Probing strangeness hadronisation with event-by-event production of multistrange hadrons with ALICE

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LHC Seminar
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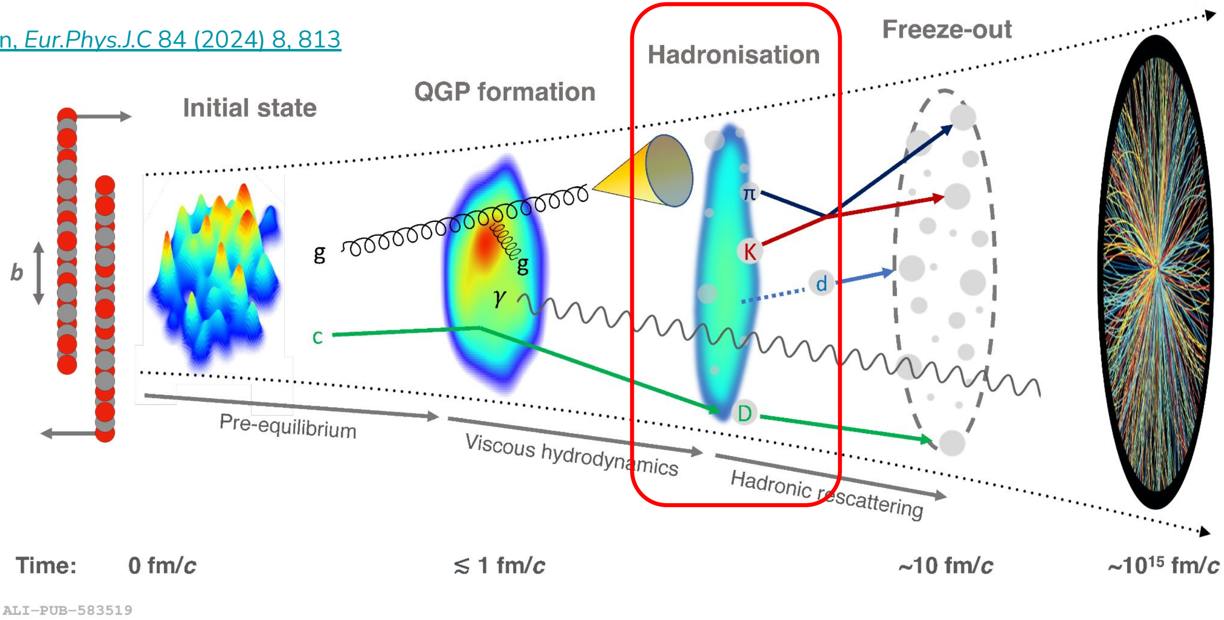
Outline

- Introduction
  - Enhanced strangeness production in hadronic and heavy-ion collisions
  - (Strangeness) hadronisation models
- Defining the observables
  - Event-by-event fluctuations as a probe of hadronisation
  - Cumulants and correlations
- Data analysis
  - Candidate identification
  - Efficiency corrections
- Results from ALICE Collaboration, arxiv:2405.19890
  - Fully-corrected fluctuation observables
  - Comparison with models
- Conclusions and outlook

Hadron production in heavy-ion collisions

- Standard model of heavy-ion collisions
  - The evolution of the system produced in each event occurs through multiple stages
  - Hadronisation → recombination of colour degrees-of-freedom into colour singlets
    - Investigated through measurements of hadron production

ALICE Collaboration, *Eur.Phys.J.C* 84 (2024) 8, 813



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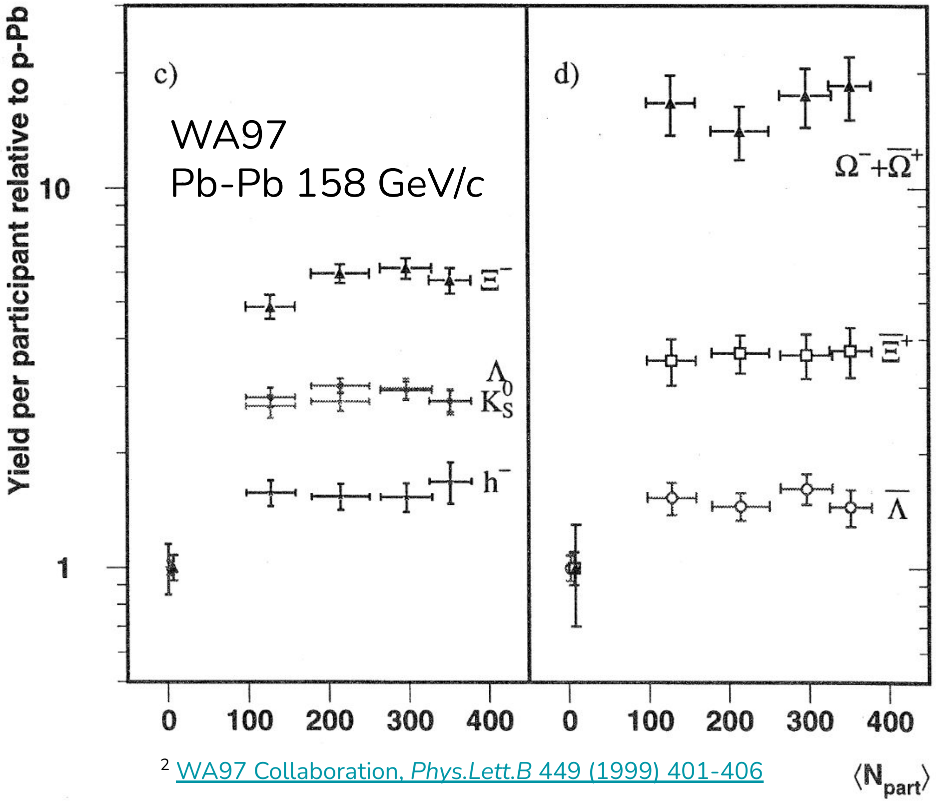
Strangeness enhancement: the origins

- Enhancement of strange hadron yields in heavy-ion collisions
  - Initially proposed as a smoking gun of the formation of thermalised strongly-interacting matter[1]
  - Observation of enhanced production at the SPS in Pb–Pb collisions[2,3,4], by STAR at RHIC in Au–Au collisions[5]
  - $\langle N_{part} \rangle$ ~ centrality ~ multiplicity

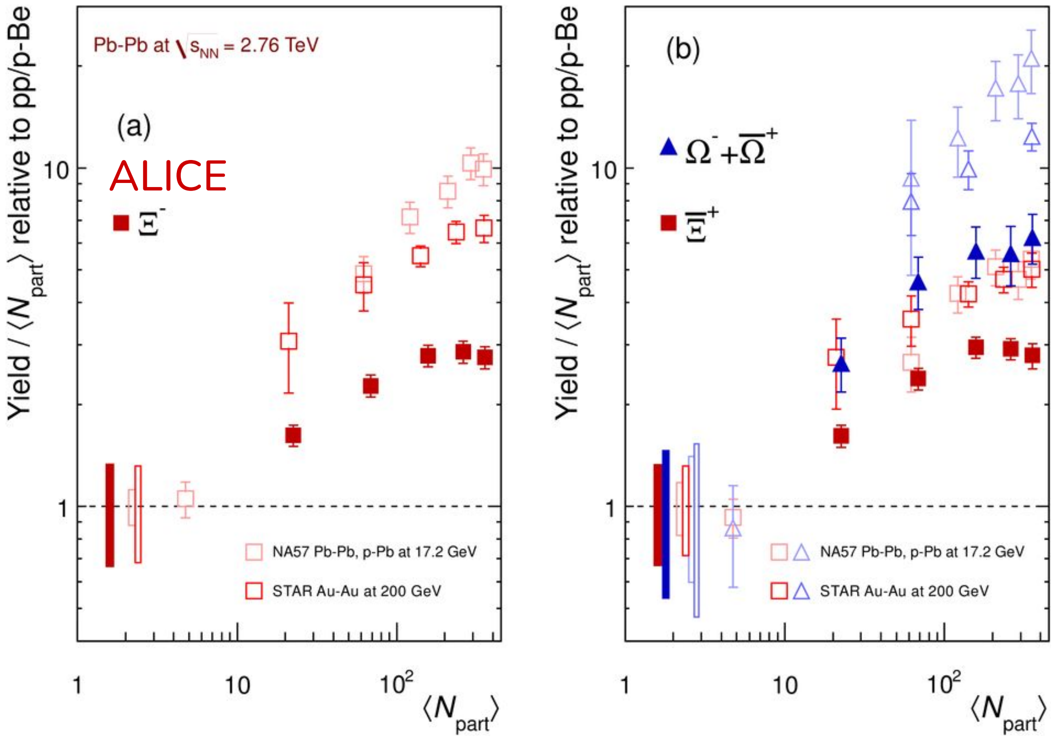
[1] J. Rafelski and B. Müller, Phys. Rev. Lett. 48, 1066 (1982)
[3] NA49 Collaboration, *Phys.Lett.B* 538 (2002) 275-281
[4] NA57 Collaboration, *Phys.Lett.B* 595 (2004) 68-74
[5] STAR Collaboration, *Phys.Rev.C* 77 (2008) 044908



[2] WA97 Collaboration, *Phys.Lett.B* 449 (1999) 401-406

Strangeness enhancement at the LHC

- First measurements by ALICE in Pb–Pb at 2.76 TeV
  - Increase of multistrange hadron yields with respect to the pp baseline
  - Decrease of the relative enhancement at higher centre-of-mass energy due to the increased relative strangeness production in pp collisions
  - What does the small-system “baseline” look like?

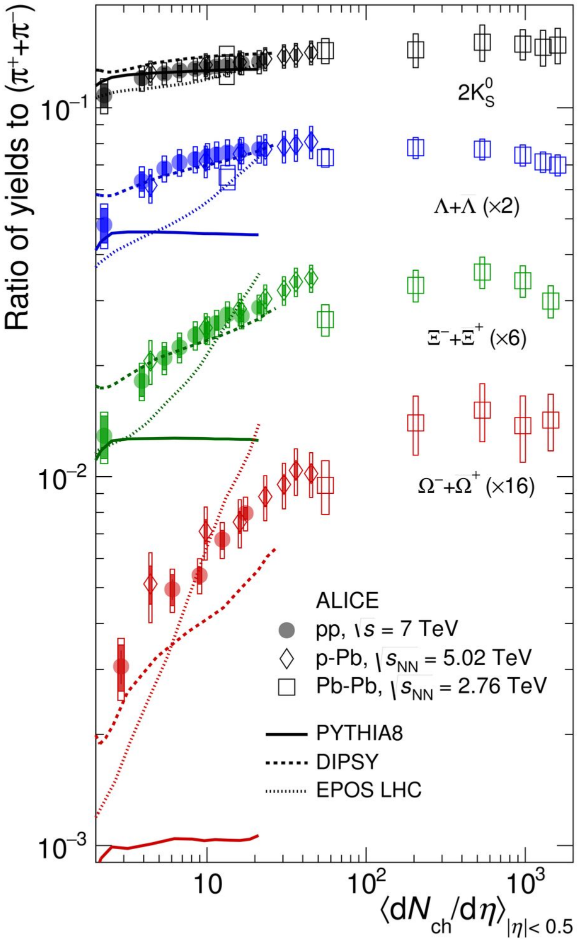


[ALICE Collaboration, *Phys.Lett.B* 728 (2014) 216-227](#)

High-multiplicity pp and p–Pb collisions at the LHC

ALICE

- (Multi)strange-hadron-to-pion yield ratios as a function of multiplicity
  - Continuous evolution from low-multiplicity pp to central (head-on) Pb–Pb
  - The yields measured in high-multiplicity pp and p–Pb reach the values observed in Pb–Pb
  - Which physical mechanism regulates strange hadron production?

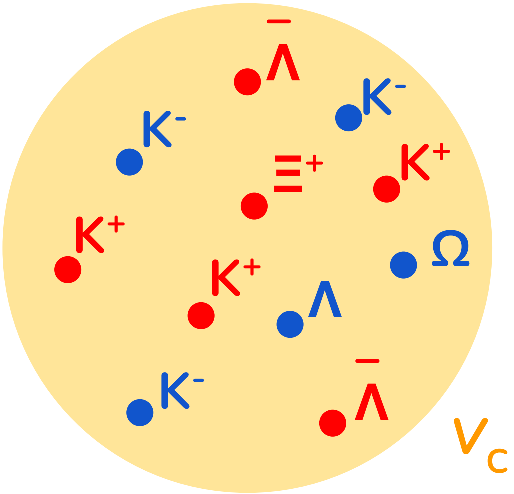


ALICE Collaboration, *Nature Physics*, 13, 535-539 (2017)

(Strangeness) hadronisation models

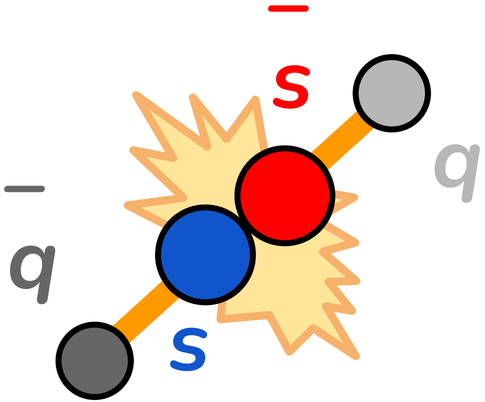
- Hadronization → non-perturbative many-body problem → no *ab-initio* calculations
- Phenomenological models based on different assumptions are used

Statistical hadronisation



[1] V. Vovchenko and V. Koch, Phys. Rev. C 103, 044903 (2021)
[2] J. Cleymans et al, Phys. Rev. C 103, 014904 (2021)

Lund string fragmentation



[3] C. Bierlich et al., arXiv:2203.11601 [hep-ph]
[4] Xin-Nian Wang and Miklos Gyulassy, Phys. Rev. D 44, 3501

→ Both approaches successfully describe average hadron yields

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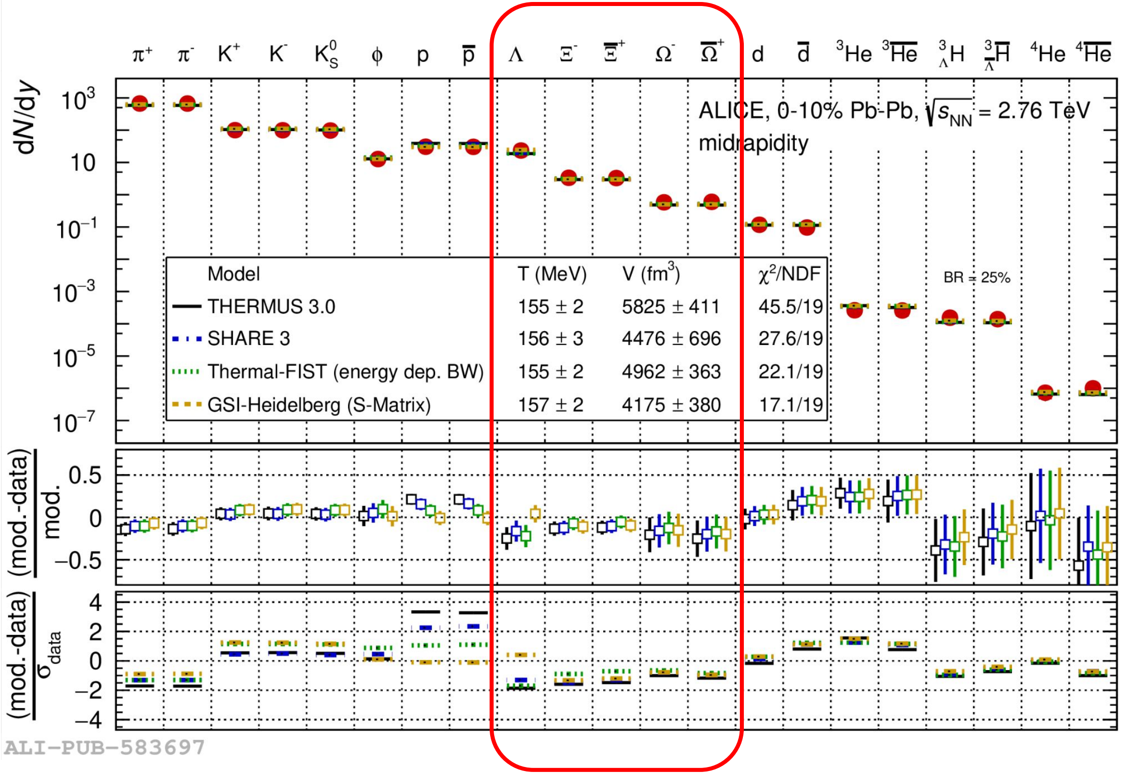
Statistical hadronisation model

- Statistical-mechanical model of hadronisation
  - Fireball → hadron-resonance gas (HRG) in thermodynamic equilibrium
    → Reproducing QCD EoS below $T \sim 160$ MeV
  - Heavy-ion collisions → yields at midrapidity are well described by a grand canonical ensemble
  - Thermal parameters V, T, μ

[1]A. Andronic et al., *Nature* 561 (2018) 7723, 321-330

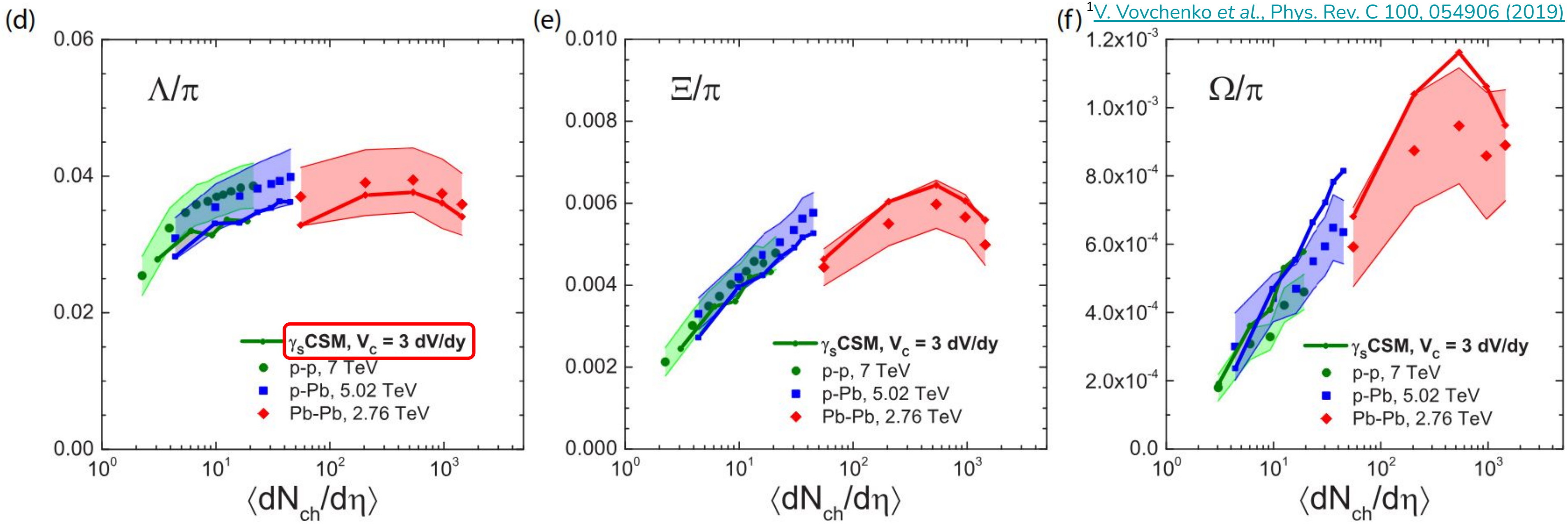


[2]ALICE Collaboration, *Eur.Phys.J.C* 84 (2024) 8, 813

Canonical suppression of strangeness

- Statistical hadronisation in small systems is treated within canonical ensemble
  - Exact conservation of quantum numbers within the canonical volume, $V_c = k\, dV/dy$
    → Parameter of box approximation implemented by different models[1, 2]
  - Partial strangeness equilibration can be modelled by saturation parameter[1], $\gamma_s \leq 1$

[1] V. Vovchenko et al., Phys. Rev. C 100, 054906 (2019)



[2] J. Cleymans et al, Phys. Rev. C 103, 014904 (2021)

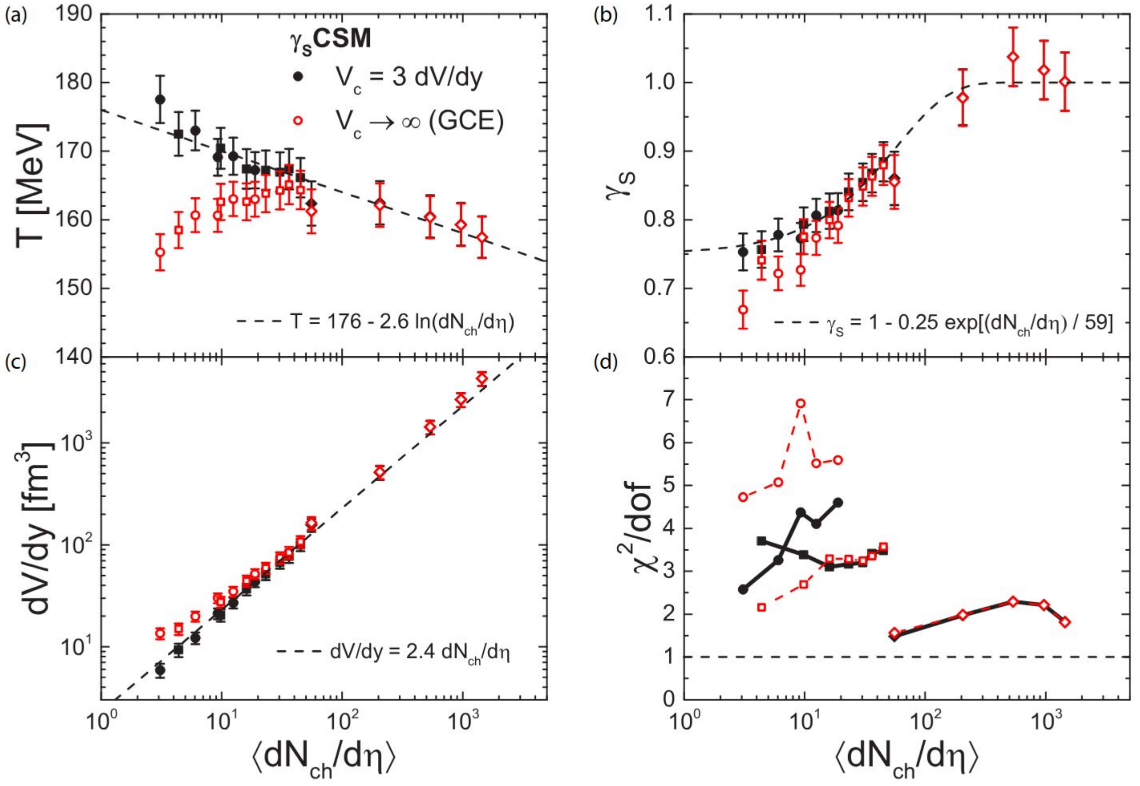
Canonical statistical hadronisation parameters

Thermal-FIST[1,2]

- The model parameters are extracted by fitting the hadron yields measured at the LHC in pp, p–Pb, and Pb–Pb
- The data are best described by $V_c = 3\ dV/dy$
- Simple parameterisations vs. multiplicity

[1]V.Vovchenko et al., *Comput.Phys.Commun.* 244 (2019) 295-310

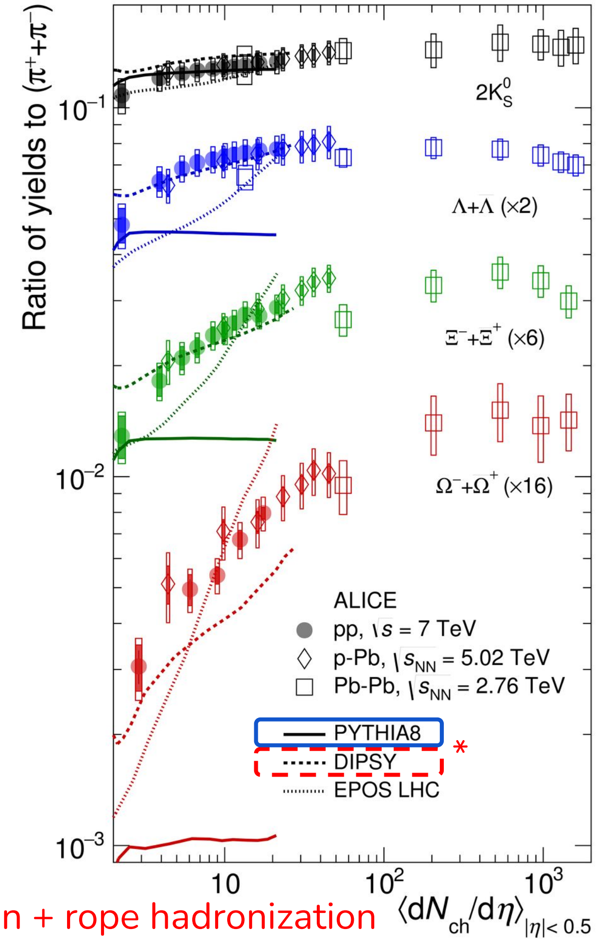
[2]V. Vovchenko *et al.*, Phys. Rev. C 100, 054906 (2019)



Lund string fragmentation

- Quark-antiquark pair production through the breaking of color string
  - Implemented by event generators such as Pythia 8 and HIJING
  - Simple string fragmentation
    → flavour suppression regulated by quark masses[1]
  - Strangeness and baryon enhancement reproduced adding rope hadronisation[2] + color reconnection[3] + string shoving[4]

[1]P. Skands, *Eur.Phys.J.C* 74 (2014) 8, 3024
[2]C. Bierlich, *JHEP* 03 (2015) 148
[3]J. R. Christiansen et al., *JHEP* 08 (2015) 003
[4]C. Berlich, arxiv:1612.05132 [hep-ph]



ALICE Collaboration, *Nature Physics*, 13, 535-539 (2017)

*string fragmentation + rope hadronization

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Lund string fragmentation (2)

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  - Implemented by event generators such as Pythia 8 and HIJING
  - Simple string fragmentation
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[3]J. R. Christiansen et al., *JHEP* 08 (2015) 003
[4]C. Berlich, arxiv:1612.05132 [hep-ph]

[5]R. Nayak *et al.*, Phys. Rev. D 100, 074023 (2019)

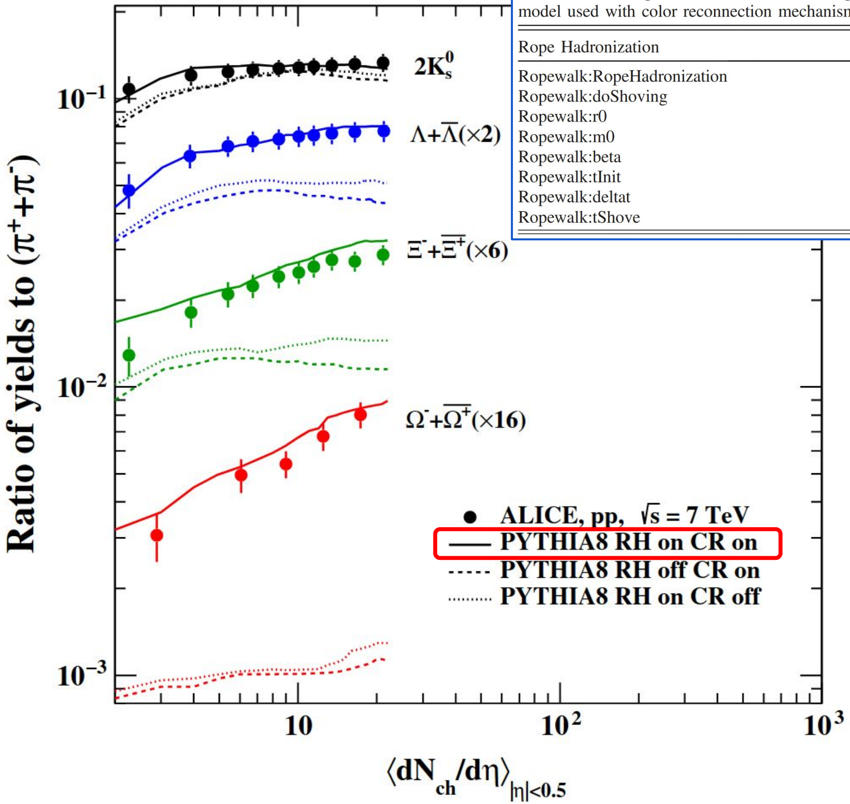
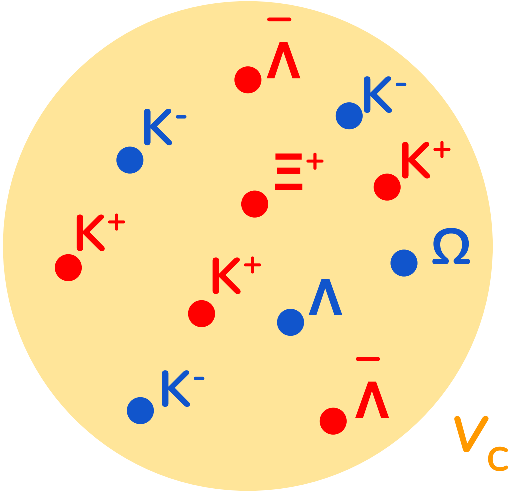


TABLE I. The parameter values of the rope hadronization model used with color reconnection mechanism.

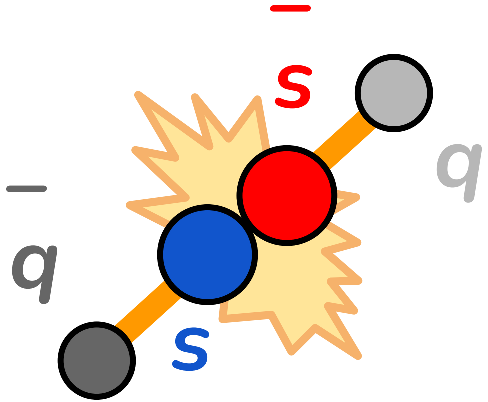
Rope Hadronization	Values
Ropewalk:RopeHadronization	On
Ropewalk:doShoving	On
Ropewalk:r0	0.5
Ropewalk:m0	0.2
Ropewalk:beta	1.0
Ropewalk:tInit	1.0
Ropewalk:deltat	0.05
Ropewalk:tShove	10.0

Quantum-number conservation in hadronization models

- Canonical statistical hadronisation
  - Long-range rapidity correlations
  - Like- and unlike-sign correlations induced by quantum number conservation over extended volume



- Lund string fragmentation
  - Short-range rapidity correlations
  - Mostly correlation of unlike-sign quantum numbers due to quark-antiquark pair creation



→ Can be probed via event-by-event observables

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Event-by-event fluctuation observables

- Hadron yields are measured in a phase-space region limited by detector acceptance
  - Quantum numbers conserved by hadronization fluctuate on an event-by-event basis
  - Experiment → fluctuation of the yields of hadrons carrying conserved quantum numbers

Event-by-event fluctuation observables (2)

- Hadron yields are measured in a phase-space region limited by detector acceptance
  - Quantum numbers conserved by hadronization fluctuate on an event-by-event basis
  - Experiment → fluctuation of the yields of hadrons carrying conserved quantum numbers
  - Quantified by the cumulants of the hadron multiplicity distribution

Cumulants

$\kappa_1 = \langle n \rangle$ Mean value

$\kappa_2 = \langle (n - \langle n \rangle)^2 \rangle$ (Co)variance

$\kappa_{11}(n, m) = \langle (n - \langle n \rangle)(m - \langle m \rangle) \rangle$

$$\kappa_{11}(m, n) = \langle mn \rangle - \langle m \rangle \langle n \rangle$$

probe m-n correlation

→ Two species are required to probe same- and opposite-strangeness-sign correlations

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Net-Ξ– net-kaon correlation

- Same- and opposite-sign correlations → 2 different species → charged kaons and Ξ
  - Negligible effect of heavy resonance decays
- Observables: cumulant ratios of the net-particles number up to the second order

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Net-Ξ– net-kaon correlation (2)

- Same- and opposite-sign correlations → 2 different species → charged kaons and Ξ
  - Negligible effect of heavy resonance decays
- Observables: cumulant ratios of the net-particles number up to the second order

$$\kappa_2(\overline{\Xi}^+ - \Xi^-) = \kappa_2(\overline{\Xi}^+) + \kappa_2(\Xi^-) - 2\kappa_{11}(\overline{\Xi}^+, \Xi^-)$$

$$\kappa_{11}(\Delta\Xi, \Delta\mathrm{K}) = \kappa_{11}(\overline{\Xi}^+, \mathrm{K}^+) + \kappa_{11}(\Xi^-, \mathrm{K}^-) - \kappa_{11}(\overline{\Xi}^+, \mathrm{K}^-) - \kappa_{11}(\Xi^-, \mathrm{K}^+)$$

same-sign | opposite-sign

$$\rho_{\Delta\Xi\Delta\mathrm{K}} = \frac{\kappa_{11}(\Delta\Xi, \Delta\mathrm{K})}{\sqrt{\kappa_{2,\Delta\Xi}\kappa_{2,\Delta\mathrm{K}}}}$$

Pearson correlation coefficient

Cumulants

$\kappa_1 = \langle n \rangle$ Mean value

$\kappa_2 = \langle (n - \langle n \rangle)^2 \rangle$ (Co)variance

$\kappa_{11}(n, m) = \langle (n - \langle n \rangle)(m - \langle m \rangle) \rangle$

Net-particles

$\Delta\Xi = n_{\overline{\Xi}^+} - n_{\Xi^-}$

$\Delta\mathrm{K} = n_{\mathrm{K}^+} - n_{\mathrm{K}^-}$

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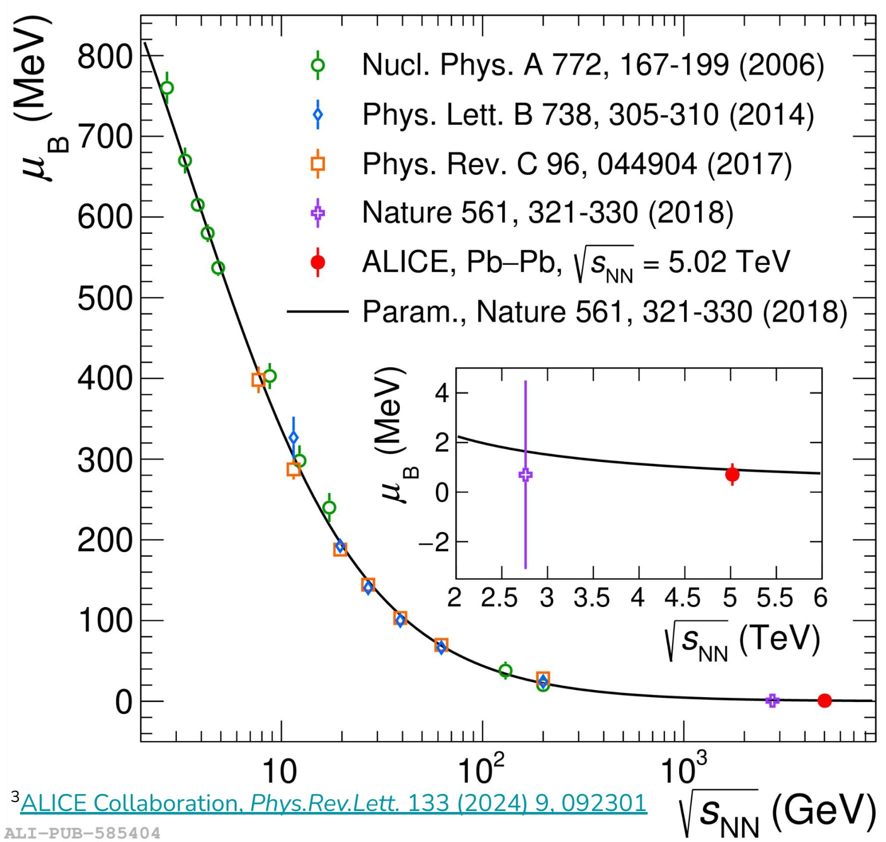
Why net-particle numbers?

- The event-by-event observables are measured in finite multiplicity intervals
  - Multiplicity (volume) fluctuations emerge on top of fluctuations induced by the hadronisation process
- Suppressed in net-particle number fluctuations if antimatter balances matter[1]
  - This condition is achieved at the LHC from pp to Pb–Pb collisions[2,3]

$$\mu_B \sim n_B - n_{\bar{B}}$$



[1] P. Braun-Munzinger et al., Nucl. Phys. A 960 (2017) 114-130
[2] ALICE Collaboration, *Phys.Rev.Lett.* 105 (2010) 072002
[3] ALICE Collaboration, *Phys.Rev.Lett.* 133 (2024) 9, 092301

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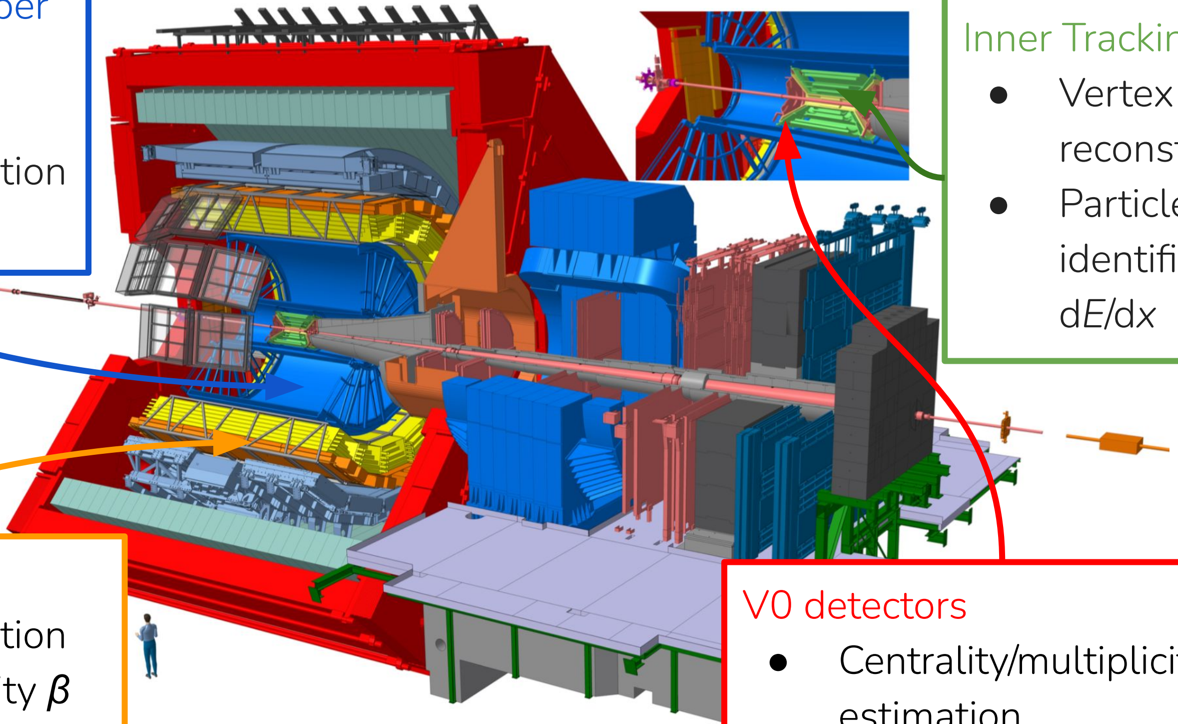
The ALICE detector in Run 2



Time Projection Chamber

- Main tracking detector
- Particle identification via dE/dx

Inner Tracking System

- Vertex and track reconstruction
- Particle identification via dE/dx

Time-Of-Flight

- Particle identification via particle velocity β

V0 detectors

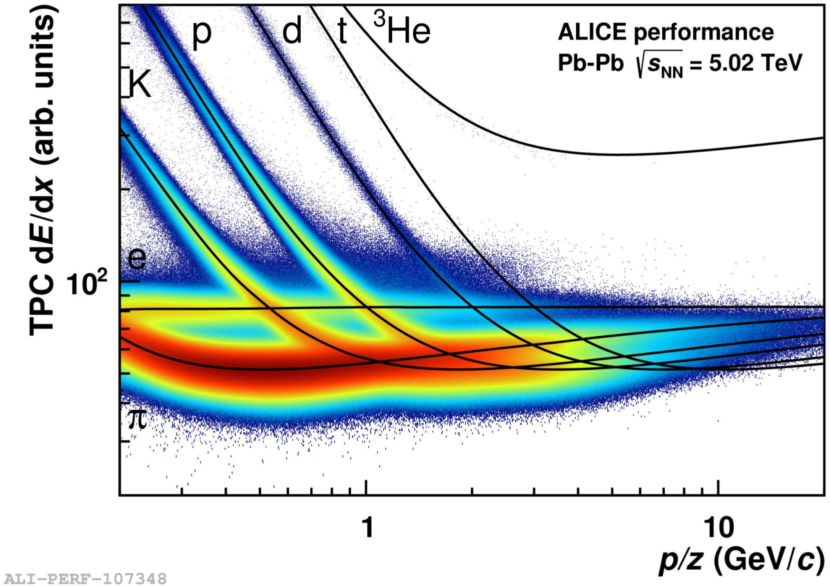
- Centrality/multiplicity estimation
- Trigger

Analysis strategy

- Data samples
  - 600M pp, 400M p–Pb, and 300M Pb–Pb inelastic events recorded in the LHC Run 2
- Candidate-by-candidate identification

Analysis strategy (2)

- Data samples
  - 600M pp, 400M p–Pb, and 300M Pb–Pb inelastic events recorded in the LHC Run 2
- Candidate-by-candidate identification
- Charged kaons → $0.2 < p_T < 1.0$ GeV/c
  - Tracked in the detector
  - Particle identification (PID)
    - dE/dx in ITS, TPC
    - β with TOF ($p_T > 0.4$ GeV/c)



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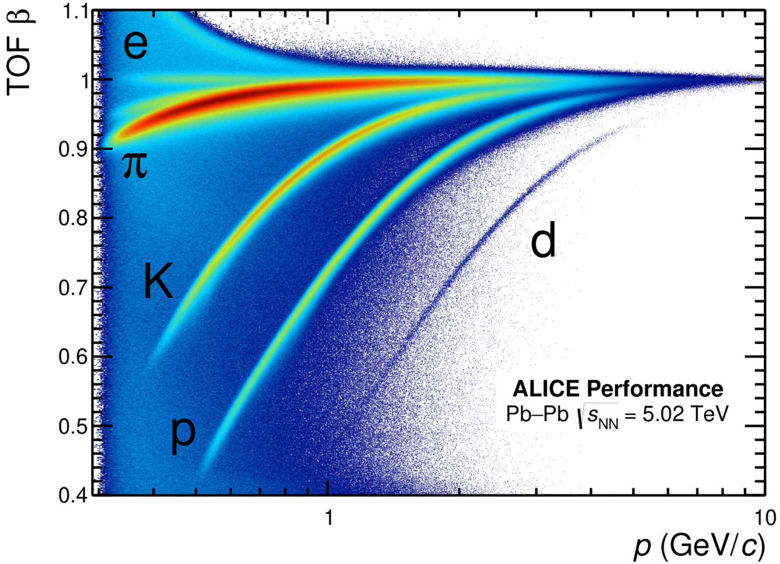

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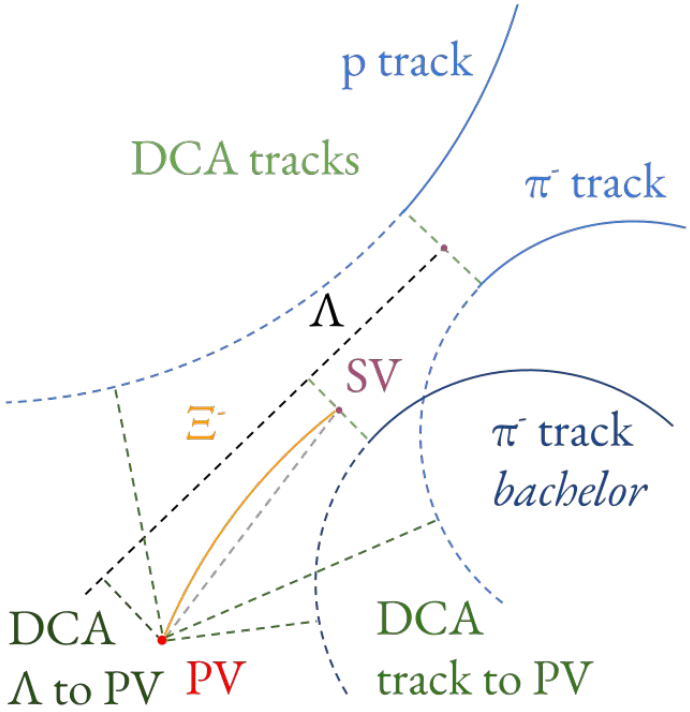
Analysis strategy (3)

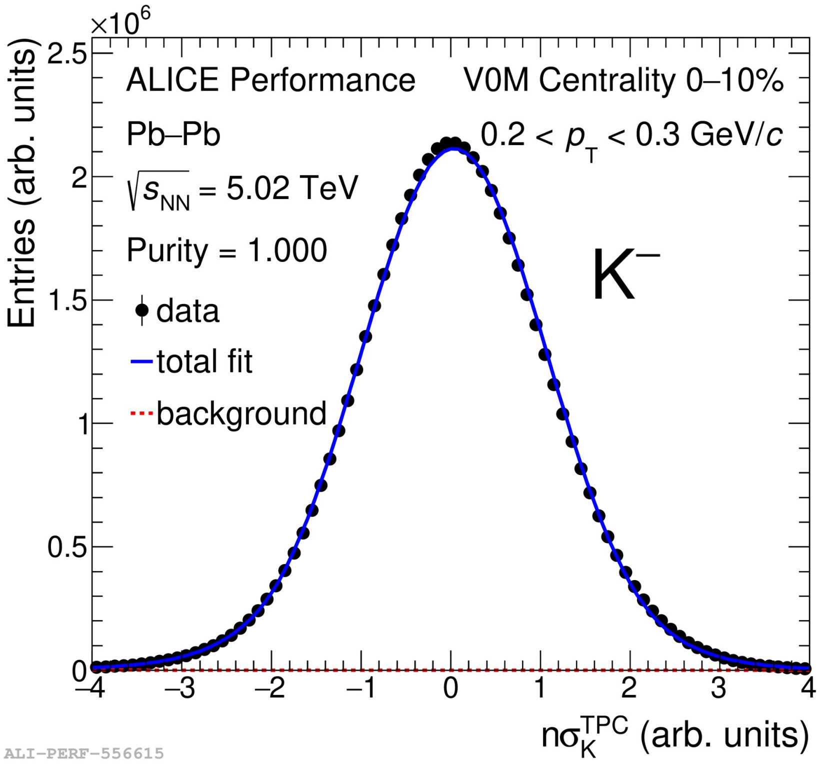
- Data samples
  - 600M pp, 400M p–Pb, and 300M Pb–Pb inelastic events recorded in the LHC Run 2
- Candidate-by-candidate identification
  - Charged $\Xi \rightarrow 1.0 < p_T < 3.0$ GeV/c
    - Reconstructed through cascade decay
    - Boosted decision trees (BDTs), using topological decay variables as input

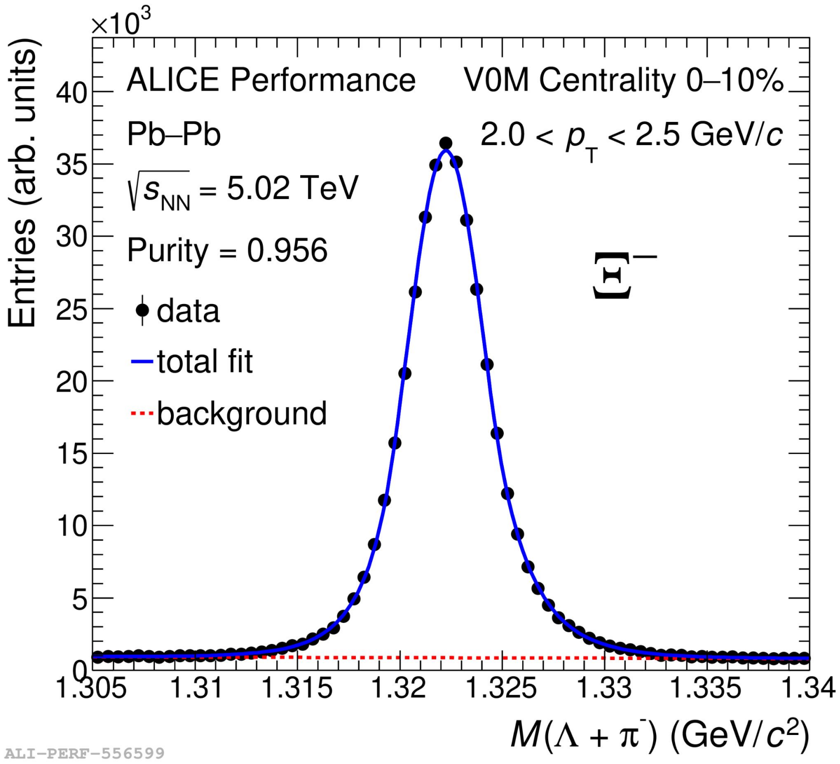


[1] ALICE Collaboration, ALICE-PUBLIC-2023-003
[2] ALICE Collaboration, *Phys.Rev.Lett.* 133 (2024) 9, 092301

Candidate identification performance

- Signal purity ≳ 95% across p_T and multiplicity
  - The residual impurity has a negligible effect in the measured observables





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Efficiency correction

- Raw cumulants are corrected by reconstruction and selection efficiency
  - 5% – 30% for kaons
  - 1% – 8% for Ξ (including BDT)
- Analytical formulas for corrected cumulants assuming binomial detector response
  - The binomiality is checked through MC simulations
  - Validation of the efficiency correction formulas via MC closure test

Binomial model

$$P_{\text{obs}}(n) = \sum_N P_{\text{true}}(N) B_{\epsilon,N}(n)$$

[1]T. Nonaka et al., Phys. Rev. C 95, 064912 (2017)

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Binomial model

$$P_{\text{obs}}(n) = \sum_N P_{\text{true}}(N) B_{\epsilon,N}(n)$$

- $\kappa_1 = \langle q_1 \rangle$
- $\kappa_2 = \langle q_1^2 \rangle - \langle q_1 \rangle^2 + \langle q_1 \rangle - \langle q_2 \rangle$
- $\kappa_{11}(A, B) = \langle q_{1,A} q_{1,B} \rangle - \langle q_{1,A} \rangle \langle q_{1,B} \rangle$

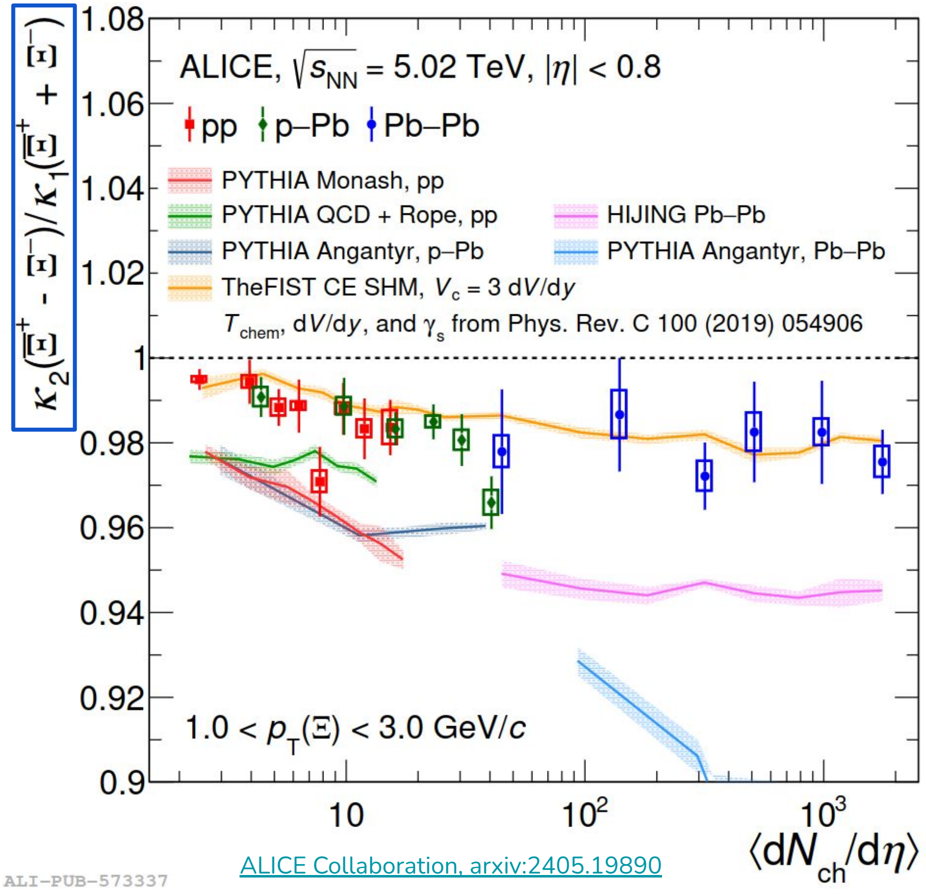
$$q_\alpha = \sum^{M}_{i=1} (N_i / \varepsilon_i^\alpha)$$

M = number of p_T bins
ε_i = efficiency in i-th p_T bin
N_i = raw counts in i-th p_T bin

[1] T. Nonaka et al., Phys. Rev. C 95, 064912 (2017)

Results: net-Ξ normalised second-order cumulant

- Normalised to uncorrelated baseline
  - Difference of two Poissonian random variables → Skellam distribution
  - A and B Poissonian $\Rightarrow \kappa_2 (A - B) = \kappa_1 (A + B)$

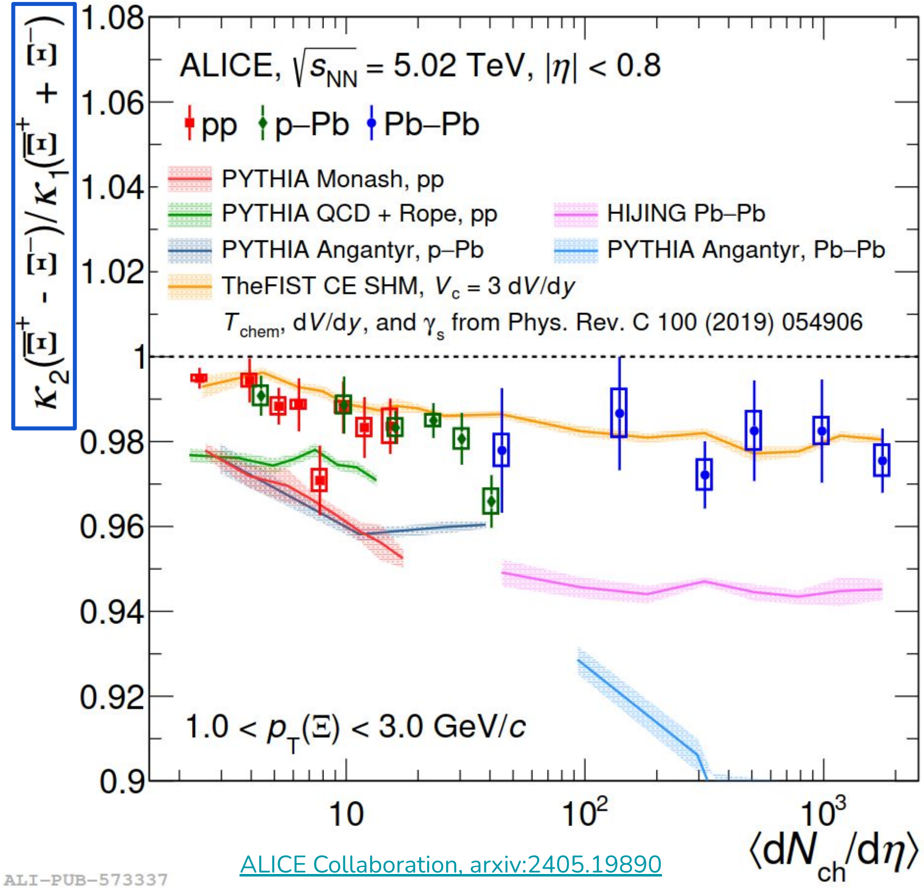


ALICE Collaboration, arxiv:2405.19890

Results: net-Ξ normalised second-order cumulant (2)

- Normalised to uncorrelated baseline
  - Difference of two Poissonian random variables → Skellam distribution
  - A and B Poissonian $\Rightarrow \kappa_2\,(A - B) = \kappa_1\,(A + B)$
- Deviations from unity in all colliding systems
  - The size is determined by the correlations between unlike-sign quantum numbers

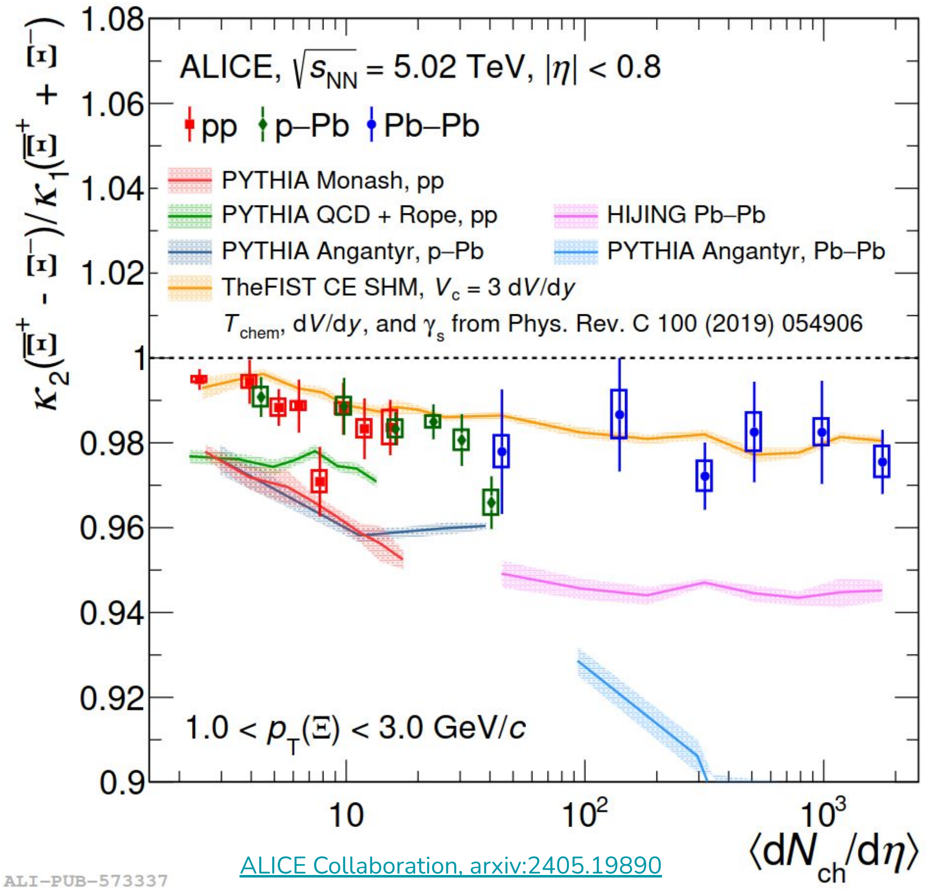
$$\kappa_2(\overline{\Xi}^+ - \Xi^-) = \kappa_2(\overline{\Xi}^+) + \kappa_2(\Xi^-) - 2\kappa_{11}(\overline{\Xi}^+, \Xi^-)$$



ALICE Collaboration, arxiv:2405.19890

Results: net-Ξ normalised second-order cumulant (3)

- Continuous evolution from low-multiplicity pp to central Pb–Pb
  - Common physical mechanism?

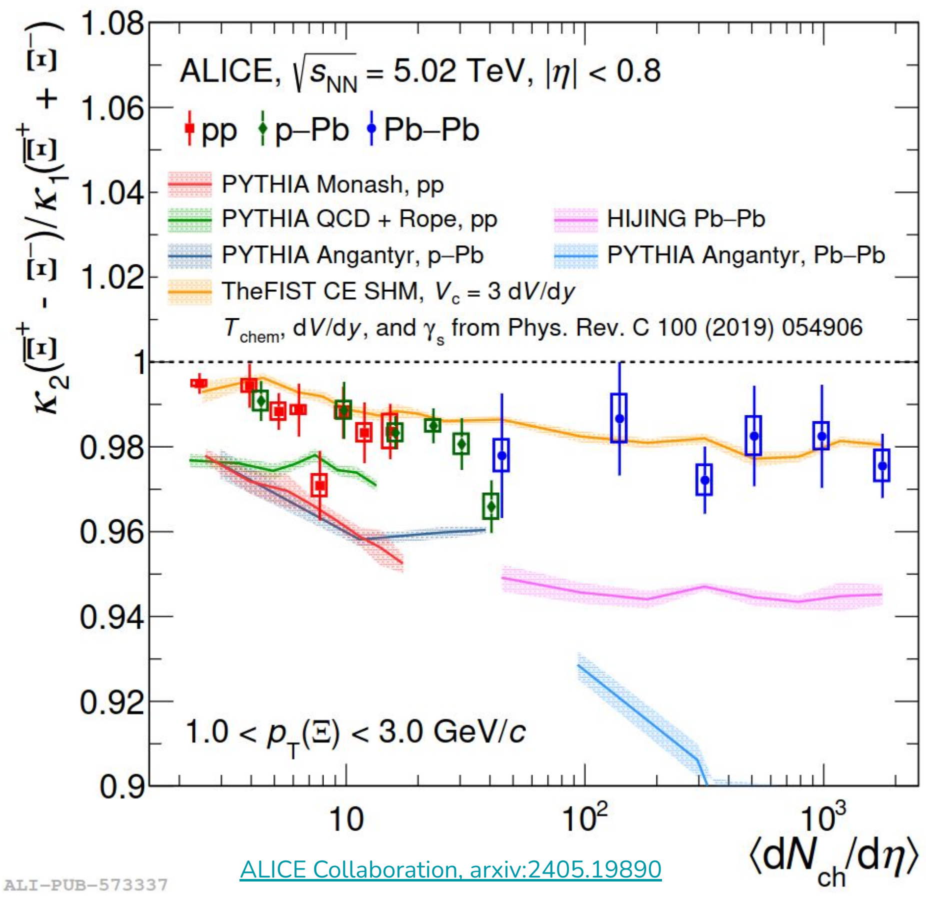


ALICE Collaboration, arxiv:2405.19890

Results: net-Ξ normalised second-order cumulant (4)

- Continuous evolution from low-multiplicity pp to central Pb–Pb
  - Common physical mechanism?
- String fragmentation predictions consistently off the data
  - Pythia 8 Monash
    → No mechanism for strangeness enhancement
  - Pythia 8 QCD CR + Ropes
    → Deviation > 5σ in pp

⇒ Milder unlike-sign correlation in data than expected by string fragmentation models, also seen in angular correlations[1]

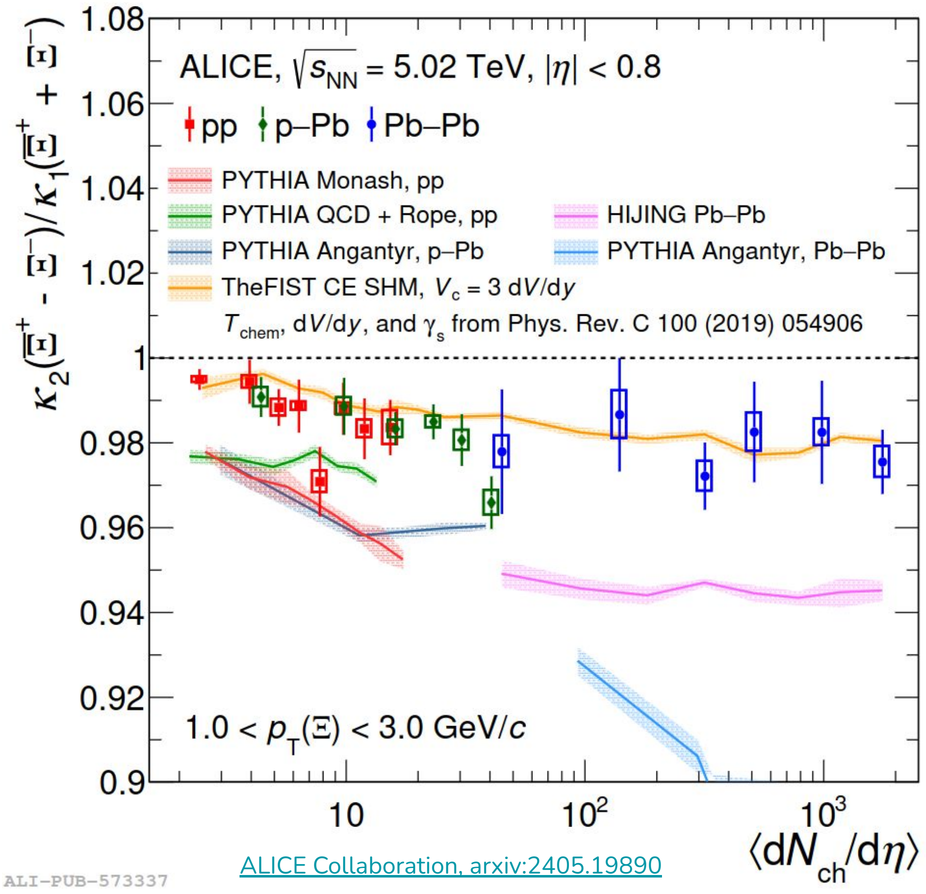


ALICE Collaboration, arxiv:2405.19890

[1] ALICE Collaboration, *JHEP* 09 (2024) 102

Results: net-Ξ normalised second-order cumulant (5)

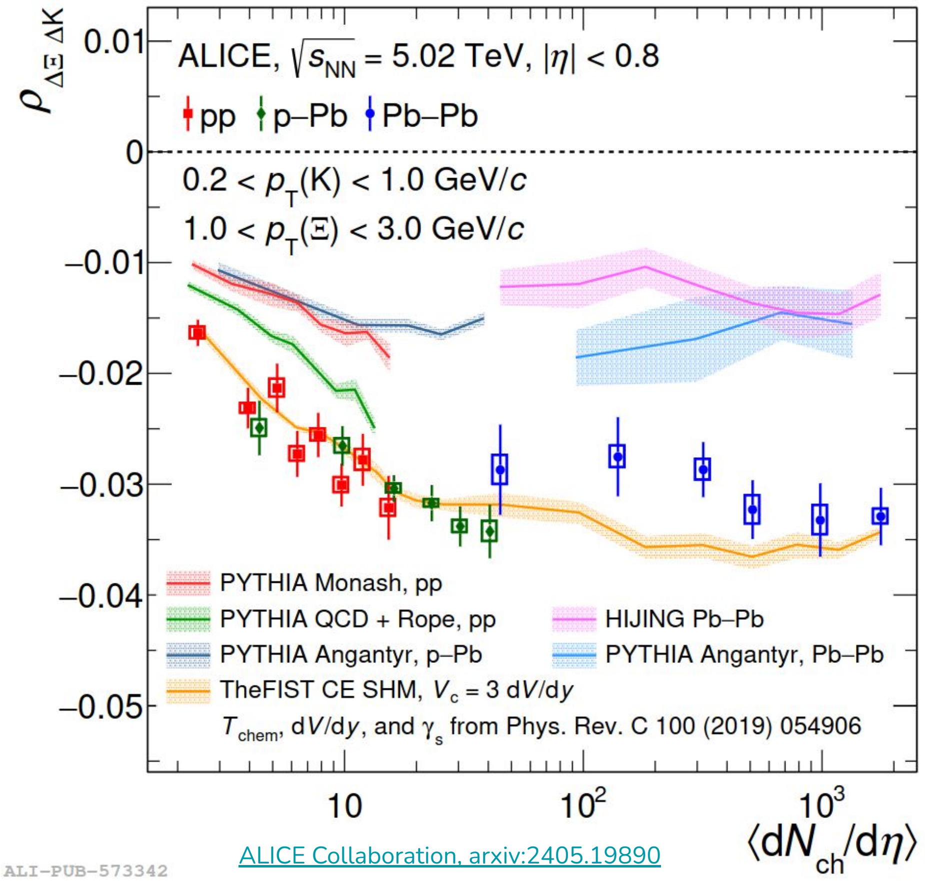
- Continuous evolution from low-multiplicity pp to central Pb–Pb
  - Common physical mechanism?
- String fragmentation predictions consistently off the data
  - Pythia 8 QCD CR + Ropes
    → Deviation > 5σ in pp
- The measurements are described by canonical statistical hadronisation
  - Thermal FIST → $V_C \sim 3$ dV/dy down to pp



ALICE Collaboration, arxiv:2405.19890

Results: net-K–net-Ξ correlation coefficient

- Decreasing trend with increasing charged-particle multiplicity
  - Interplay between fixed p_T acceptance and evolution of p_T spectrum due to flow-like correlations
- Continuous transitions between different colliding systems
  - Common production mechanism?



ALICE Collaboration, arxiv:2405.19890

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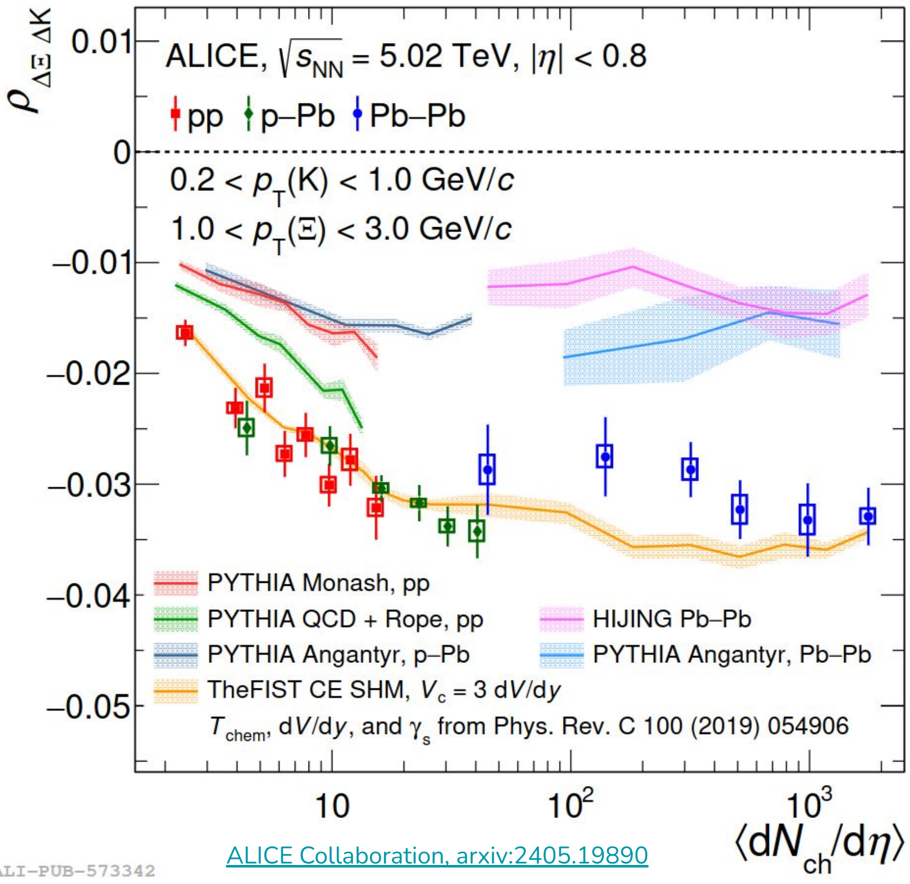
Results: net-K–net-Ξ correlation coefficient (2)

- Skellam baseline = 0
- Significant anticorrelation caused by strangeness conservation ($B_K = 0$)
  - Both like- and unlike-sign correlations

$$\kappa_{11}(\Delta\Xi, \Delta\mathrm{K}) = \kappa_{11}(\overline{\Xi}^{+}, \mathrm{K}^{+}) + \kappa_{11}(\Xi^{-}, \mathrm{K}^{-}) + -\kappa_{11}(\overline{\Xi}^{+}, \mathrm{K}^{-}) - \kappa_{11}(\Xi^{-}, \mathrm{K}^{+})$$

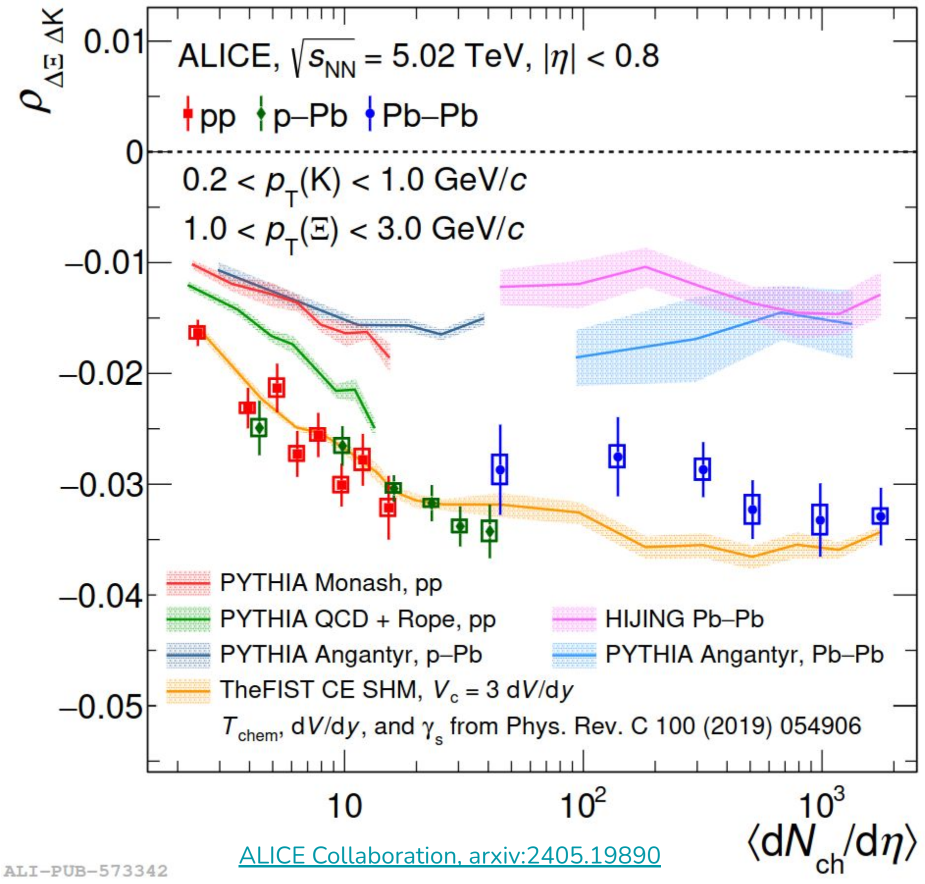


ALICE Collaboration, arxiv:2405.19890

Results: net-K–net-Ξ correlation coefficient (3)

- Skellam baseline = 0
- Significant anticorrelation caused by strangeness conservation
- String fragmentation predicts smaller anticorrelation than data
  - Mainly unlike-sign correlation, stronger than the observed one
  - Pythia 8 QCD CR + Ropes → Deviation > 5σ in pp

$$\kappa_{11}(\Delta\Xi, \Delta \mathrm{K}) = \kappa_{11}(\overline{\Xi}^{+}, \mathrm{K}^{+}) + \kappa_{11}(\Xi^{-}, \mathrm{K}^{-}) + $$
$$-\kappa_{11}(\overline{\Xi}^{+}, \mathrm{K}^{-}) - \kappa_{11}(\Xi^{-}, \mathrm{K}^{+})$$



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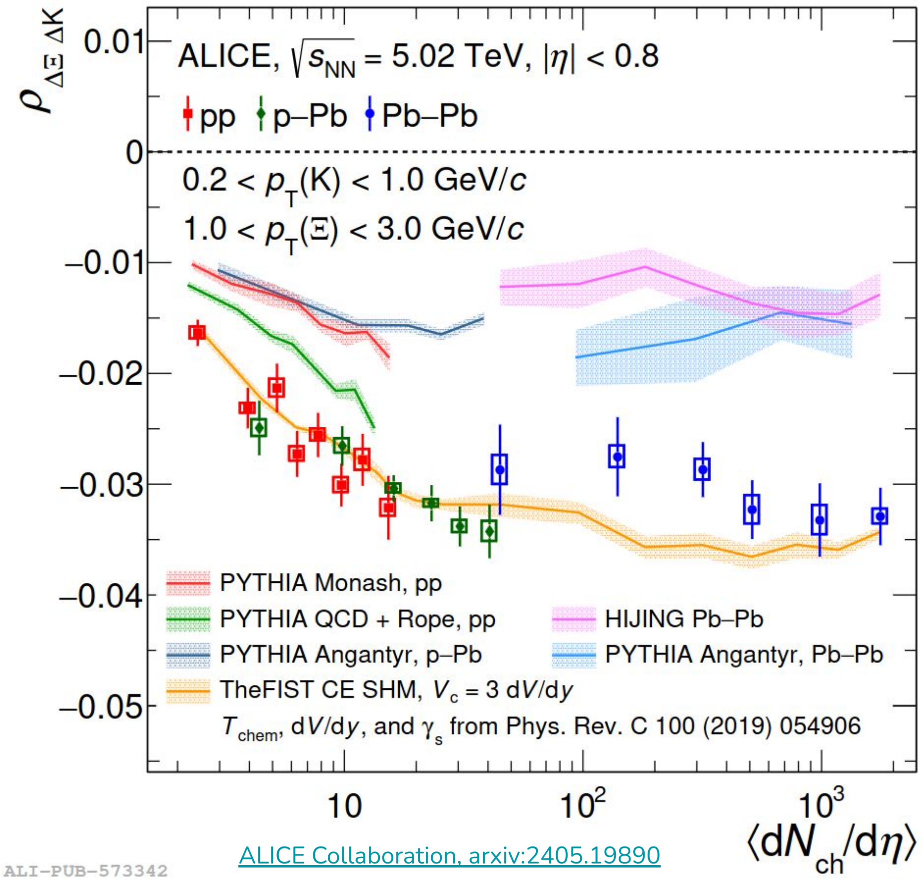
Results: net-K–net-Ξ correlation coefficient (4)

- Skellam baseline = 0
- Significant anticorrelation caused by strangeness conservation
- String fragmentation predicts smaller anticorrelation than data
  - Pythia 8 QCD CR + Ropes
    → Deviation > 5σ in pp
- Canonical statistical hadronisation
  - Long-range like- and unlike-sign correlation

$$\kappa_{11}(\Delta\Xi, \Delta K) = \boxed{\kappa_{11}(\overline{\Xi}^{+}, K^{+}) + \kappa_{11}(\Xi^{-}, K^{-})} + \boxed{-\kappa_{11}(\overline{\Xi}^{+}, K^{-}) - \kappa_{11}(\Xi^{-}, K^{+})}$$



ALICE Collaboration, arxiv:2405.19890

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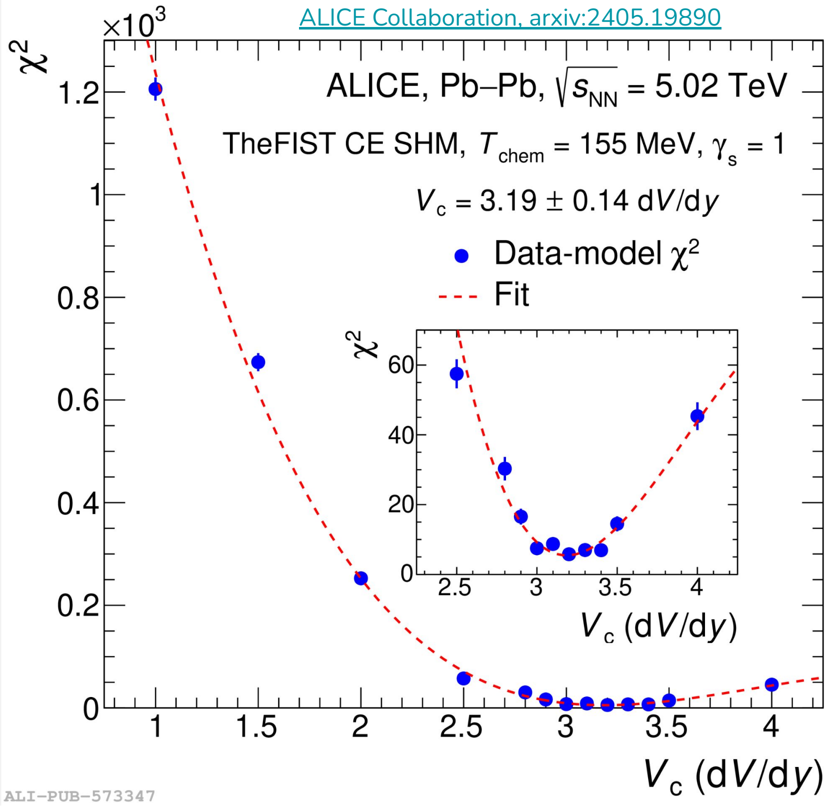
Canonical volume parameter

- Combined χ^2 fit of the event-by-event fluctuation observables in Pb–Pb using Thermal-FIST calculations
  - In pp, canonical volume is constrained by yield measurements
- Variation of k factor in $V_c = k\ dV/dy$
  - $T = 155$ MeV, $\gamma_s = 1$
- The canonical volume is compatible with 3 dV/dy obtained in small systems from Ξ/π ratio

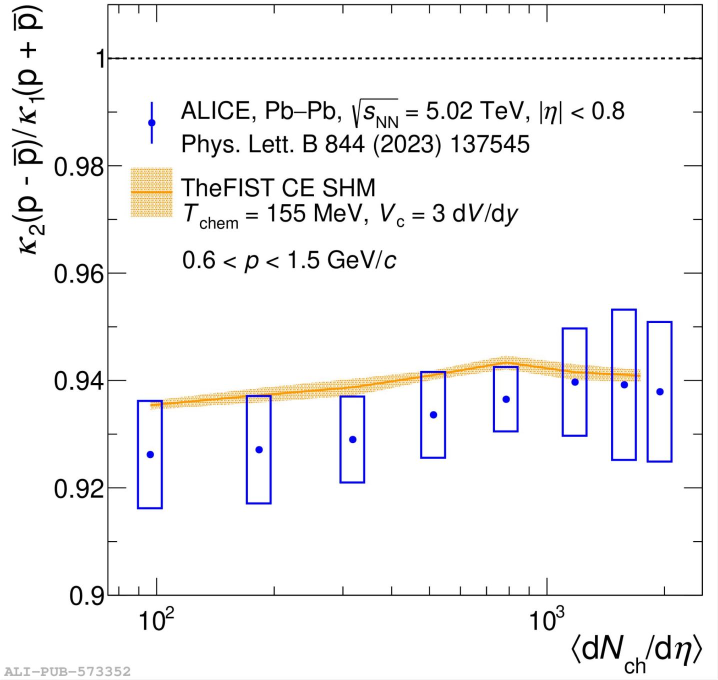
ALICE Collaboration, arxiv:2405.19890

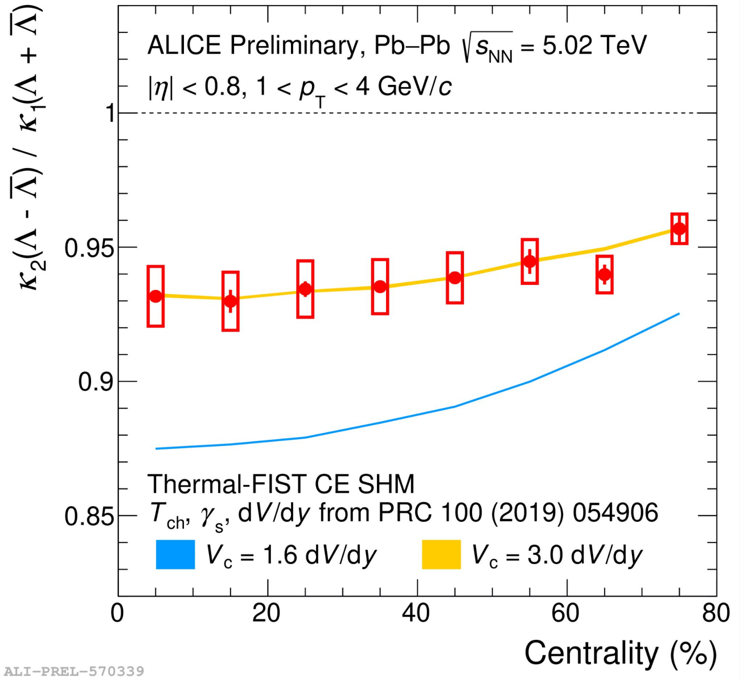


Comparison with other hadron species

- Second-order fluctuations in Pb–Pb are measured by ALICE also for other species
- Net-Λ and net-proton → $V_c = 3\ dV/dy$ matches the measured fluctuations
  - Common volume parameter for different quantum-number content

ALICE Collaboration, *Phys.Lett.B* 844 (2023) 137545





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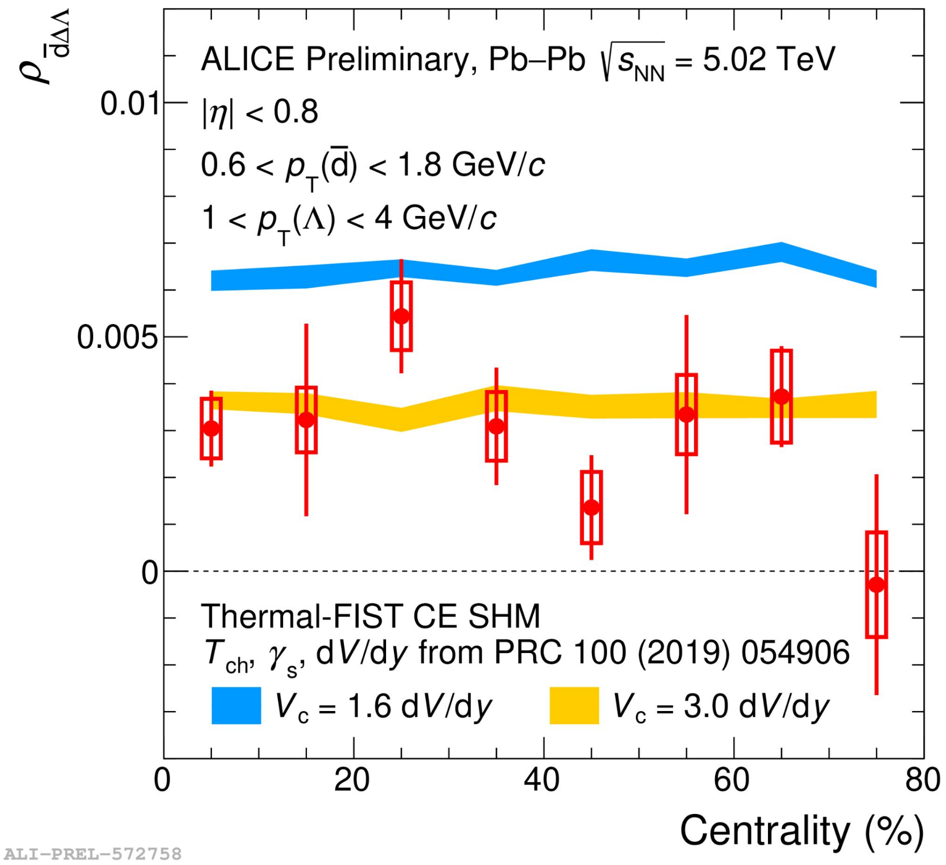
Comparison with other hadron species (2)

- Correlation coefficient between antideuteron and net-Λ multiplicities
- Only sensitive to processes underlying nuclear formation
  - Hyperons are not contained inside light-nuclei
- Same volume parameter as other baryons → quantum-number conservation picture coherent across hadron species



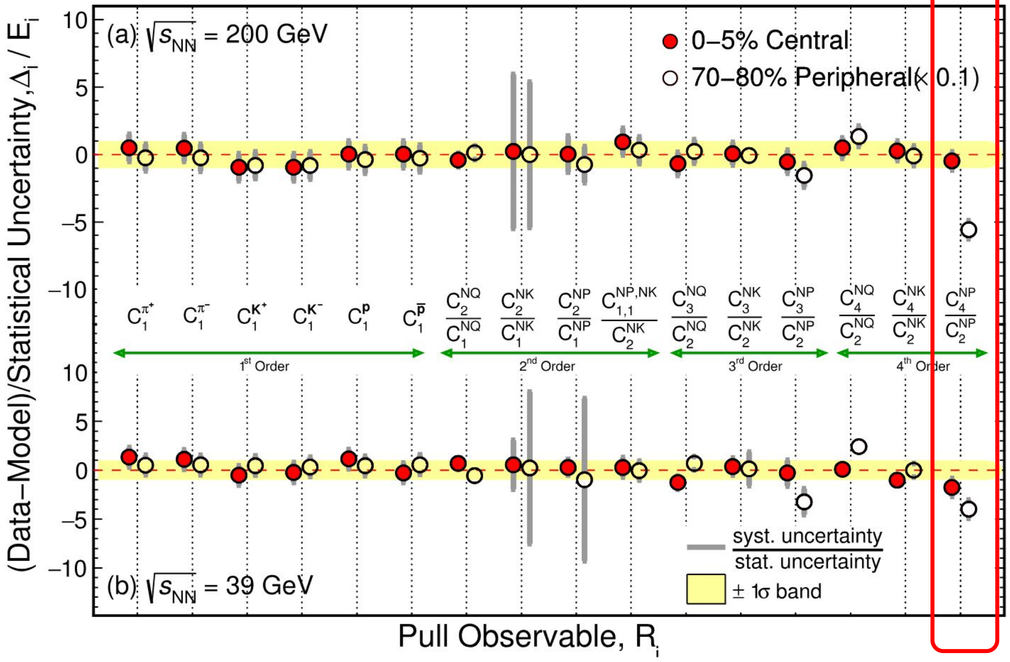
Beyond the second order

- Measuring higher-order cumulants in pp, p–Pb, and Pb–Pb
  - Does the continuous evolution with multiplicity hold for all quantum numbers at all orders?
  - Does the statistical hadronisation approach hold beyond 2nd order?

Beyond the second order (2)

- Measuring higher-order cumulants in pp, p–Pb, and Pb–Pb
  - Does the continuous evolution with multiplicity hold for all quantum numbers at all orders?
  - Does the statistical hadronisation approach hold beyond 2nd order?
- STAR data vs. HRG calculations
  - Tension for net-proton at the 4th order in peripheral collisions in Au–Au at 200 GeV
- Is this true also at the at the ultra-TeV scale of the LHC?

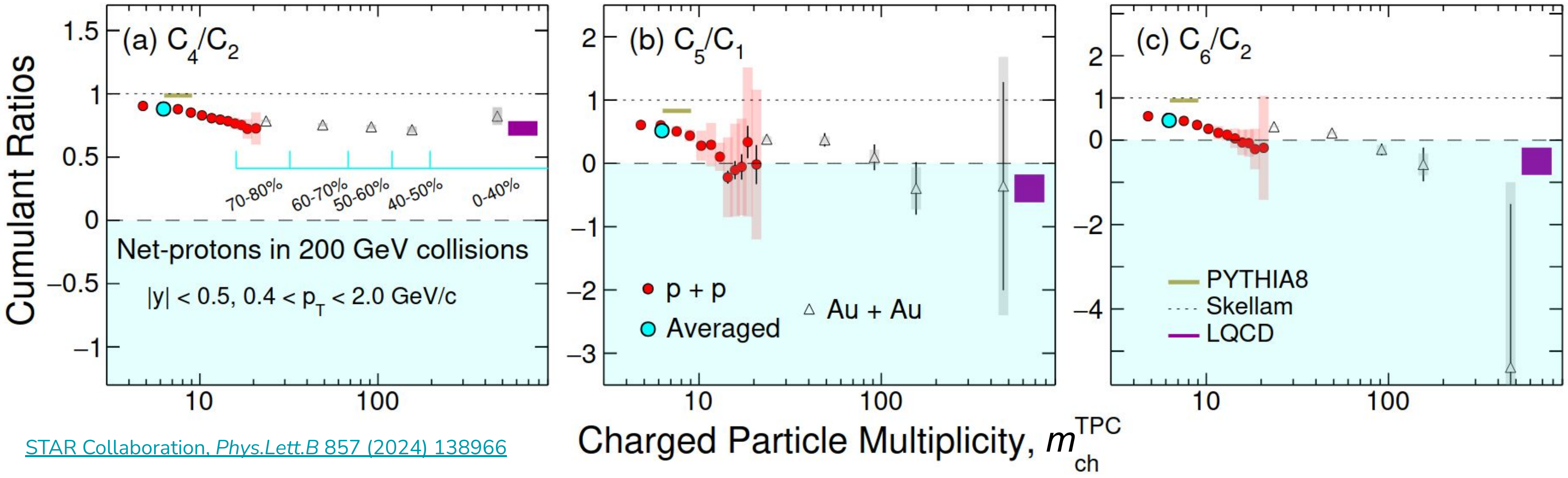
NP = net-proton



S. Gupta et al., *Phys.Lett.B* 829 (2022) 137021

Beyond the second order (3)

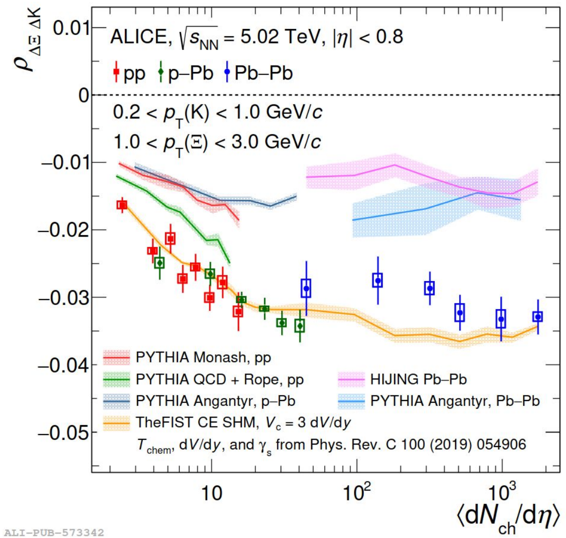
- Net-proton fluctuations measured by STAR in pp at 200 GeV
  - Consistently deviating from Skellam and Pytiha 8 baseline
  - 6th order fluctuations approach negative values → lattice QCD baseline (QGP)!
- ALICE can extend this to higher multiplicities with better precision

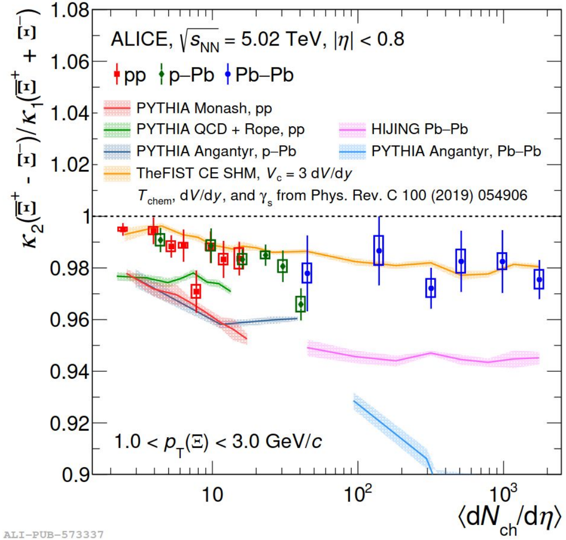


STAR Collaboration, *Phys.Lett.B* 857 (2024) 138966

Summary

- First measurement of event-by-event fluctuations of multistrange baryons from pp to Pb–Pb
- Probing the hadronisation mechanism
  - At present, the data are described only by canonical statistical hadronisation (Thermal-FIST)
  - String-fragmentation based MC generators would require the implementation of longer-range and same-sign correlations to match the data





ALICE Collaboration, arxiv:2405.19890