Statistical Hadronization of Hypertriton and Other Loosely Bound Nuclei

Workshop PHD 2025

Hjalmar Brunßen
in collaboration with
Johanna Stachel, Peter Braun-Munzinger and Anton Andronic

14 April 2025

Physikalisches Institut, Universität Heidelberg

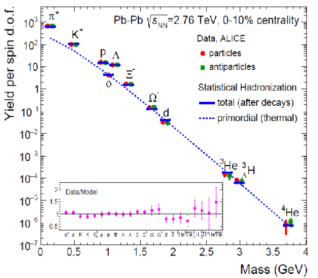
Hadronization of the QGP

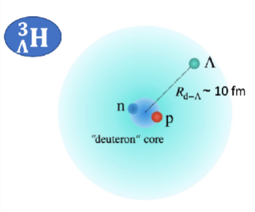
- hadronization in hadron-hadron and heavy-ion collisions at LHC
- hadron and nucleus yields well reproduced by statistical hadronization model

Hypertriton:

- described as bound state of deuteron and Λ
- Λ separation energy $B_\Lambda = 0.13\ \mathrm{MeV}$
- not a point-like particle $\sqrt{\langle r^2 \rangle} \approx 5\ \mathrm{fm}$
- topic of this talk: test how size matters for hadronization

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel: Nature 561 (2018) 321





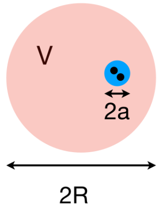
Berndt Müller

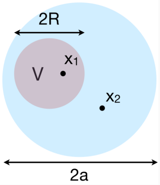
How to take into account the nucleus size

- based on idea from Berndt Müller SQM2022 (arXiv:2209.00070)

$$P = \int d^3p\, e^{-E_p/T} \int d^3x_1\, d^3x_2\, \left|\psi_p(\mathbf{x}_1 - \mathbf{x}_2)\right|^2 \theta_V(\mathbf{x}_1)\, \theta_V(\mathbf{x}_2).$$

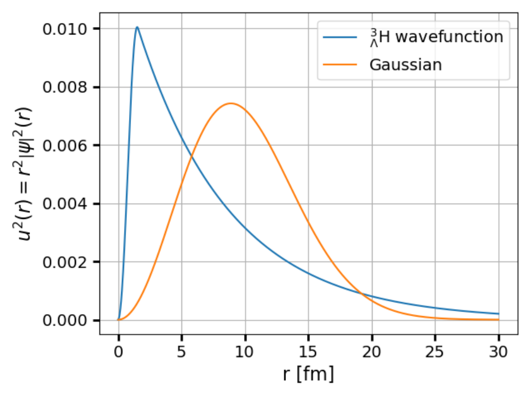
- point-like limit: integrate over whole wavefunction
- for loosely bound nuclei: correction $P(a)/P(0)$
- calculate correction: sample random points $\vec{x}_1$ in volume,
  integrate wave function $|\psi(\vec{x} - \vec{x}_1)|^2$ over V
  particle size correction: average containment of wavefunction

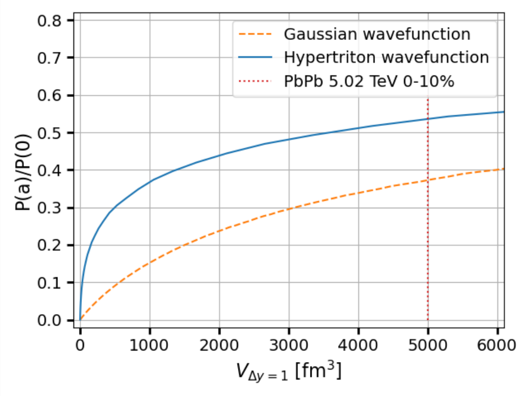




Berndt Müller

Gaussian Wave Function Not Sufficient

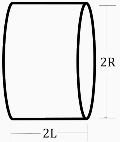


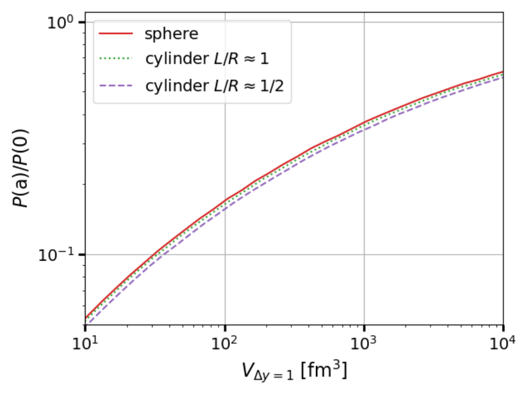


- $^3_\Lambda$H wave function from Braun-Munzinger, Dönigus arXiv:1809.04681
- hypertriton extends to large radii
- even for central PbPb collisions: suppression by 50%

Volume Construction

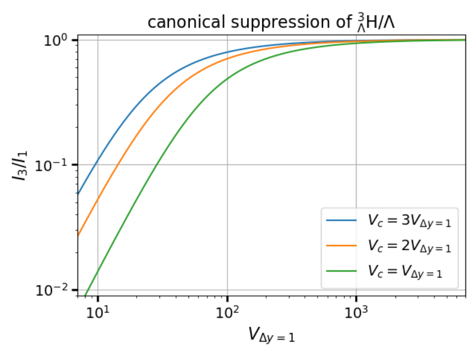
- cylinder of volume $V_{\Delta y=1}$:
  length from longitudinal Bjorken flow
  $L = \tau_{\mathrm{fo}} \sinh(y)$,
  radius matched to volume
- for PbPb $\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}$:
  $L = 5.4\ \mathrm{fm}$
  $R_{\mathrm{T}} = 11\ \mathrm{fm}$





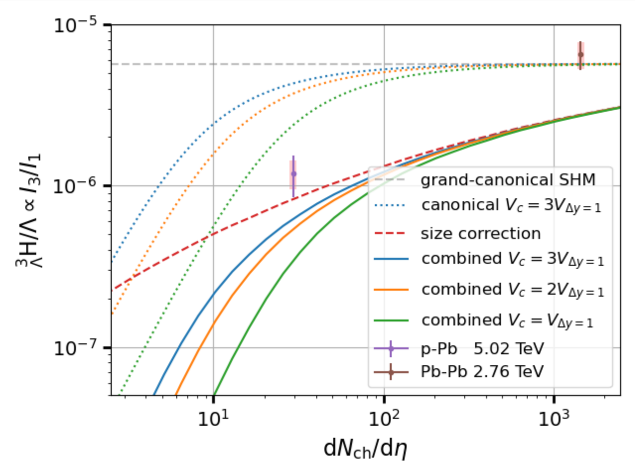
Canonical and Strangeness Correction

- for smaller systems, the hadronization described in canonical ensemble
- canonical correction $n_{\text{th}}^{\text{C}} = n_{\text{th}}^{\text{GC}} \frac{I_n\left(2N_{\text{th}}^{\text{B}}\right)}{I_0\left(2N_{\text{th}}^{\text{B}}\right)}$ with $N_{\text{th}}^{\text{B}} = V_{\text{c}} n_{\text{th}}^{\text{B}}$
- strangeness correction $n_{\text{th}}^{\text{C}} = n_{\text{th}}^{\text{GC}} \frac{I_s\left(2N_{\text{th}}^{\text{S}}\right)}{I_0\left(2N_{\text{th}}^{\text{S}}\right)}$
- size correction is considered in addition to canonical correction



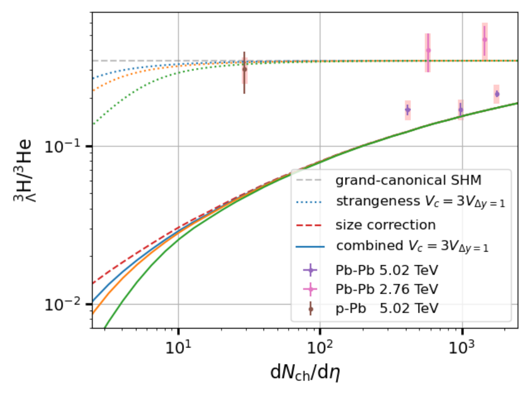
Results: ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ yield ratio

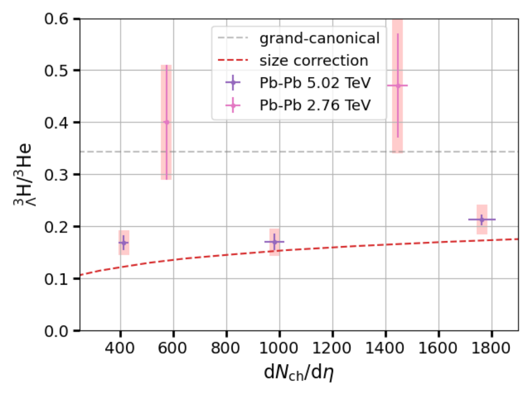
- linearity $\mathrm{d}N_{\mathrm{ch}}\,/\,\mathrm{d}y \propto V_{\Delta y=1}$ applied
- size corrected result smaller than ALICE data



${}^{3}_{\Lambda}H/{}^{3}He$: Size Correction Not Seen for Small Systems

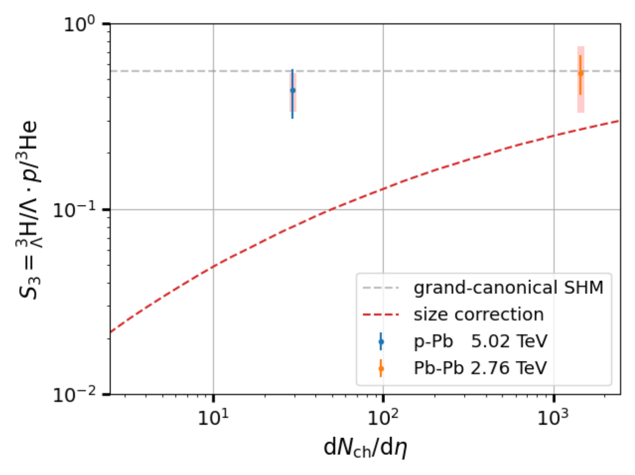
- new PbPb 5.02 TeV measurement: 2σ below 2.76 TeV data
- pPb data point does not support size correction





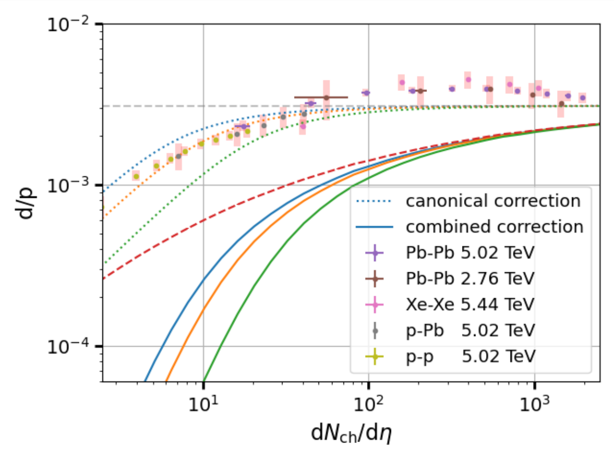
S_3: No System Size Dependence in Data

- $S_3 = \frac{{}^{3}_{\Lambda}\mathrm{H}}{\Lambda} \frac{\mathrm{p}}{{}^{3}\mathrm{He}}$ no canonical correction, size correction should be visible



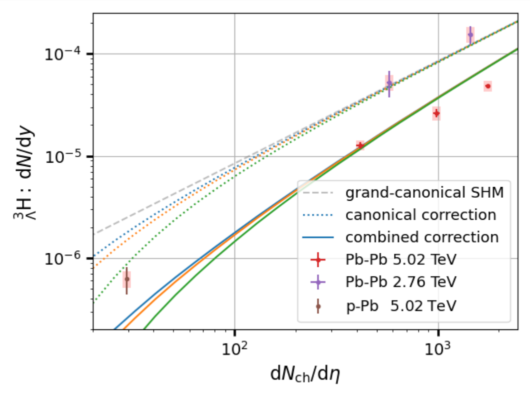
No Size Effect Visible in d/p

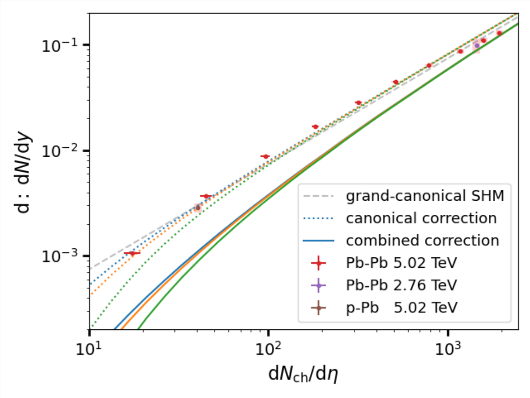
- same for deuteron ($\sqrt{\langle r^2 \rangle} \approx 2.1\ \mathrm{fm}$), more tightly bound $\Rightarrow$ smaller correction
- deuteron well described without size correction



${}^{3}_{\Lambda}$H and d yields

- also possible to calculate correction for single-particle yields



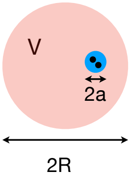


Summary and Outlook

- tested an idea how to take into account nucleus size within the statistical hadronization model
- $^3_\Lambda$H: large correction predicted
- size correction not seen in data over all system sizes
- for S_3, d and d/p: data points do not show any clear particle size effect
- next steps: investigate size effect also for $^3\mathrm{He}$
  compare STAR data with size corrected SHM

Backup Slides

SHM *does* care about hadron size

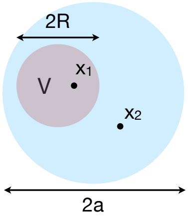


$$P_H = \mathrm{Tr}[e^{-H/T}\theta(V_H)] = \int d^3p \, \langle \psi_p | e^{-H/T} \theta_V | \psi_p \rangle$$

$$P_H = \int d^3p \, e^{-E_p/T} \int d^3x_1 \, d^3x_2 \, |\psi_p(x_1 - x_2)|^2 \theta_V(x_1)\theta_V(x_2)$$

When $a \ll R$, integrate out (x_1–x_2):

$$P_H \approx \int d^3p \, e^{-E_p/T} \int d^3X \, \theta_V(X) = V_H \int d^3p \, e^{-E_p/T}$$

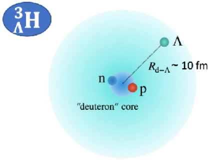


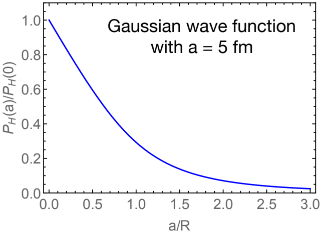
When $a \gg R$, requires $|x_1 - x_2| < R$:

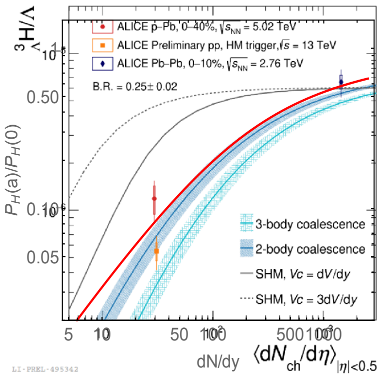
$$P_H \approx \int d^3p \, e^{-E_p/T} \int d^3x_1 \, d^3x_2 \, |\psi_p(0)|^2 \theta_V(x_1)\theta_V(x_2)$$

$$P_H \approx V_H^2 \int d^3p \, e^{-E_p/T} |\psi_p(0)|^2 \propto \frac{V_H^2}{a^3} \int d^3p \, e^{-E_p/T}$$

Particle size matters







Particle size effect similar to 2-body coalescence.

(n-p) distance is small compared to fireball radius.

Next Step: Having a look at STAR data: Preliminary, Work in progress