Canonical treatment of strangeness and light nuclei production

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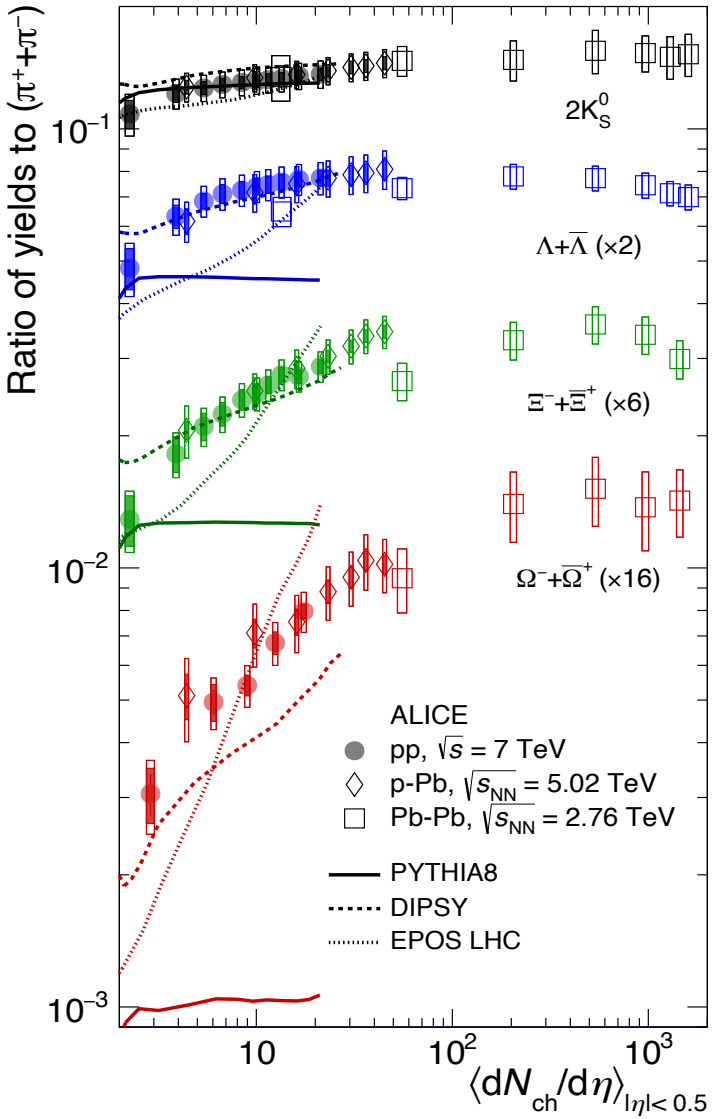
Aspects of Criticality – II
EMMI Workshop at the
University of Wrocław

Strangeness suppression in small system

ALICE Coll., Nature Phys. 13 (2017) 535-539.



Dependence of strange particle to pion yield ratios on multiplicity is studied in ALICE

- Suppression of ratio with decreasing multiplicity in observed in pp and p-Pb collisions -- small systems.
- Suppression is more for particles with more strangeness content (S).

→ Linked to “strangeness canonical effect”

J. Cleymans, E. Suhonen & K. Redlich., Z. Phys. C 51 (1991) 137; Z. Phys. C 76 (1997) 269; S. Hamieh, A. Tounsi & K. Redlich, Phys. Lett. B486 (2000), Eur. Phys. J. C24 (2002); J. Cleymans, H. Oeschler & K. Redlich, Phys. Rev. C59 (1999) 1663.

Strangeness canonical ensemble

Partition function depends on thermodynamic quantities and the Hamiltonian describing the system as

$$Z^{GC}(\mu) = Tr\left[e^{-\beta(H-\vec{\mu}.\vec{Q})}\right]$$

Canonical treatment of strangeness: At LHC -- $\mu \sim 0$, the partition function with exact strangeness conservation (S=0) is

$$Z_S^C = Tr\left[e^{-\beta H}\delta_S\right]$$

Multiplicity of a particle with strangeness quantum number S in the given experimental acceptance

$$\langle N_S \rangle_A^C \approx V_A n_s^{GC} \frac{I_S(S_1)}{I_0(S_1)}$$

here,

V_A is effective fireball volume; $\frac{I_S(S_1)}{I_0(S_1)}$ is suppression factor; $S_1 = V_C \sum n_i(T)$,

V_C is full space volume where S is exactly conserved.

- Fitting data with the thermal model (SCE) and also included interactions among hadrons using S-matrix corrections

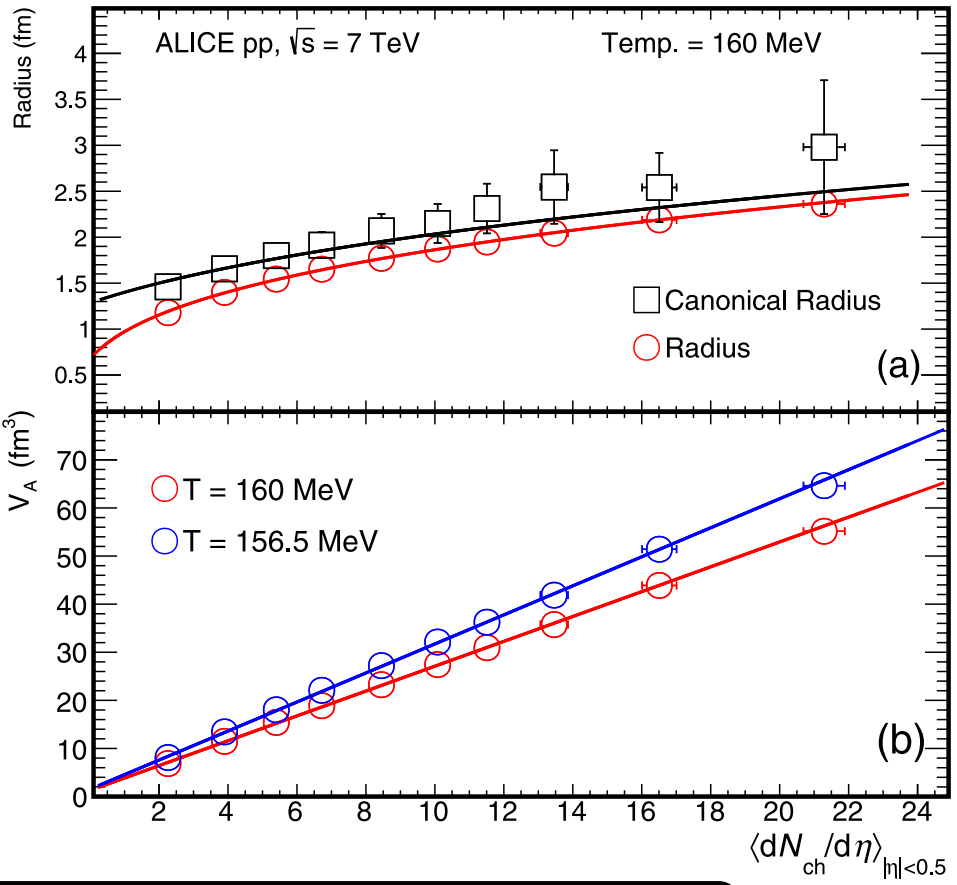
Canonical suppression effect in Strangeness sector

- Fitted particle yields – $\pi, K_S^0, p, \Lambda, \Xi, \Omega$ in pp collisions at √s = 7 TeV for various multiplicity bins.
- Fixed parameters:
  - T = 156.5 MeV and 160 MeV;
  - $\gamma_s = 1$
- Free parameters: V_A and V_C

At T=156.5 MeV

$$V_A = 1.55 + 3.02 \times \frac{dN_{ch}}{d\eta}$$

$$V_C = 12.32 + 2.58 \times \frac{dN_{ch}}{d\eta}$$

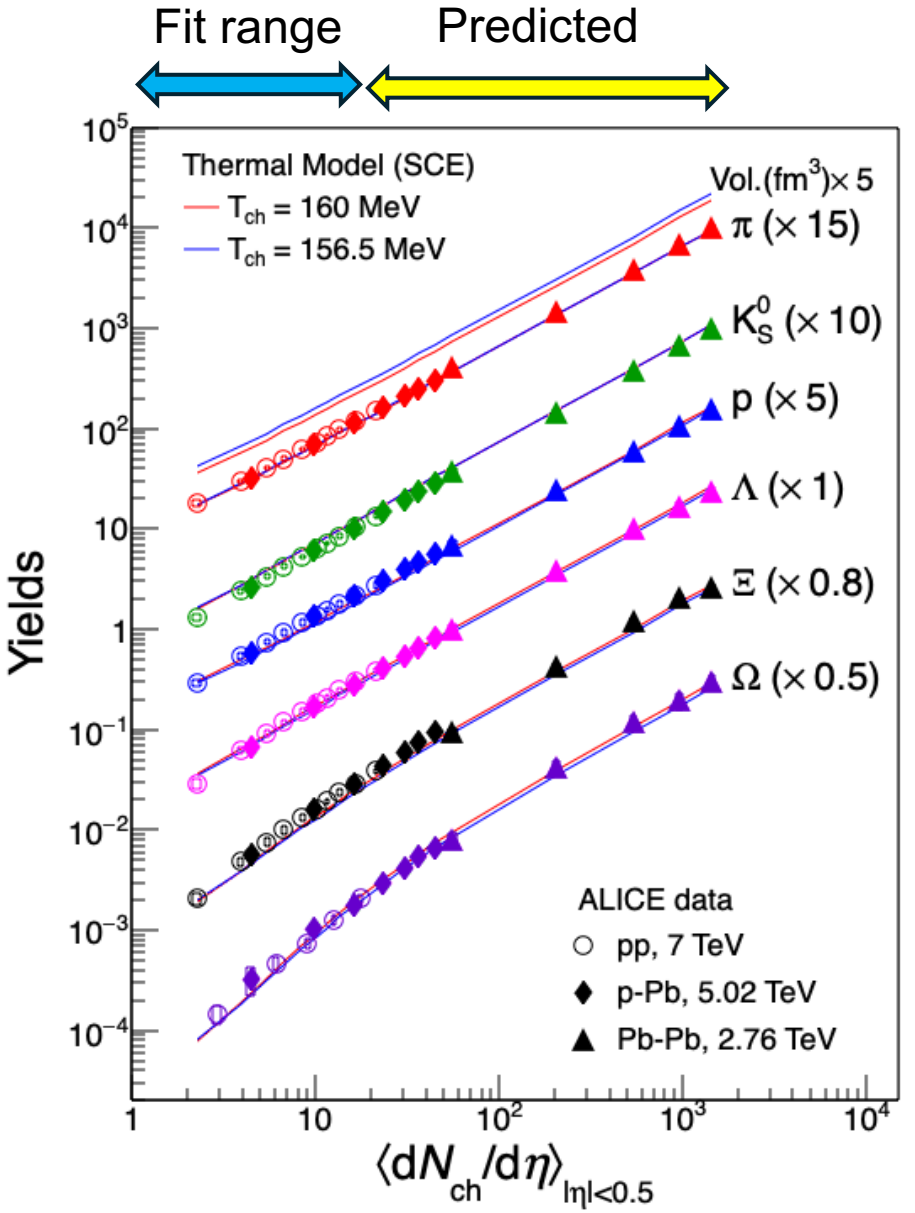


Effective volume (V_A) and canonical volume (V_C) increase linearly with multiplicity.

J. Cleymans, Pok Man Lo, NS & K. Redlich, Phys. Rev. C103 (2021) 014904.

Canonical suppression effect in Strangeness sector

- Strange and multi-strange yields prediction are in agreement with data.
- Particle yields are found to be independent of collision system and energy.

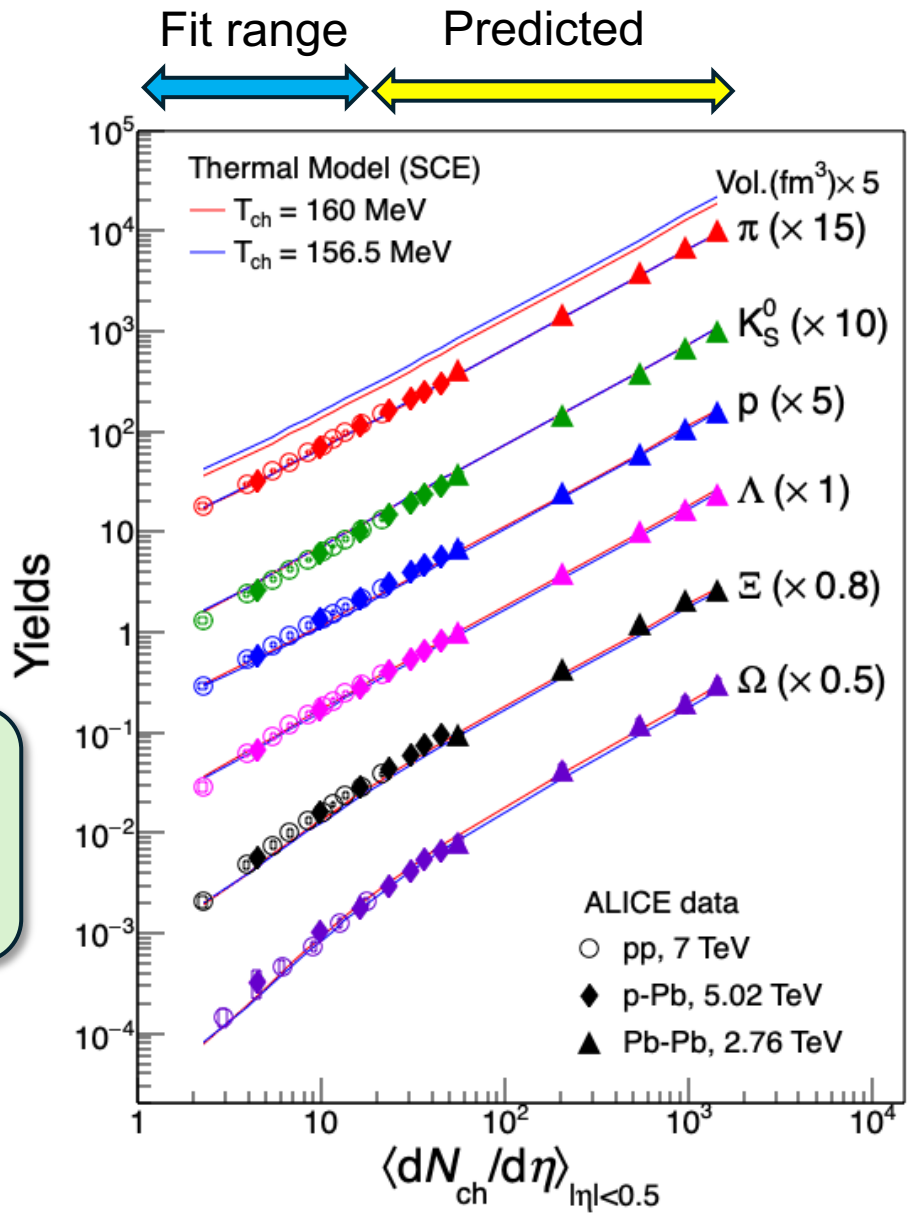


Canonical suppression effect in Strangeness sector

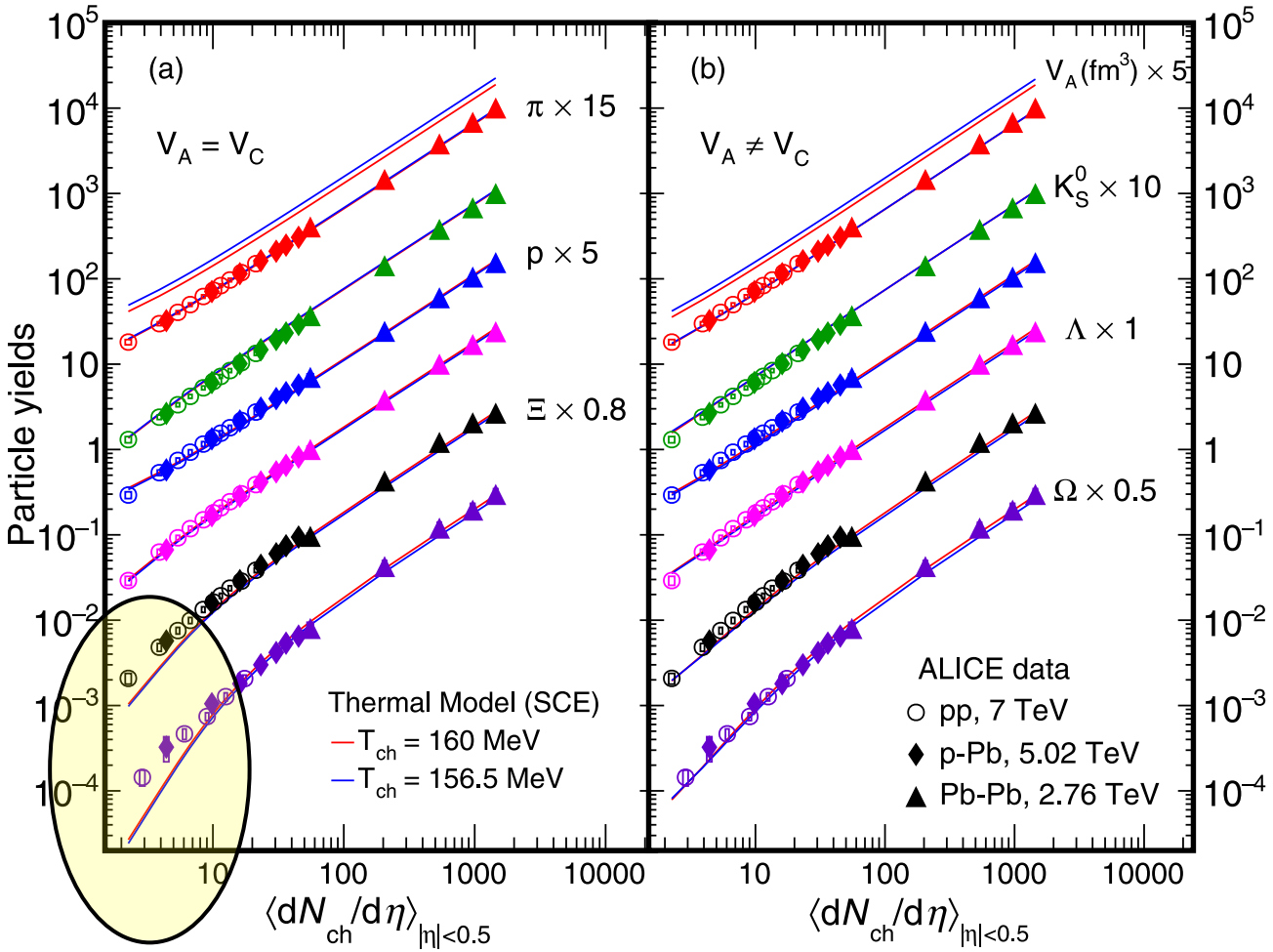
- Strange and multi-strange yields prediction are in agreement with data.
- Particle yields are found to be independent of collision system and energy.

From fits -- $V_C > V_A$ for small system

We performed same study keeping $V_A = V_C$

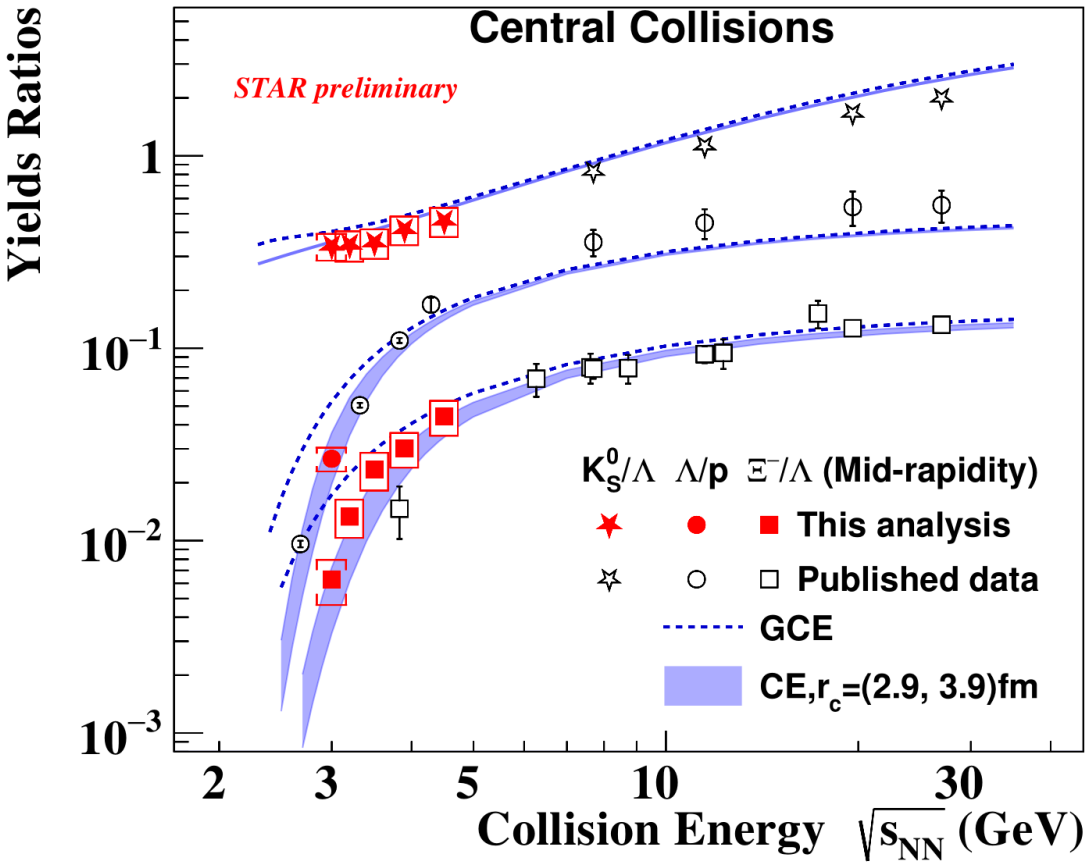


Canonical suppression effect in Strangeness sector



For small multiplicities, $V_C > V_A$ → Reduced suppression of strange-particle yields.

Strange Canonical effect in low energy

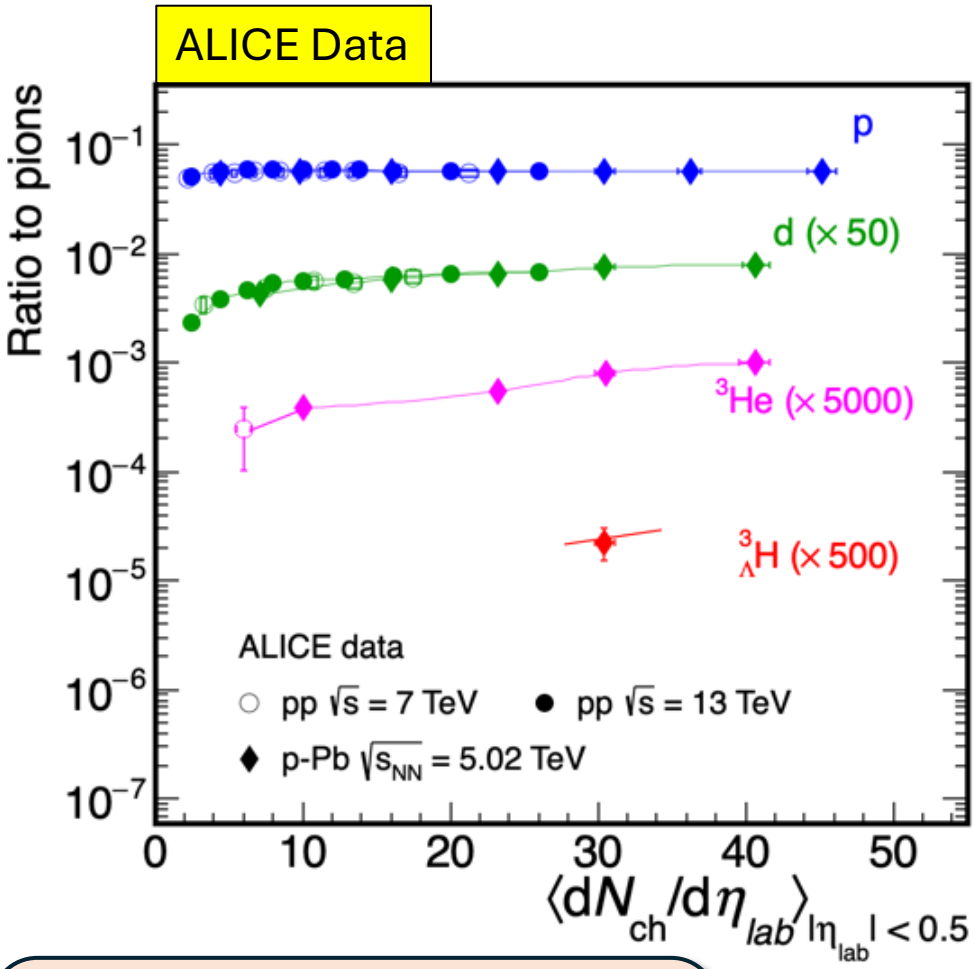


Suppression of strangeness is seen in low energy.

- At low energies i.e. $\sqrt{s_{NN}}$ < 5 GeV.
  - GCE overpredict the ratios.
  - SCE with R_C = 2.9 – 3.9 fm describes the ratios well.
- For energy > 5 GeV
  - GC and SC merge.

Hongcan Li, STAR Coll., SQM-2024

Canonical effect in Baryon sector



ALICE Coll., Phys. Rev. Lett. 128, 252003 (2022);
ALICE Coll., Eur. Phys. J. C 80, 889 (2020);
ALICE Coll., Phys. Lett. B 800, 135043 (2020);
ALICE Coll., Phys. Rev. C 93, 024917 (2016);
ALICE Coll., Phys. Rev. C 97, 024615 (2018);
ALICE Coll., Phys. Rev. C 101, 044906 (2020).

At LHC energies,

$$\frac{dN}{dy} \approx e^{-m/T_{chem.}}$$

- In small system, baryons to pion ratios is suppressed with decreasing multiplicity and increasing baryon quantum number of hadrons is observed by the ALICE Collaboration.

→ Can be linked to the "baryon canonical suppression effect".

This requires treatment of baryon quantum number canonically – Analogous to Strangeness Canonical Effect!

Implementation of BCE in Thermal model

Particle multiplicity with baryon “b” is

$$\langle N_b \rangle_A^C \approx V_A n^{GC} \frac{I_b\left(2V_C^B n_{b=1}^{th}(T)\right)}{I_0\left(2V_C^B n_{b=1}^{th}(T)\right)}$$

V_A is effective fireball volume in the acceptance;

$\frac{I_B(B_1)}{I_0(B_1)}$ ratio is suppression factor and $B_1 = V_C \sum n_i(T)$;

V_C is full space volume (correlation volume) where B is exactly conserved.

Implementation of BCE in Thermal model

- Performed fits to $\pi,\ p,\ d$ yields measured by ALICE in pp @ 13 TeV and p-Pb collisions @ 5.02 TeV for various multiplicity classes.

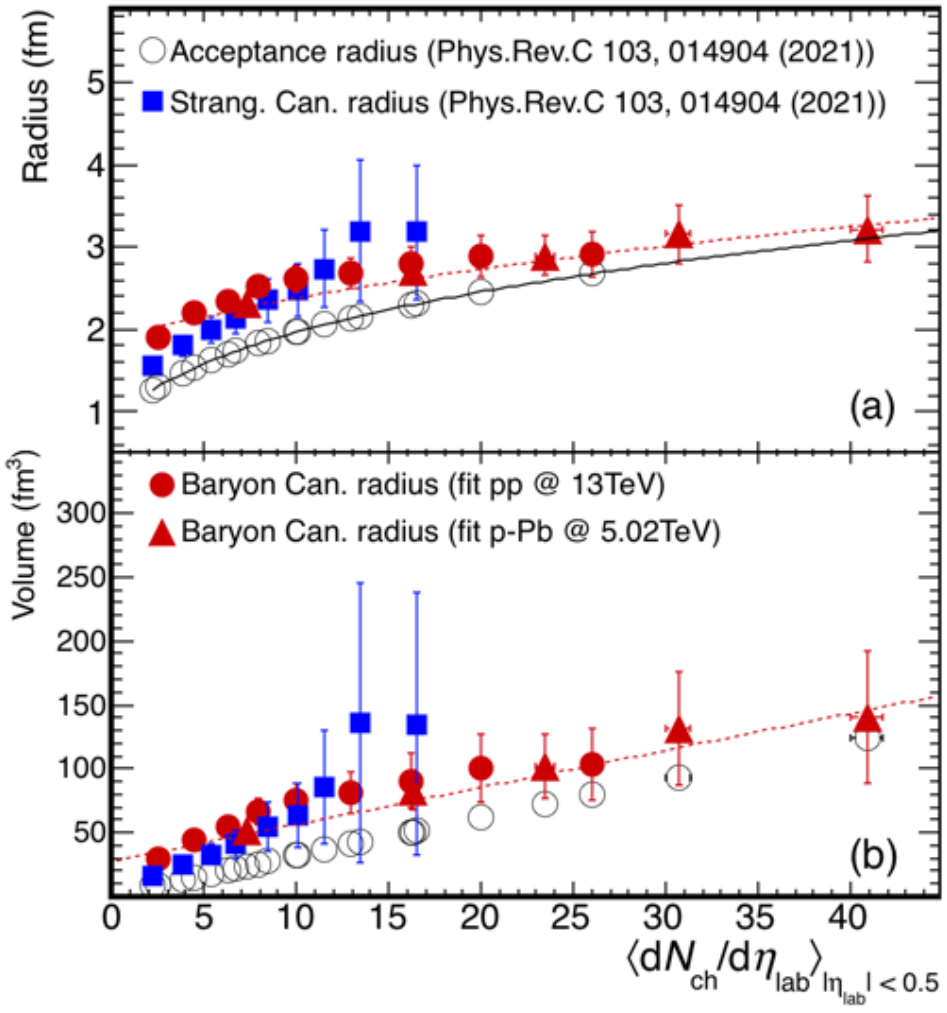
- Temp. fixed to 156.5 MeV;

- Fixed $\gamma_s = 1$

- Fixed V_A from previous analysis as system under consideration is same.

- V_C^B is only free parameter.

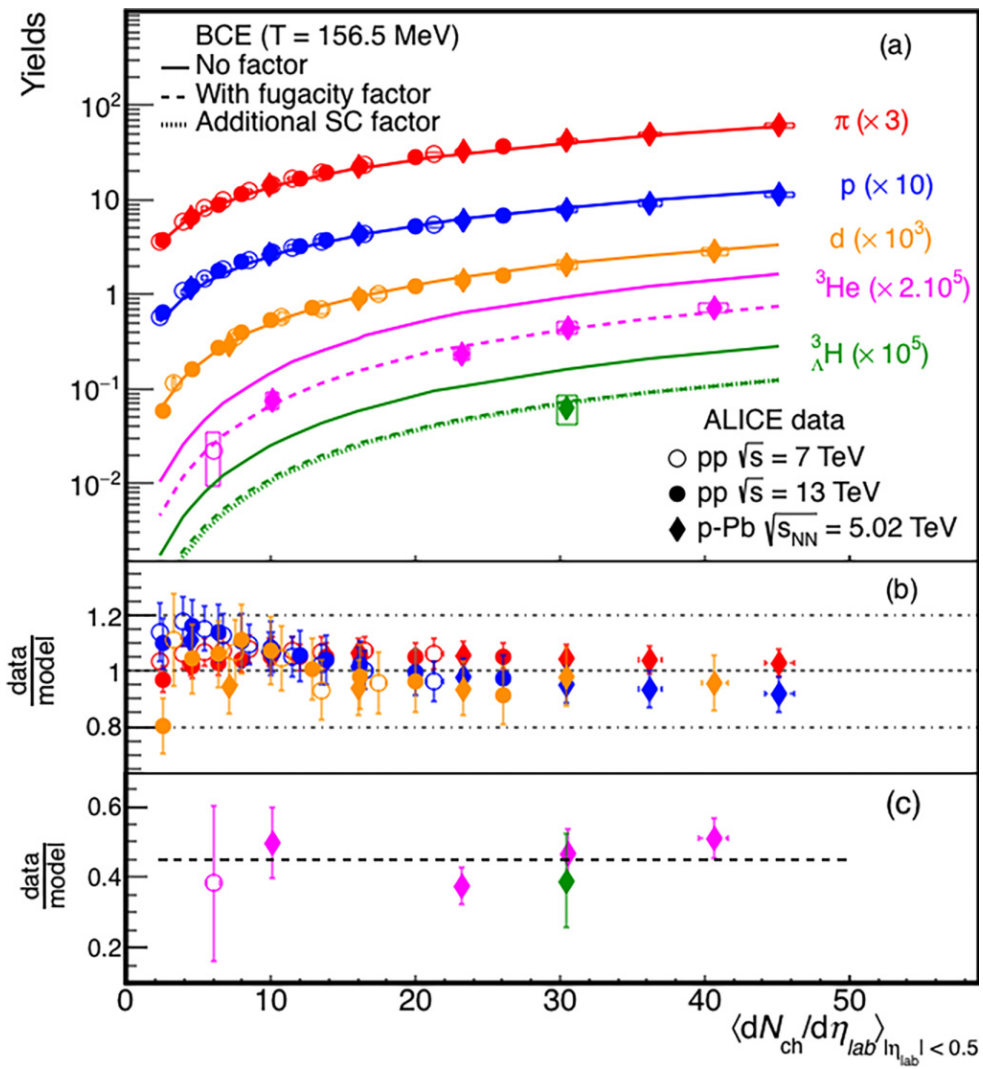
Implementation of BCE in Thermal model



- For low multiplicity:
  For $\langle dN_{ch}/d\eta \rangle \sim 2.5$
  → $R_A \approx 1.3\ fm$,
  → $R_C^S \approx 1.6\ fm$, $R_C^B \approx 1.9\ fm$
  → May be $R_C^B > R_C^S > R_A$
- At high multiplicity, canonical effect vanishes and system follow GC.
- V_C is increasing linearly with multiplicity.
- Relation from fitting pp @ 13 TeV

$$V_C = 27.3 + 2.9 \times \frac{dN_{ch}}{d\eta}$$

Comparison of Yields with BCE predictions for pp and p-Pb collisions

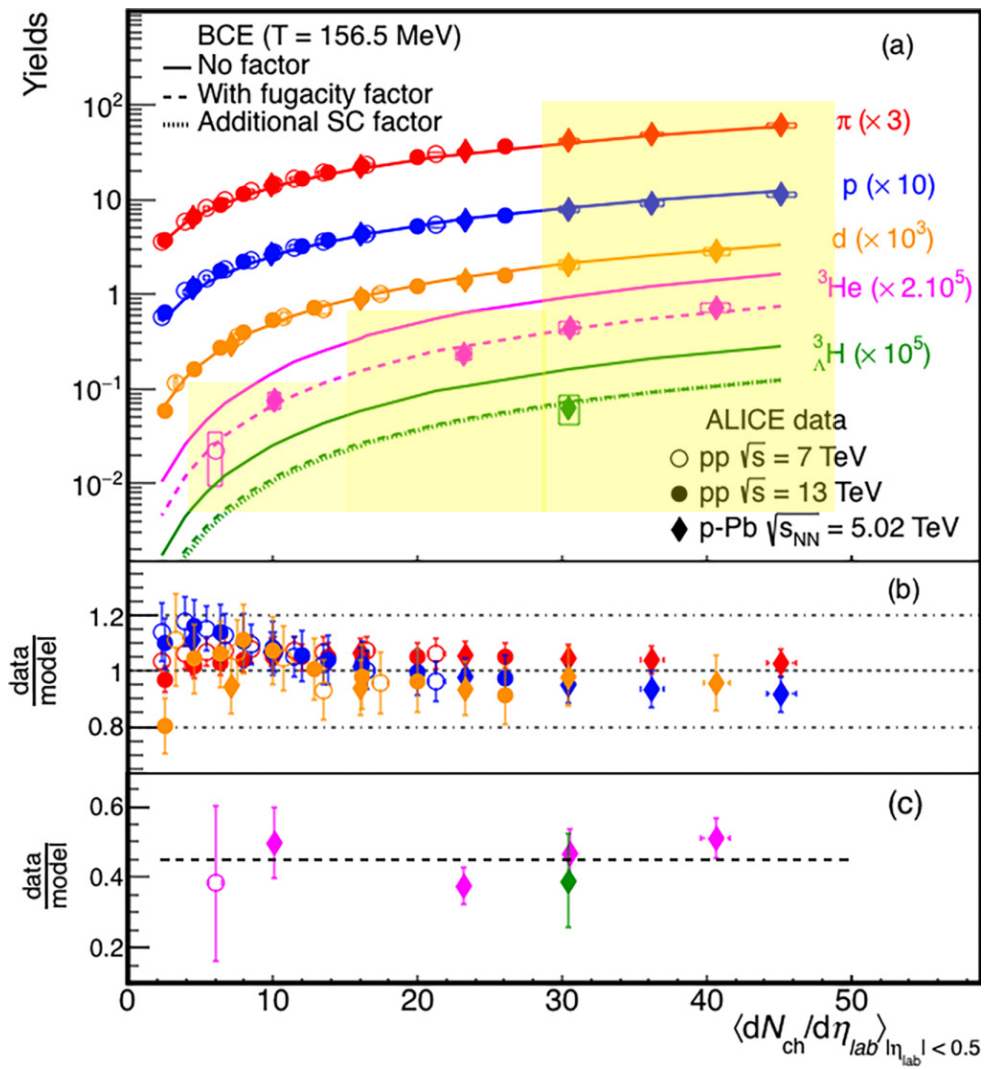


Fit range

Predicted

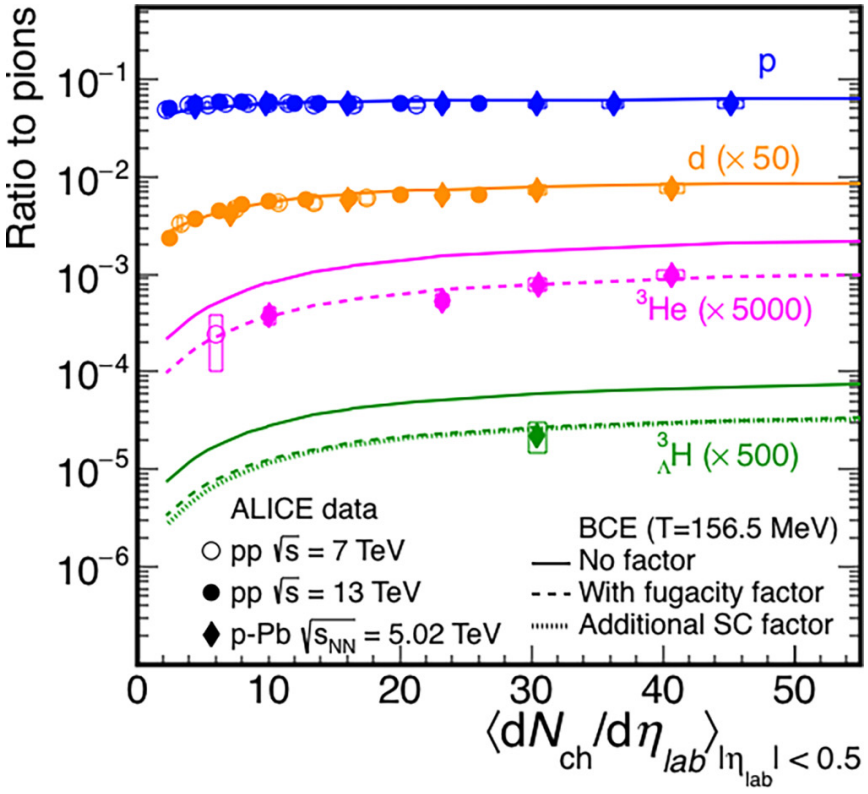
- Yields of protons and deuterons and their dependence on $\langle dN_{ch}/d\eta \rangle$ are well described by the thermal model with exact baryon conservation.

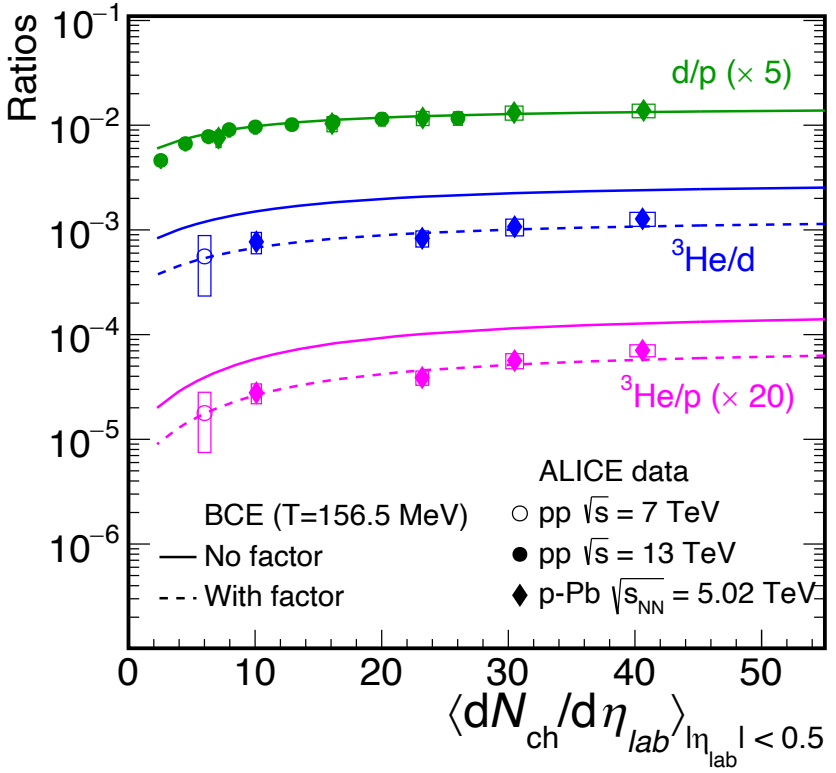
Comparison of Yields with BCE predictions for pp and p-Pb collisions



- Yields of protons and deuterons and their dependence on $\langle dN_{ch}/d\eta \rangle$ are well described by the thermal model with exact baryon conservation.
- Predicted ^{3}He and $^3_\Lambda$H yields for all multiplicity range and p and d yields for higher multiplicity classes (p-Pb collisions).
- Qualitative trend of ^{3}He and $^3_\Lambda$H i.e. suppression of baryon with decreasing $\langle dN_{ch}/d\eta \rangle$ are well described (solid lines).

Comparison of particle ratios with BCE predictions



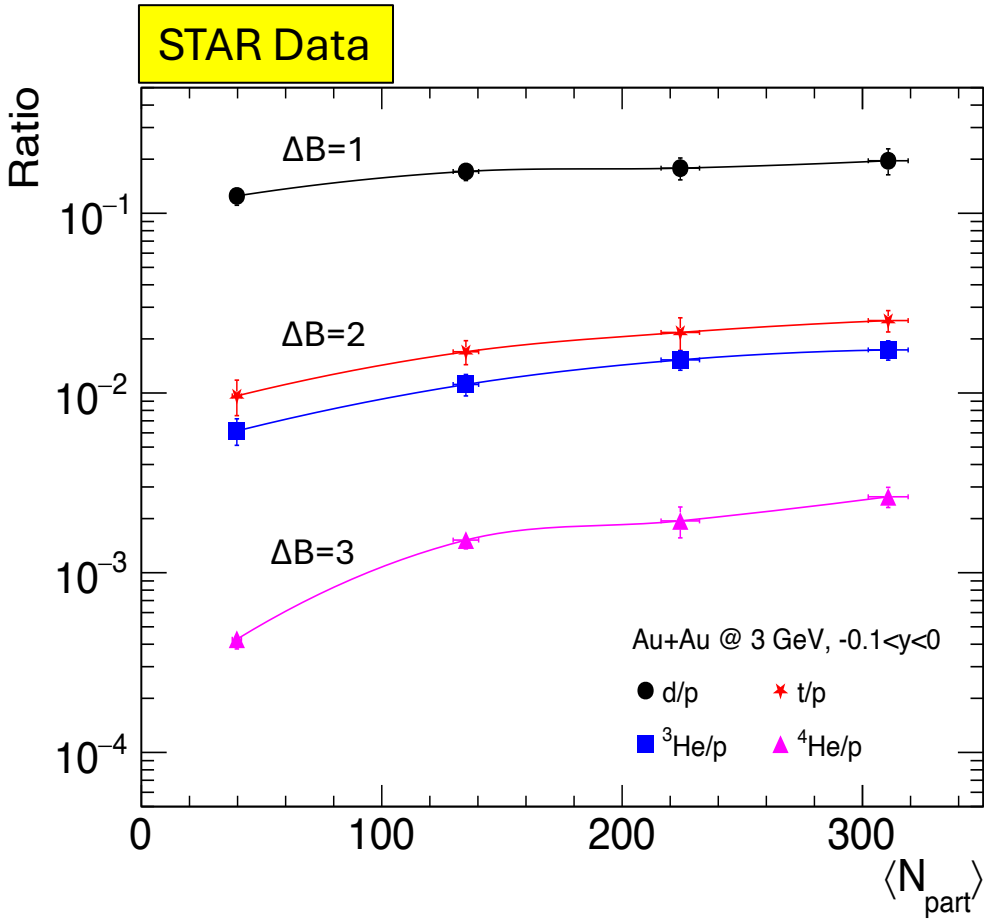


- Quantitative description of ^{3}He and $^3_\Lambda$H yields differs from data by the constant multiplicative factor

→ Can be interpreted as being due to off-chemical equilibrium effect $\lambda_b \approx 0.45$ (dotted lines)

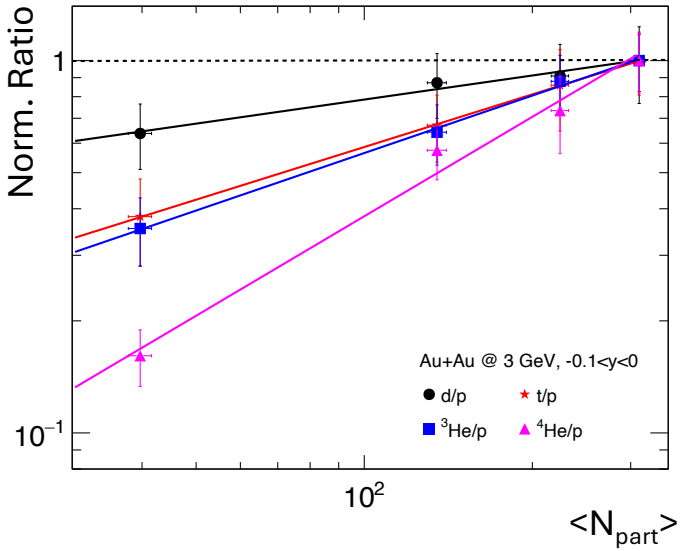
Nuclei production in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV

STAR Coll., arXiv: 2311.11020



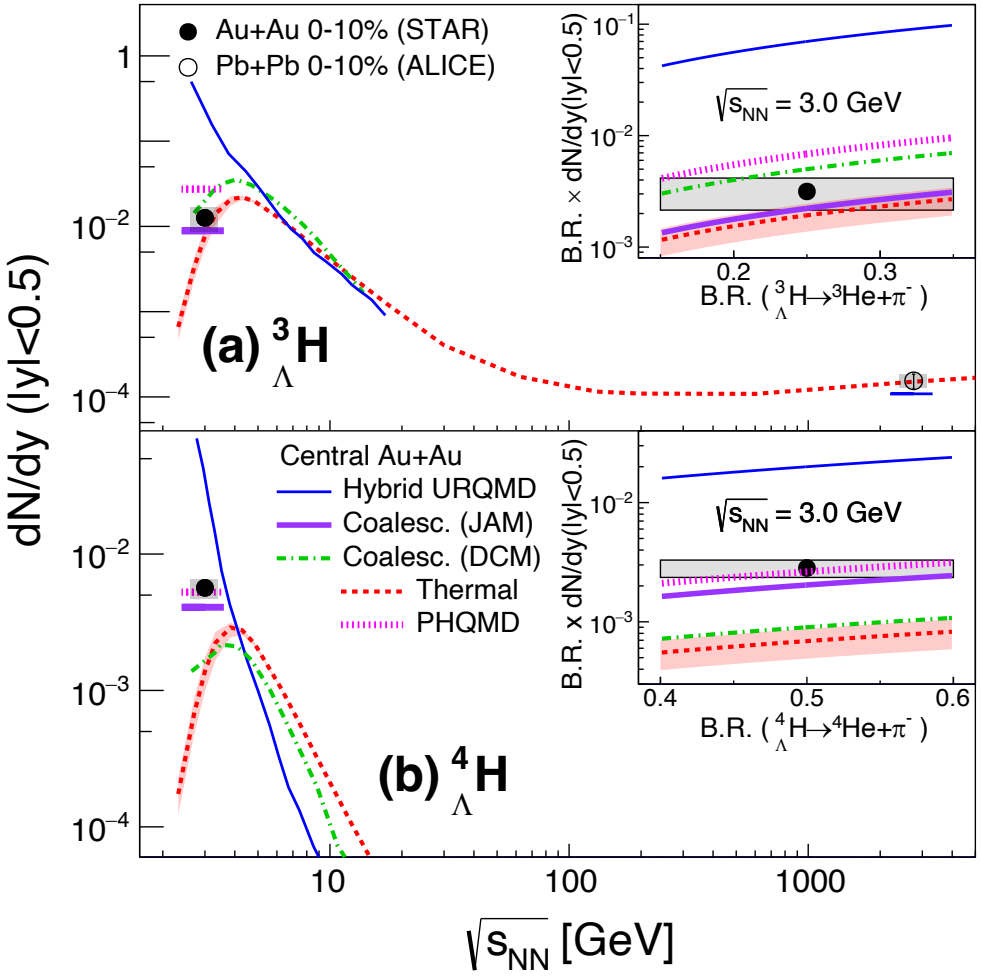
- Nuclei yield is slightly decreasing from central to peripheral collisions (i.e. with decreasing Npart)
- Slope increase with increasing mass and baryon quantum number

→ Baryon suppression at 3 GeV may be interpreted as due to the baryon canonical effect – needs investigation!



Nuclei production in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV

STAR Coll., Phys. Lett. B **825** (2022) 136865



- Thermal model explains $^{3}_{\Lambda}$H production in heavy-ion collisions ranging from 3 GeV [SCE] to 2760 GeV [GCE].
- SCE thermal model underestimates $^{4}_{\Lambda}$H production by a factor 4 in low energy (3 GeV) collisions → May be BCE is required as particle has B=4 (needs investigation).

Conclusions:

Canonical effect seems important to consider in

- Small multiplicities at LHC energies
- Also in low energy collisions at RHIC energies

Acknowledgement:

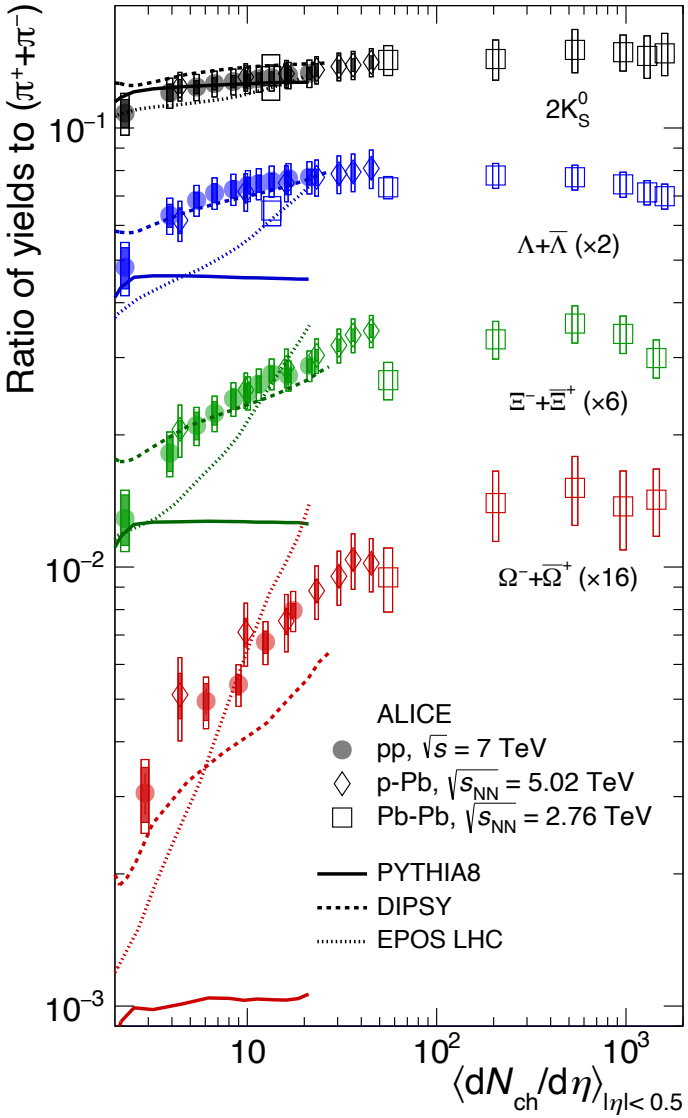
Thanks to Krzysztof Redlich, Peter Braun-Munzinger, Johanna Stachel, Pok Man Lo and Lokesh Kumar.

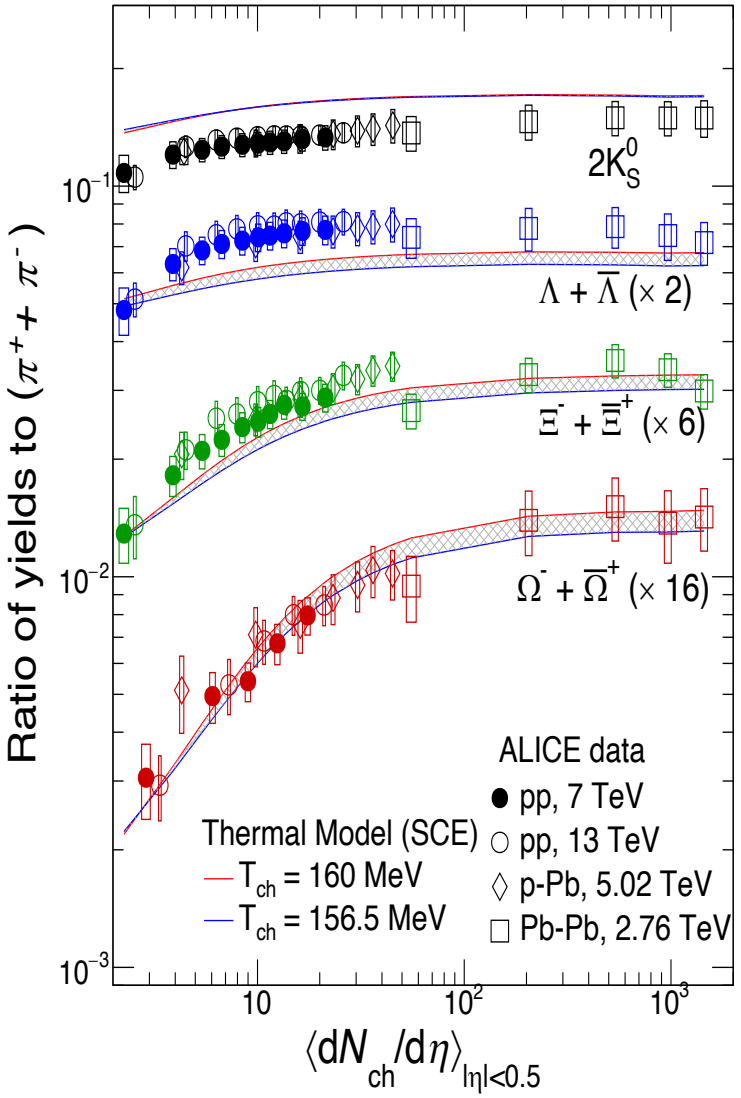
Special thanks to the ALICE and STAR collaborations for publishing beautiful data which is increasing our Physics understanding.

Thank you for your attention!

Back Up

Canonical suppression effect observed at LHC energies





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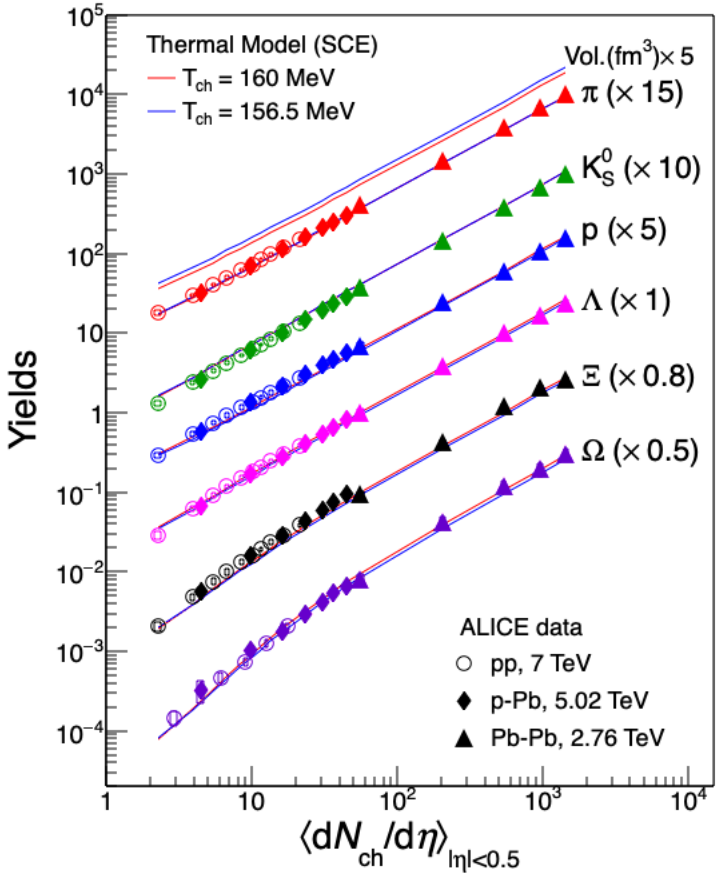

J. Cleymans, Pok Man Lo, N. S. & K.R., Phys. Rev. C103 (2021) 014904.

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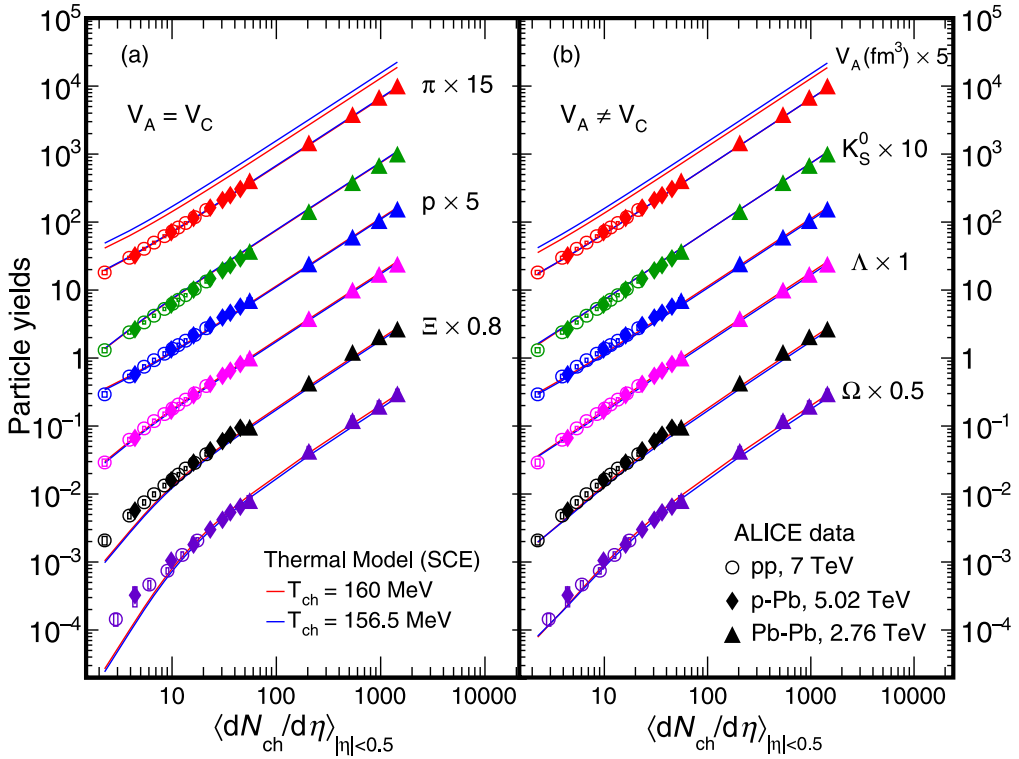

J. Cleymans, Pok Man Lo, N. S. & K.R., Phys. Rev. C103 (2021) 014904.