi-differential event classes: **similar midrapidity multiplicity** and **different leading energies**



- ♦ **Standalone**
- ● **High local multiplicity** (midrapidity)
- ○ **Low local multiplicity** (midrapidity)

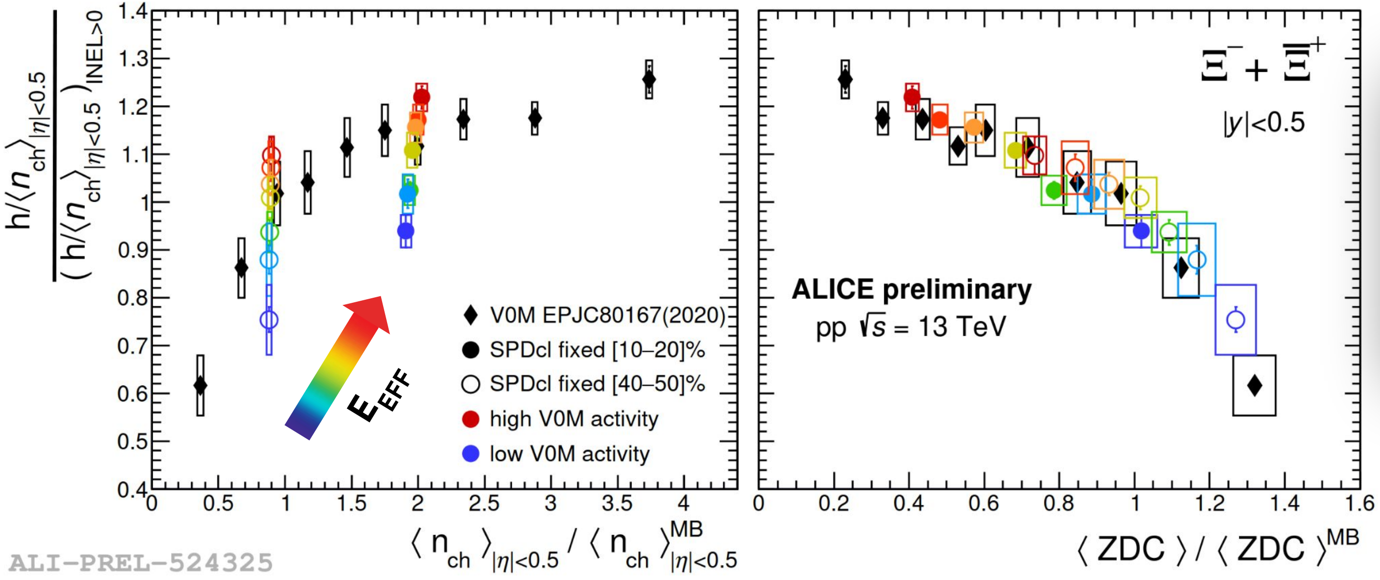


[1] JHEP 08 (2022) 086

Strangeness production at fixed multiplicity

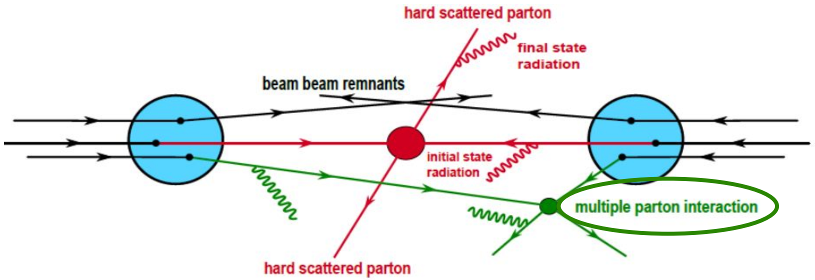
In events with the same particle multiplicity produced:

- **increase** in Ξ production per charged particle is observed for **decreasing forward energy** (ZDC)
- universal scaling trends with ZDC energy, **compatible within uncertainties**



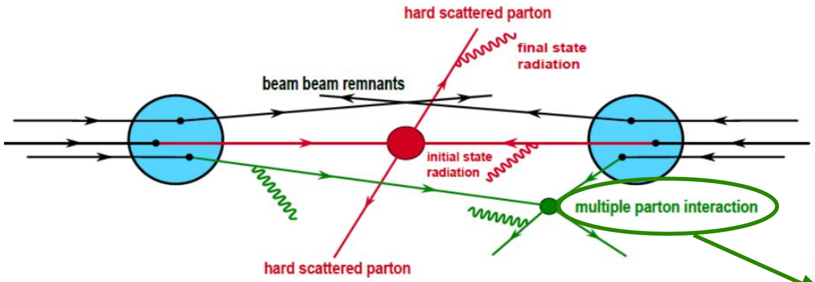
Ξ **enhancement** observed at **fixed multiplicity, correlated** with the **effective energy**

Connection to the MPIs in PYTHIA



In PYTHIA, the number of **Multiple Parton Interactions** strongly **influence** the **string hadronization processes** responsible for strange hadron production

Connection to the MPIs in PYTHIA



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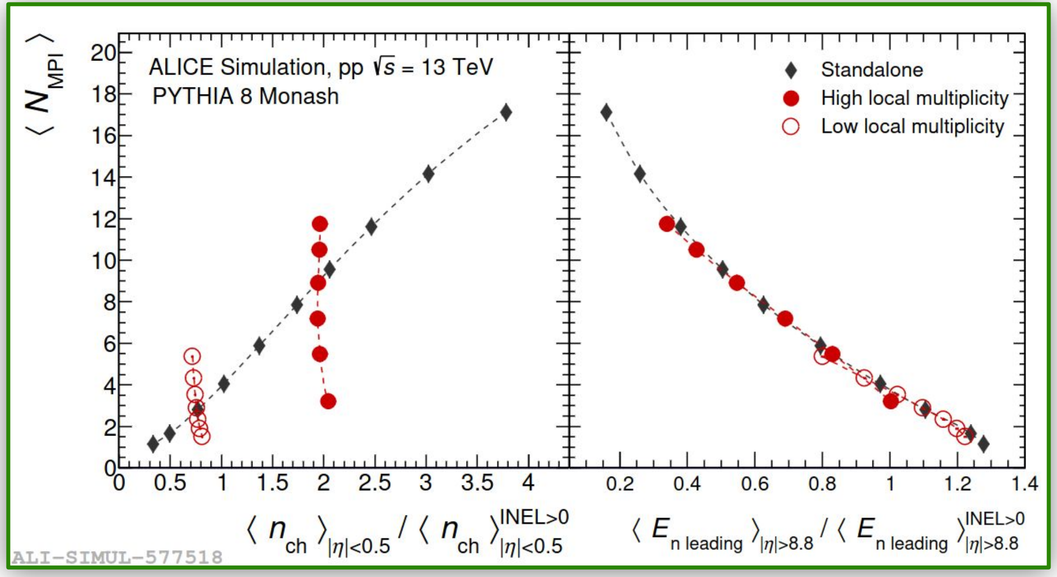
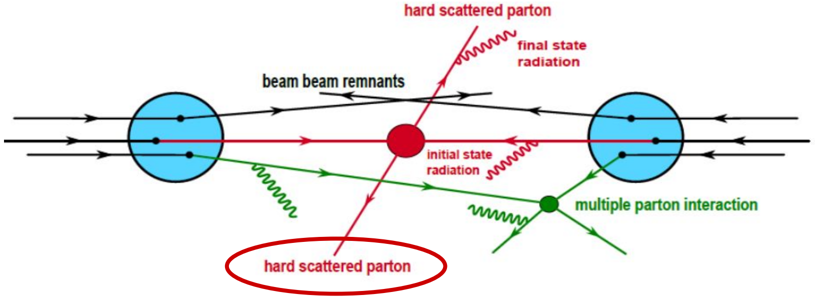


MPIs increase at fixed local multiplicity with decreasing leading energies

Universal dependence with the leading energy, i.e. common for all selections

Leading energy → a powerful observable to probe the dependence of particle production on the number of MPIs

Connection to hard-scattering processes in PYTHIA



The presence of jets at midrapidity is studied in PYTHIA considering the $\langle p_{T}^{\pi} \rangle_{|y|<0.5}$, proxy for the $\boldsymbol{p_T}$ **of the hard parton scattering process**

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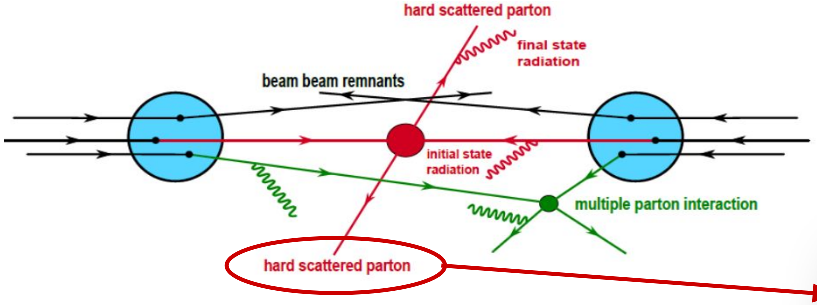

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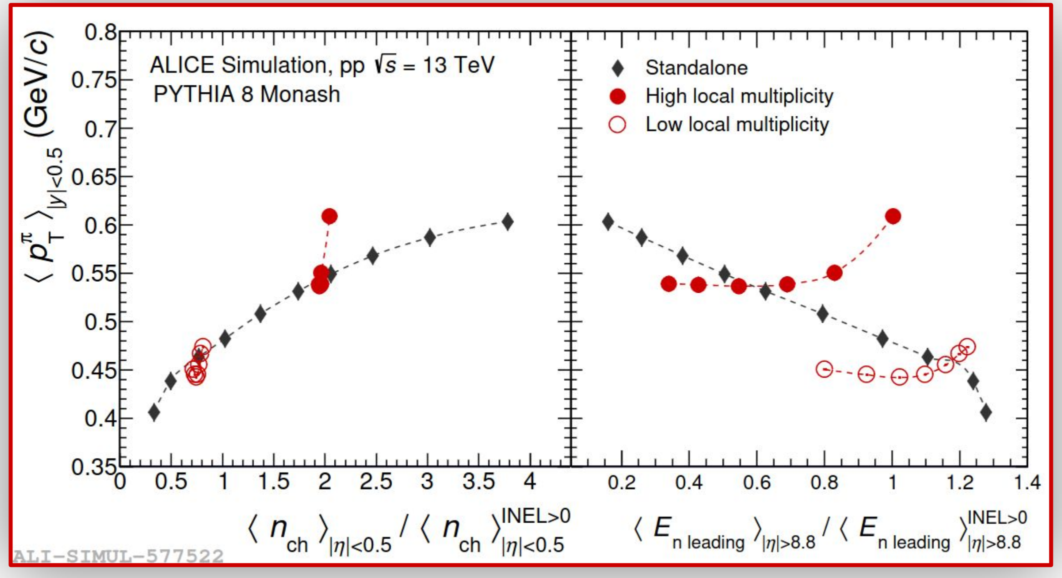
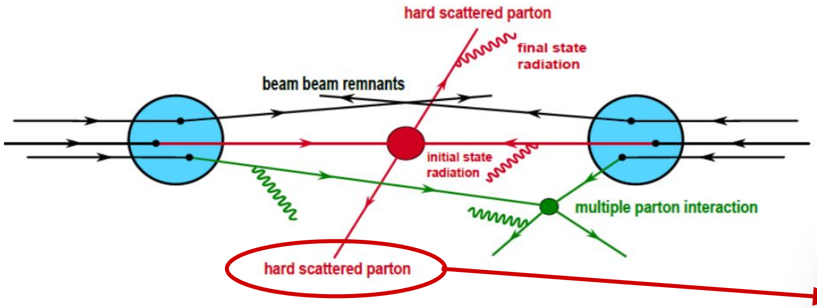


Very **mild dependence** of $\langle p_{T}^{\pi} \rangle_{|y|<0.5}$ with the **leading energy**

Local phenomena, such as jets at midrapidity, are correlated with local observables, such as the charged-multiplicity

Connection to hard-scattering processes in PYTHIA



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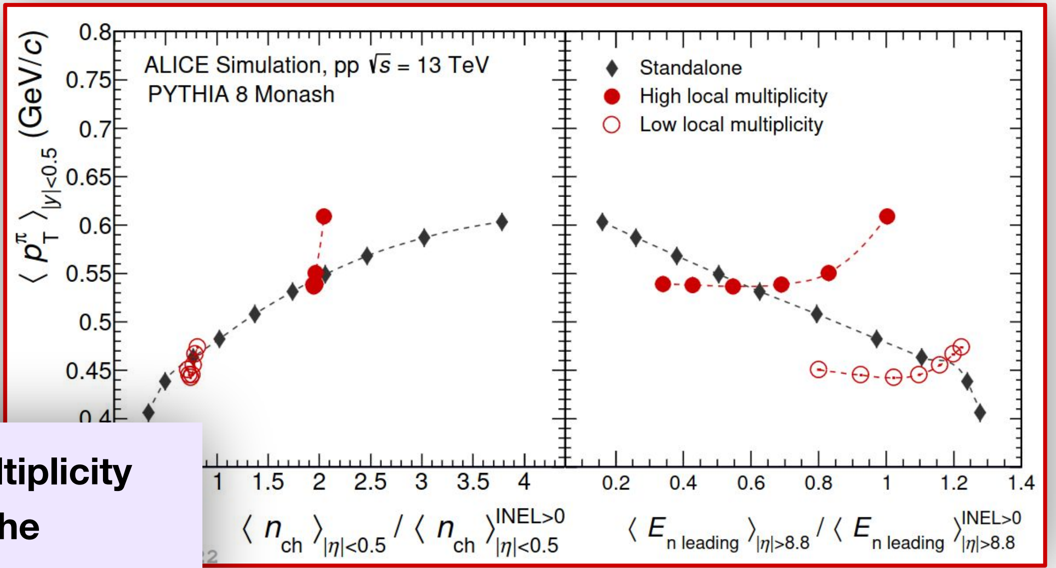

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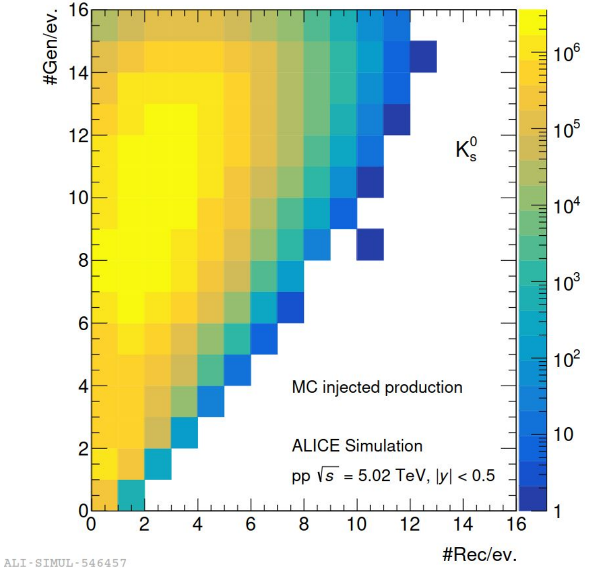
Local phenomena, such as jets at midrapidity, are correlated with local observables, such as the charged-multiplicity

The observed Ξ **enhancement at fixed multiplicity** is connected to **global properties of the event**, e.g. MPI, the effective energy

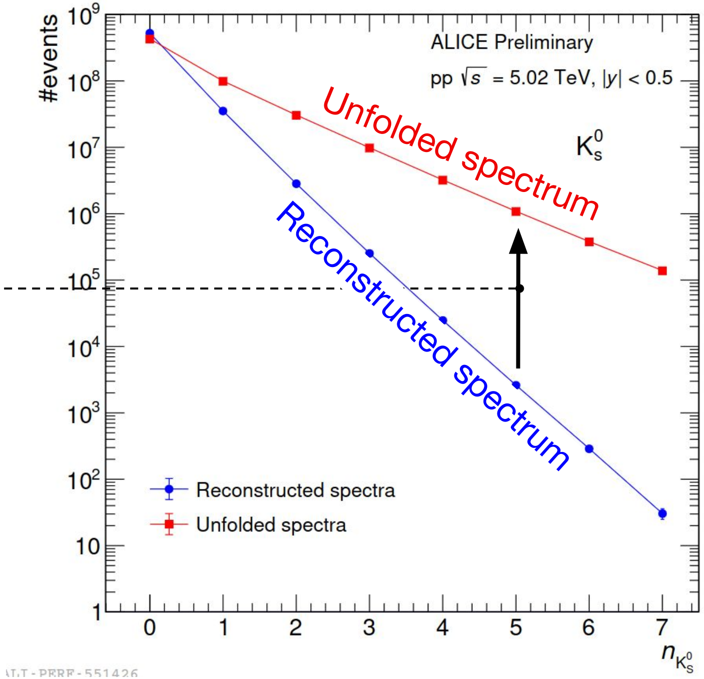
Multiple strange hadron production

Can strangeness enhancement in small systems arise from **multiple strange hadron production in high multiplicity events**?

ALICE measured the **multiplicity distribution** for the production of (multi-)**strange hadrons** in pp collisions



The detector response is taken into account via **Bayesian unfolding**

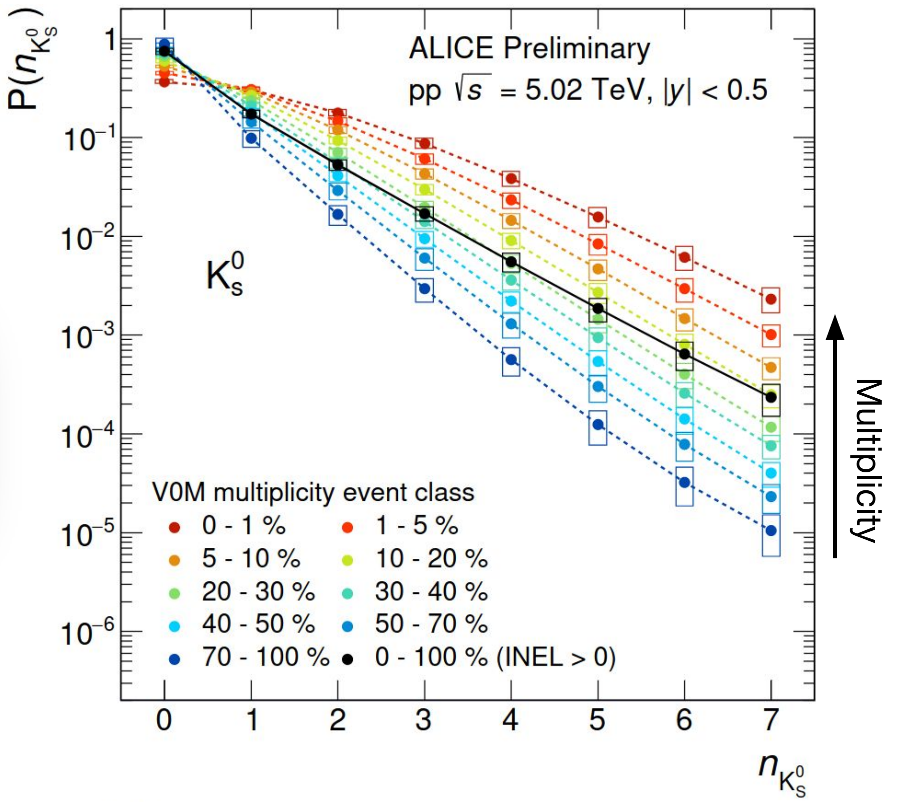


Strange particle multiplicity distribution

Probability to produce *n* strange particles of a given species per event $P(n_S)$
→ spanning across large ranges of strange hadron count
→ measured as a function of charged-multiplicity

The **probability** to produce $n \geq 1$ strange hadron per event **increases** with the charged-particle **multiplicity**

Same feature observed for all other (multi-)strange hadrons (Λ, Ξ, Ω)



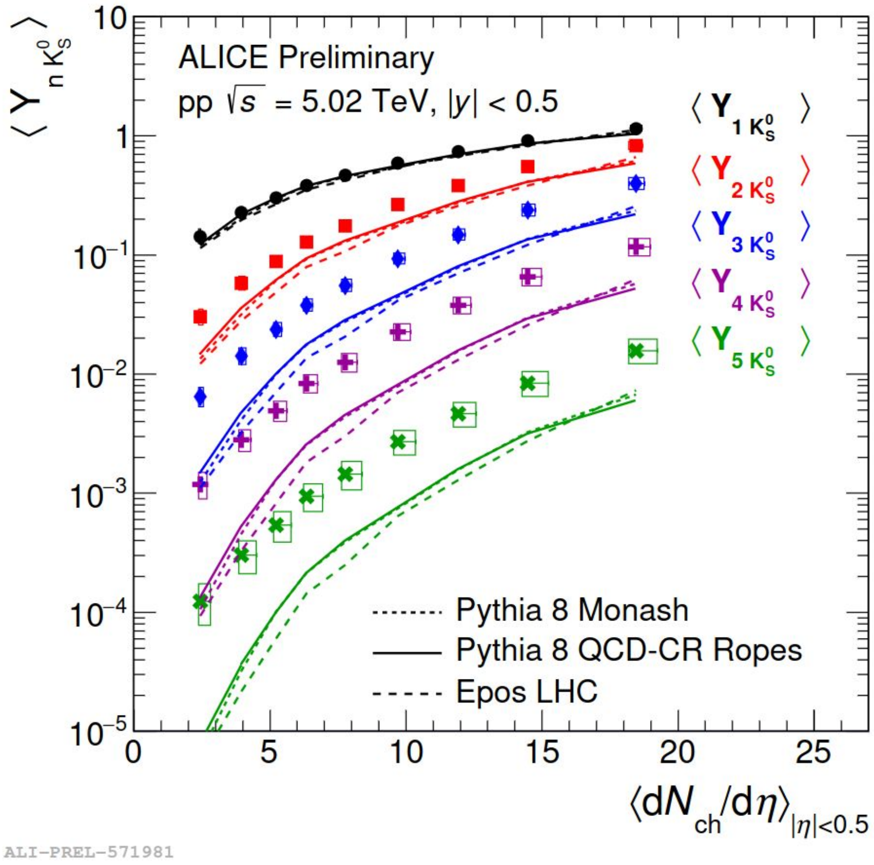
Multiple strange hadron production yields

Average production yield of 1, 2, 3, … particles/event is calculated as:

$$< Y_{k-part} >= \sum_{n=k}^{\infty} \frac{n!}{k!(n-k)!} P(n)$$

The n-particle yields increase **more than linearly** with the charged-particle multiplicity

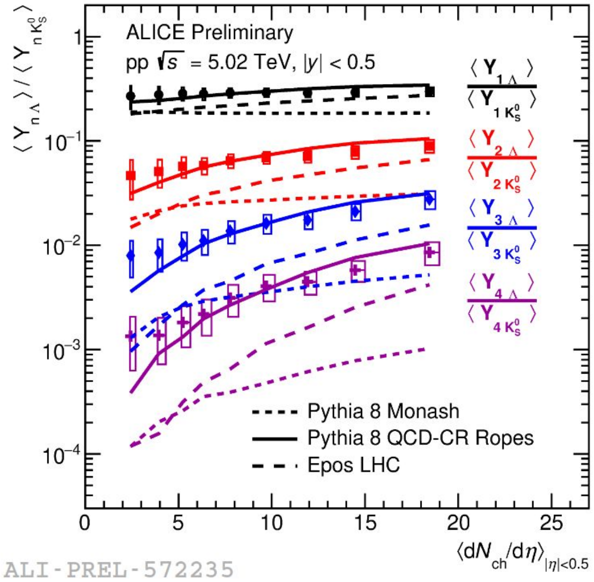
Model comparison:
the increase with multiplicity is qualitatively reproduced by PYTHIA Monash, QCD-CR Ropes and EPOS LHC, but all underestimate the n-particle yields for *n*>1



Yield ratios with ΔS = 0

$\langle Y_{n\Lambda} \rangle / \langle Y_{n K^0_S} \rangle$

ΔS = 0 → **increase vs multiplicity** for multiple hadron production



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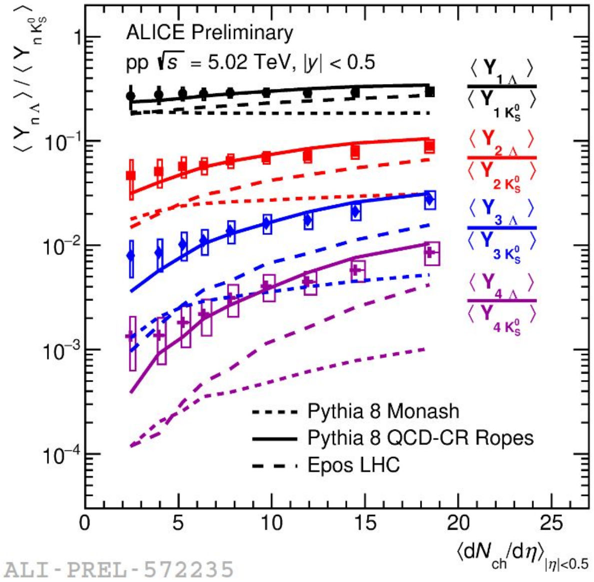

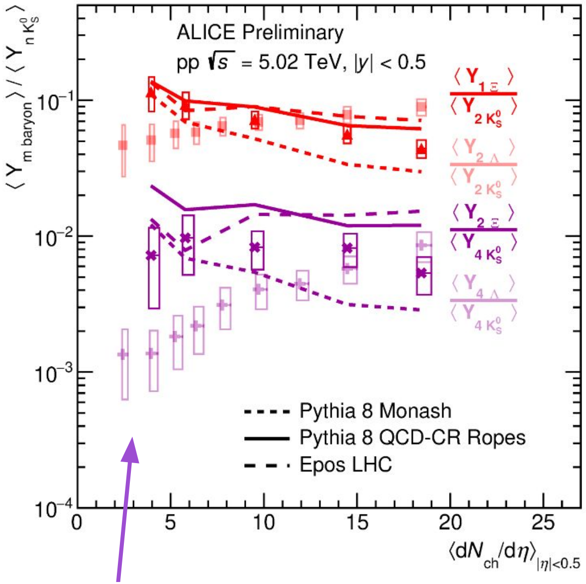

$\langle Y_{m\ baryon} \rangle / \langle Y_{n K^0_S} \rangle$

ΔS = 0 → test hadron production at fixed number of strange quarks and different light quark content

Decreasing trend **with multiplicity**

Yield ratios with ΔS = 0

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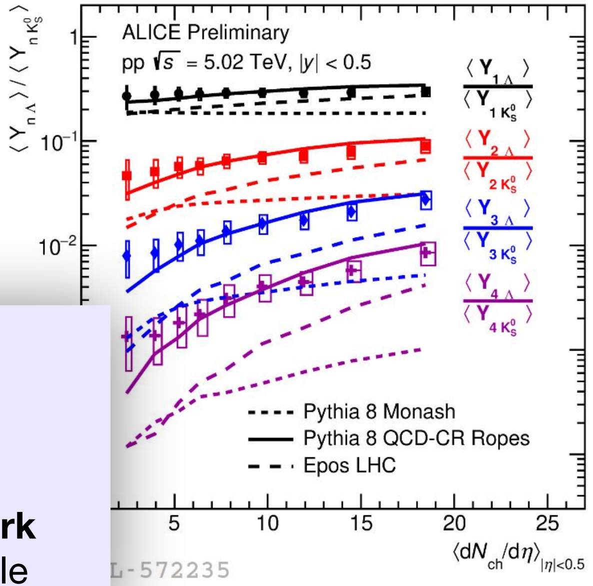
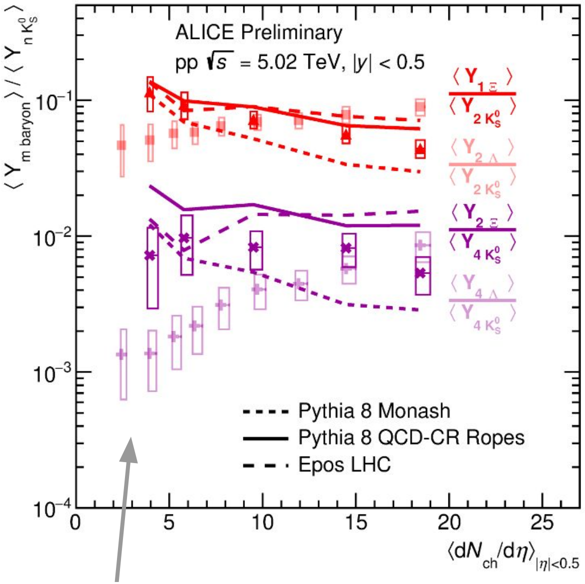




Yield ratios with ΔS = 0 show more than "simple" **strange baryon enhancement**

The **probability of light** (u,d) **quark (re-)combination** also plays a role

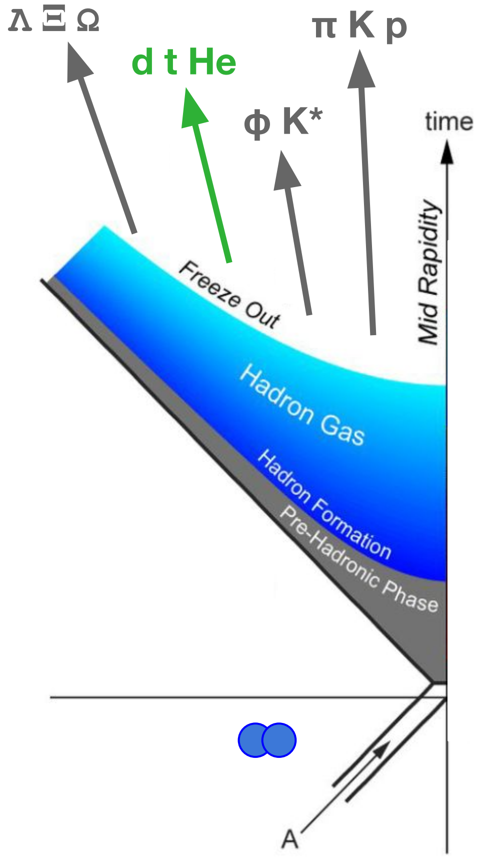
Model comparison:
All trends are rather well reproduced by Pythia 8 QCD-CR Ropes, which includes color reconnection effects

$\langle Y_{m\,baryon} \rangle / \langle Y_{n K^0_S} \rangle$

ΔS = 0 → test hadron production at fixed number of strange quarks and different light quark content

Decreasing trend **with multiplicity**

(Anti)nuclei measurements with ALICE and relevance for astrophysics



LHC: an (anti)nucleus factory

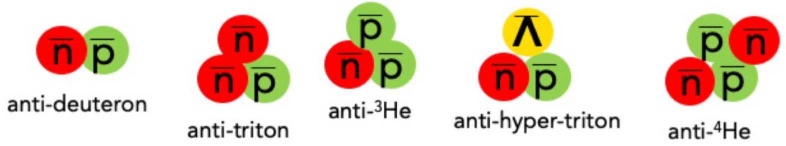
Years of light (anti)nuclei measurements at the LHC → improved understanding of their production mechanisms, but still **not fully understood**

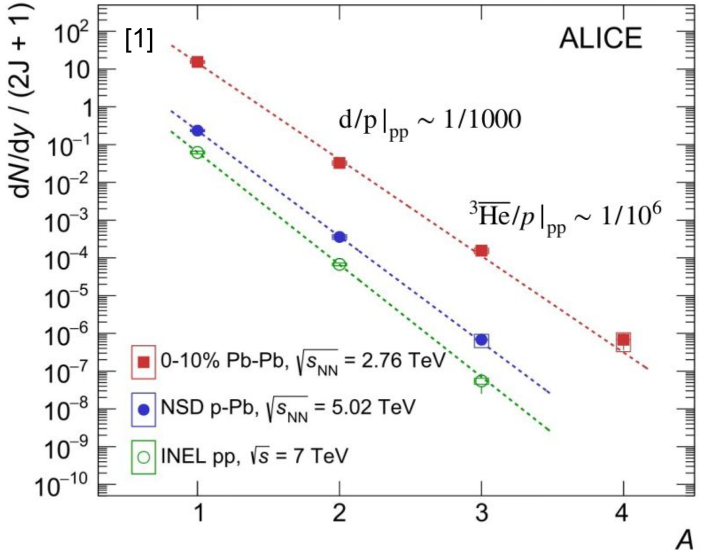
Ideal conditions at LHC energies:
antimatter / matter ~ 1

Rarely produced in high-energy collisions
→ require large integrated luminosity

Two main classes of models to describe light (anti)nuclei production

- **statistical hadronisation** model (SHM)
- **coalescence** model





[1] Acharya et al., Phys. Lett. B 800, 135043 (2020)

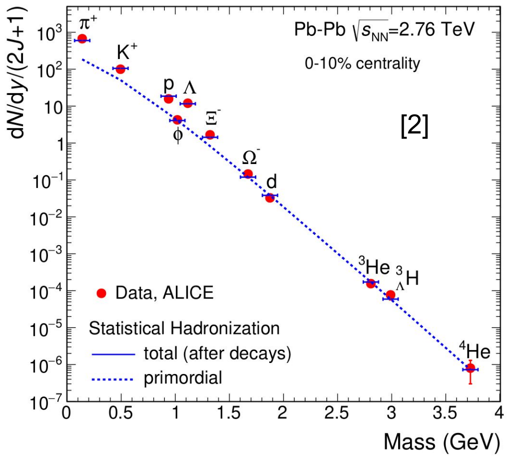
Modelling the production of (anti)nuclei

Statistical models (SHM)

Hadron production from a system in **thermal and hadrochemical equilibrium** [1,2]

$$dN/dy \propto V \exp\left(-\frac{m}{T_{ch}}\right)$$

Extension to pp in the canonical ensemble → **CSM**



[1] V. Vovchenko et al., PLB 785 (2018) 171-17
[2] Andronic, A. et al., Nature 561, 321–330 (2018)

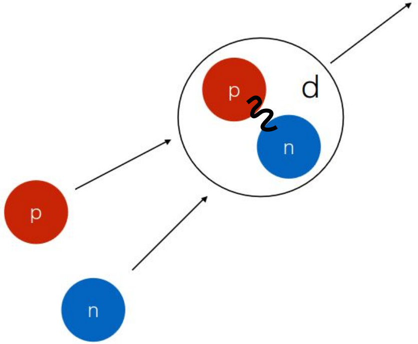
Coalescence models

Nucleons close in the phase space at the freeze-out can form a nucleus via **coalescence** [1,2]

Coalescence parameter B_A :
- is related to the coalescence probability
- depends on the source size and on the nucleus wave function

$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

where:
- A is the mass number of the nucleus
- $p_p = p_A / A$



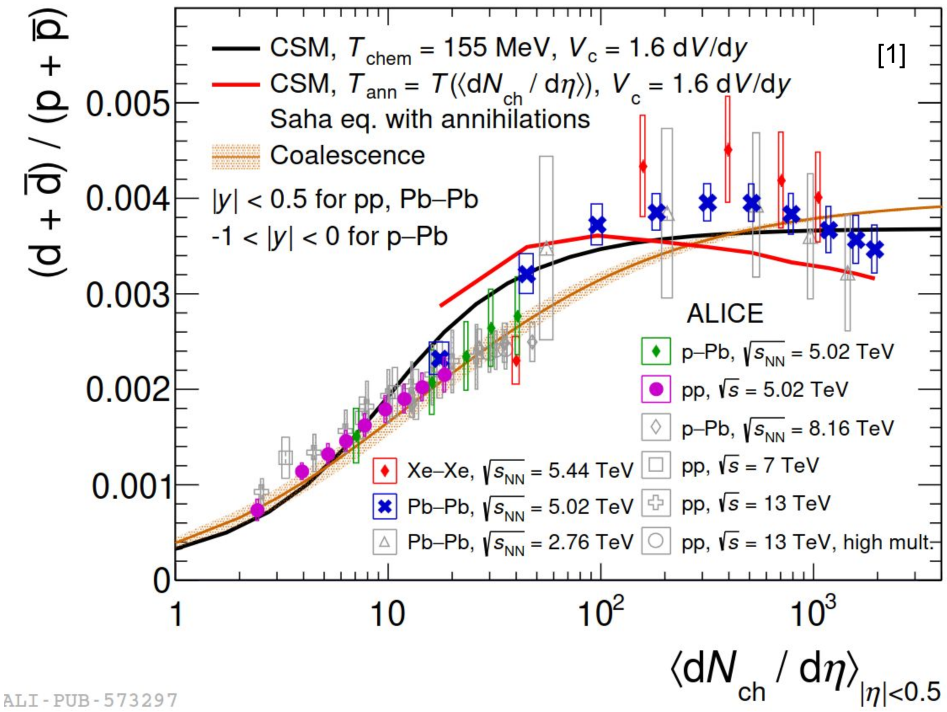
[1] J. I. Kapusta, Phys.Rev. C21, 1301 (1980)
[2] Scheibl, Heinz, Phys.Rev.C59:1585-1602 (1999)

Yield ratios: d/p

d/p ratio evolves smoothly with multiplicity
→ dependence on the system size

Both models are able to describe the data:

- CSM: canonical suppression
- Coalescence model: interplay between source size and nuclear size



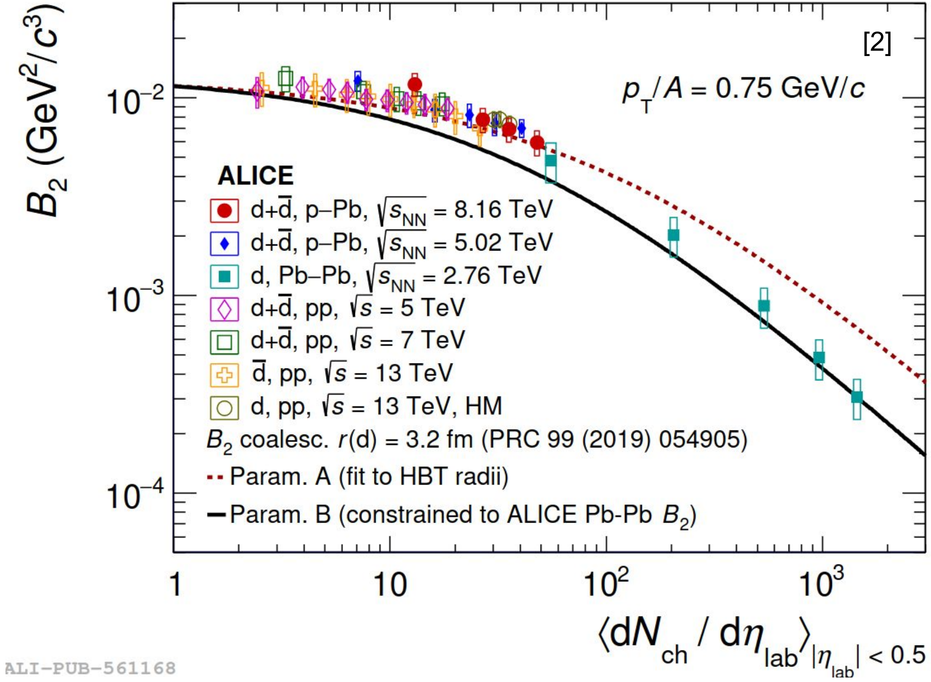
[1] arxiv:2405.19826

Coalescence probability B_A

$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

For high multiplicity Pb–Pb significant B_2 drop

→ can be explained within the coalescence model due to the **increase in the source size**



[1] arxiv:2405.19826
[2] Phys. Lett. B 846 (2023) 137795

Hypertriton production

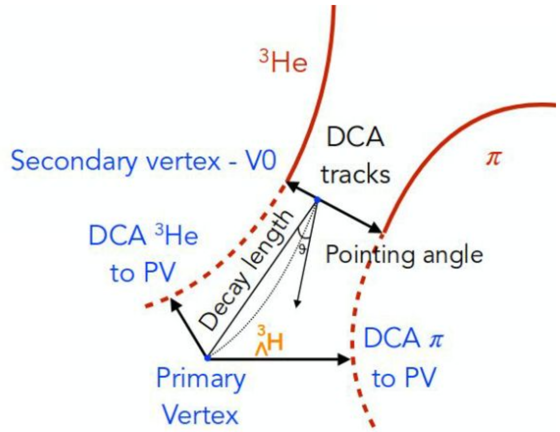
Hypertriton has a larger radius wrt deuteron:

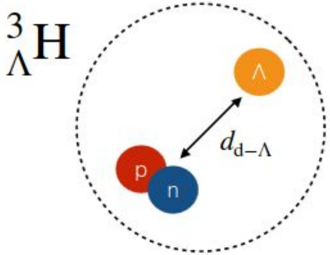
$r\left({}^{3}_{\Lambda}\mathrm{H}\right) = 10.79\ \mathrm{fm}$ (1), $r\left(\mathrm{d}\right) = 1.96\ \mathrm{fm}$

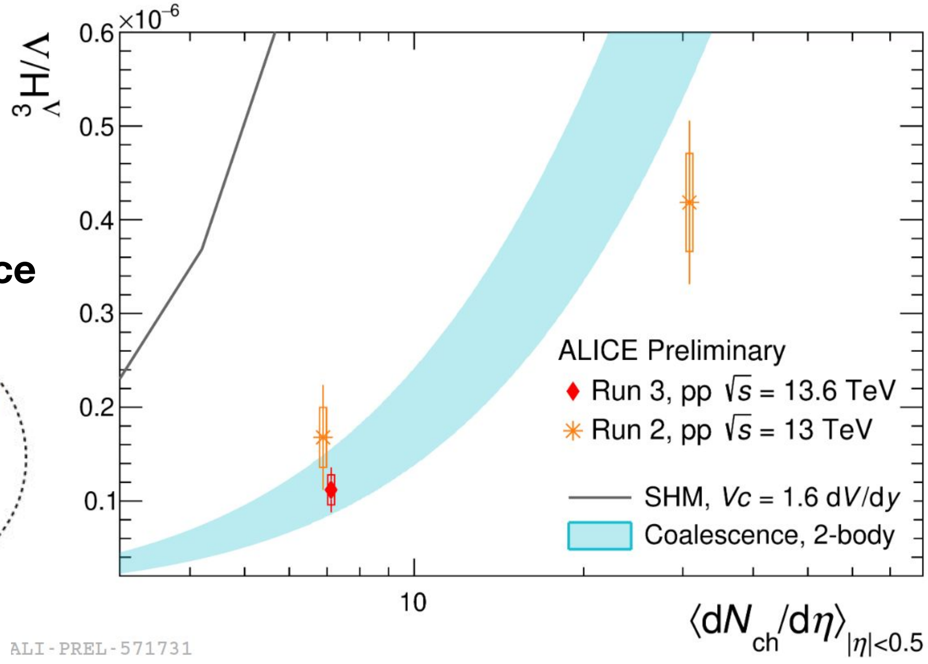
SHM and coalescence predictions significantly diverge at low multiplicity

→ ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ **in pp collisions favours coalescence**

Exploiting Run 3 larger statistics!





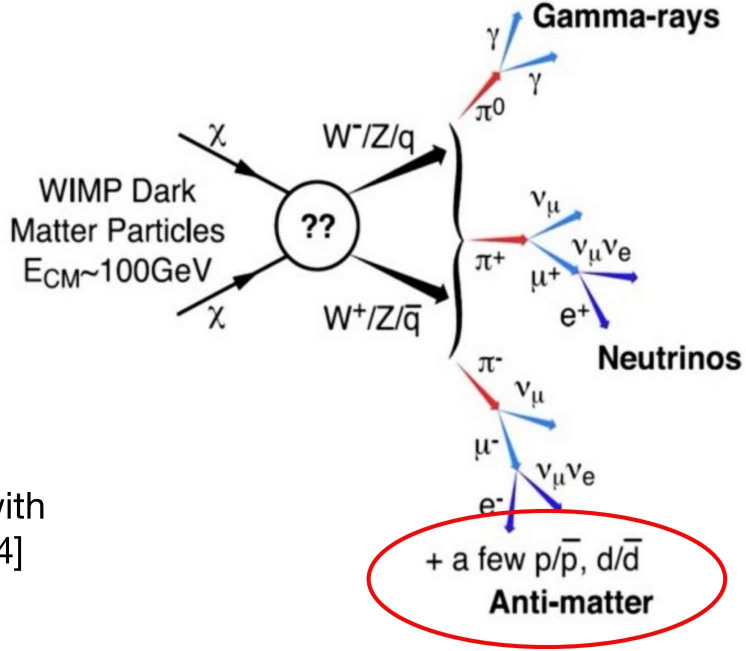


(1) F. Hildenbrand and H.-W. Hammer, Phys. Rev. C 100, 034002

Light antinuclei as probes for Dark Matter

Cosmic ray antideuteron and antihelium nuclei have been suggested as possible **probes for Dark Matter** (DM) **WIMPs** (mass ~ few GeV – few TeV) [1-3]

- Anti-p and anti-n can be produced by WIMP **annihilation into SM channels**
- anti-deuterons and anti-^{3}He are produced via **coalescence** of anti-nucleons



Subject for indirect DM searches with space-based experiments such as **AMS-02** (ongoing)

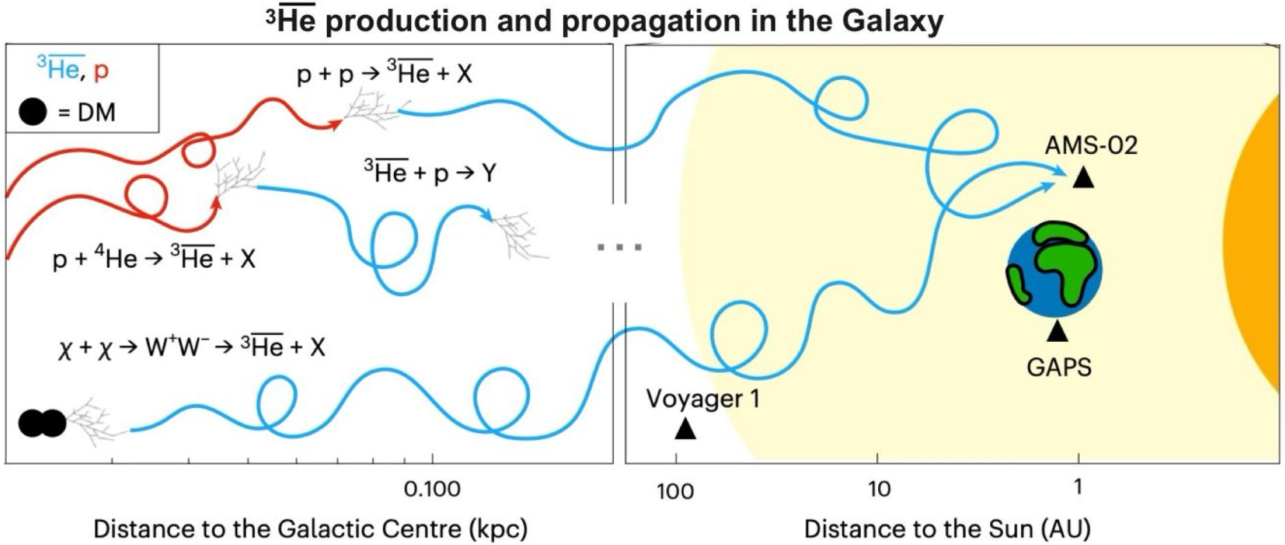
Since ~10 years AMS has collected > 220 billions CRs with few candidate events compatible with antihelium mass [4]

[1] M. Korsmeier, et al., Phys. Rev. D 97, 103011 (2018)
[2] M. Cirelli, at al., JHEP 08, 009 (2014)
[3] E. Carlson, et al., Phys. Rev. D 89, 076005 (2014)
[4] Ting, S. , CERN Colloquium (2016)

(Anti)nuclei in cosmic rays

The largest fractions of primary CR are protons and helium, **no antinuclei as primary CR**

Secondary anti-p, anti-d, anti-^{3}He produced by **interaction of primary CR** with the InterStellar Medium ISM (pp, p-He, …) constitute a **background** for the DM signal



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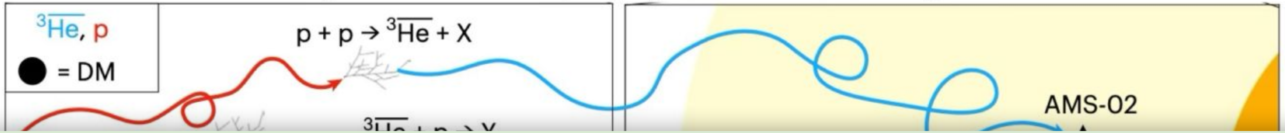
$^3\overline{\text{He}}$ production and propagation in the Galaxy



From ALICE:

- **Antinuclei formation mechanism** (coalescence) → constraint with LHC data
- **Measured antinucleus inelastic cross section** to account for absorption by ISM

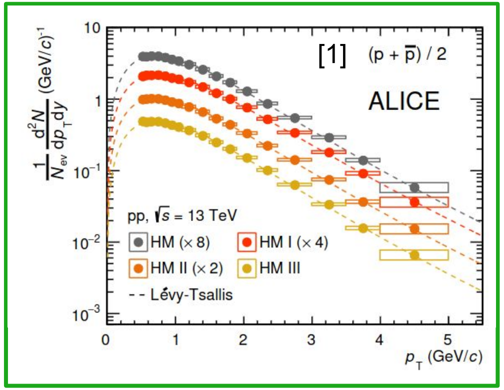
ALICE experimental input to coalescence modelling

A recent study shows that ALICE measurements of:

- proton production **yields**
- proton **source radius**

in high-multiplicity pp collisions, allow for **prediction** of the deuteron spectrum via **coalescence** with **no free parameters**

Wigner-formalism based coalescence afterburner



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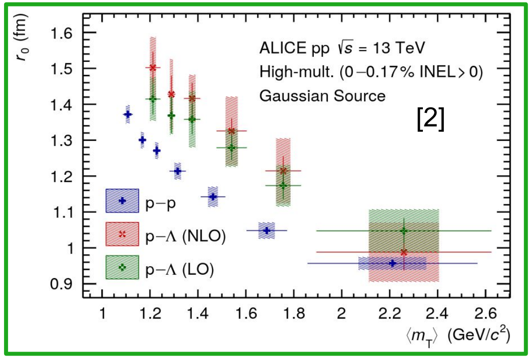
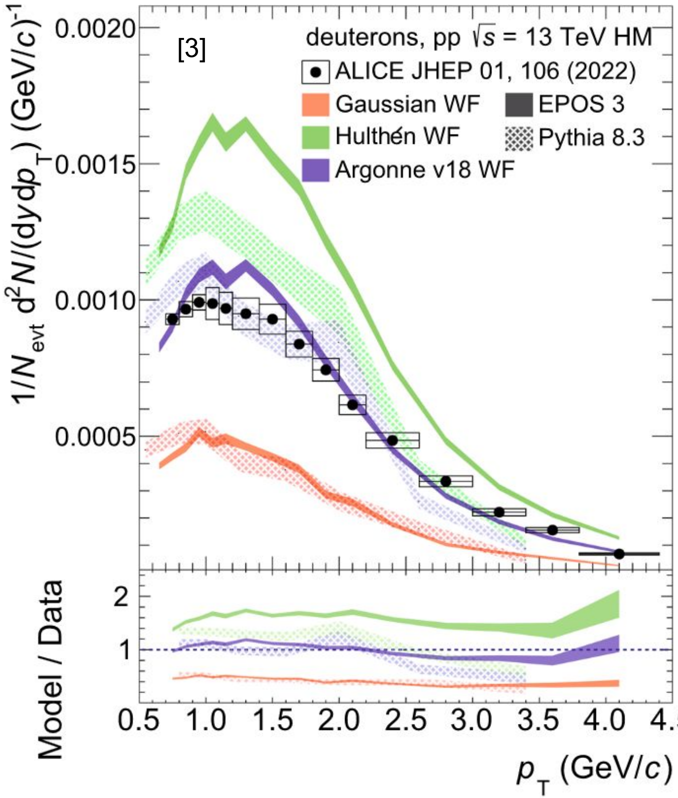


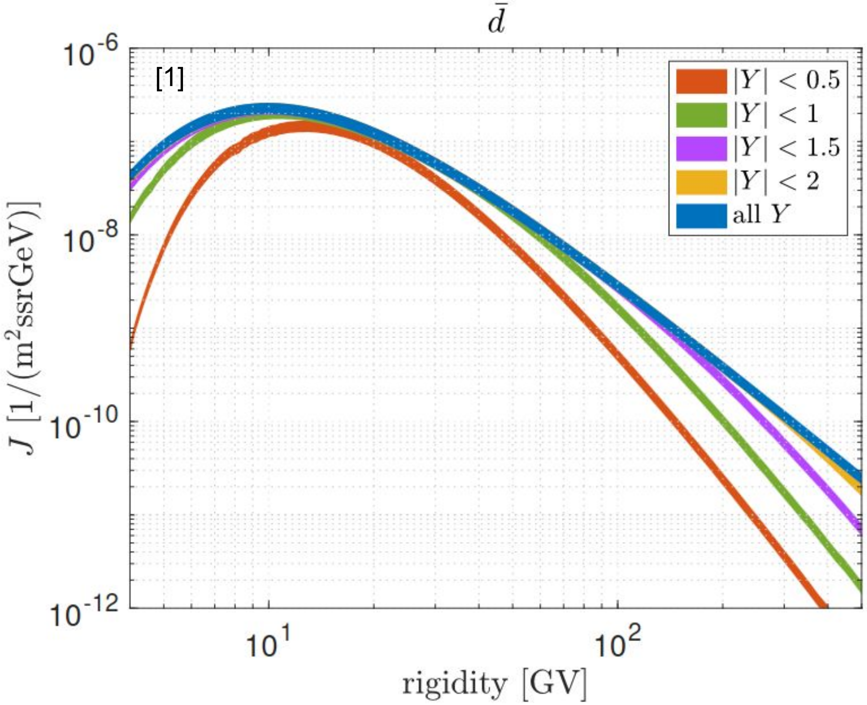


[1] JHEP 01 (2022) 106
[2] Phys. Lett. B 811 (2020) 135849
[3] Mahlein, M., *Eur. Phys. J. C* **83**, 804 (2023)

Rapidity dependence of coalescence

Model predictions based on ALICE measurements are used as input to calculate **antideuteron flux from cosmic rays** [1]

But typically ALICE measurements cover **midrapidity** (|*y*|<0.5) while astrophysical models extrapolate to the **forward** region



[1] K. Blum, Phys. Rev. C. 109. L031904

Rapidity dependence of coalescence

$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

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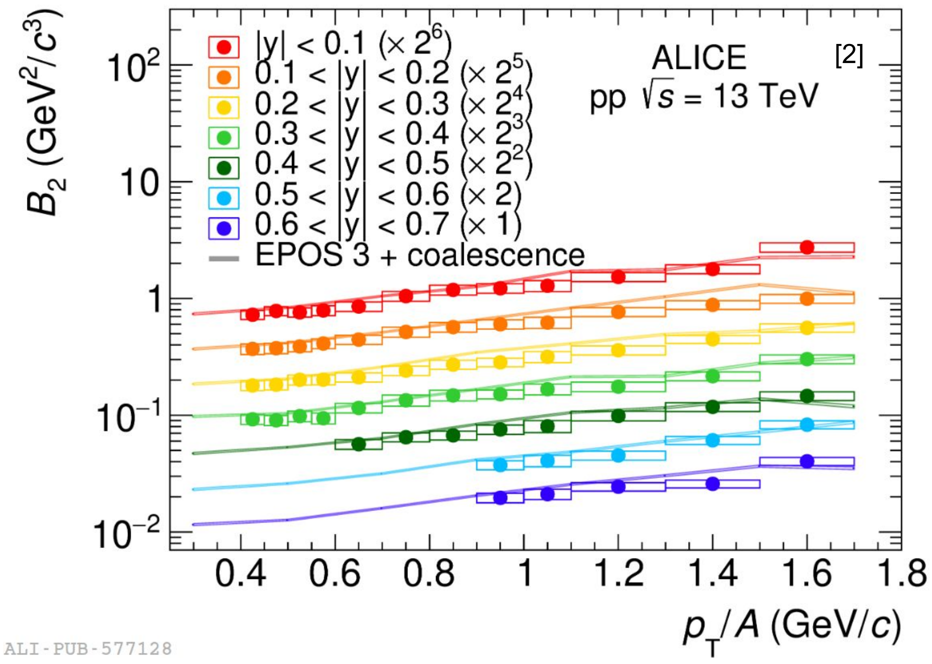
The current acceptance of the ALICE detector allows to extend the measurement of antideuteron **up to |Δy| < 0.7** [2]
→ no strong dependence on rapidity is observed

NEW!

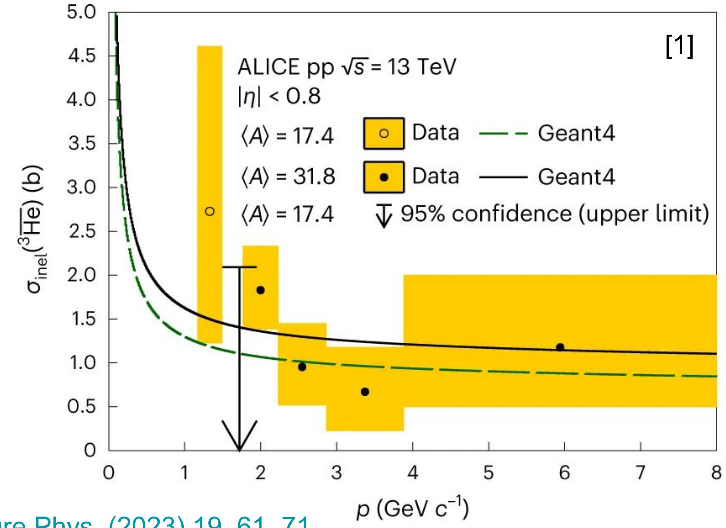


[1] K. Blum, Phys. Rev. C. 109, L031904
[2] arxiv:2407.10527

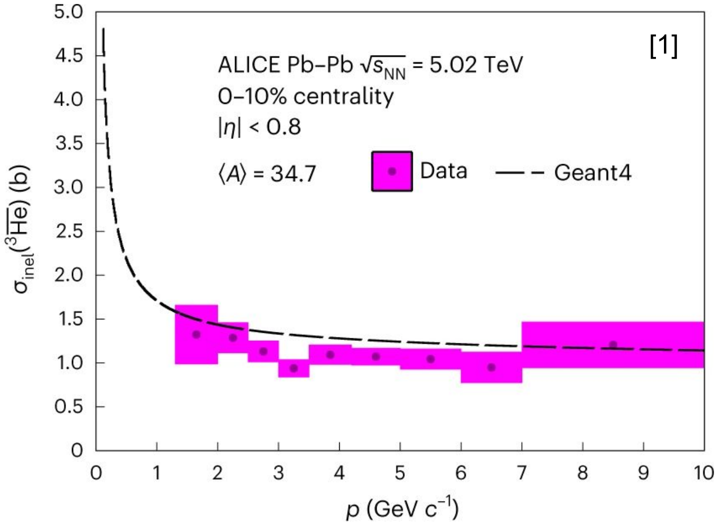
Measurement of the inelastic $^3\overline{\mathrm{He}}$ cross section

ALICE measured the **inelastic cross section** for antinuclei using the LHC as antimatter factory and the experimental apparatus as a target → **significant impact on $^3\overline{\mathrm{He}}$ propagation in space**

Antimatter-to-matter ratio:
measurement of reconstructed $^3\overline{\mathrm{He}}/^3\mathrm{He}$ ratio and compare to MC expectations



TOF/TPC-matching ratio:
measurement of reconstructed $^3\overline{\mathrm{He}}(\mathrm{TOF})/^3\overline{\mathrm{He}}(\mathrm{TPC})$ ratio and compare to MC expectations



[1] Nature Phys. (2023) 19, 61–71

Summary

In the last years ALICE tried to push our understanding of strangeness and nuclei production mechanisms in high-energy hadronic collisions

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- First measurement of **multiple strange hadron production** and yields ratio with $\Delta S = 0$

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Important insights from nuclei production and applications to Astrophysics:

- LHC can be used as **antimatter factory** to study the production of light (anti)nuclei
- Yield ratios of (anti)nuclei and hypernuclei to **constrain formation mechanisms** with applications to indirect Dark Matter searches
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More to come with LHC Run 3 increased statistics!