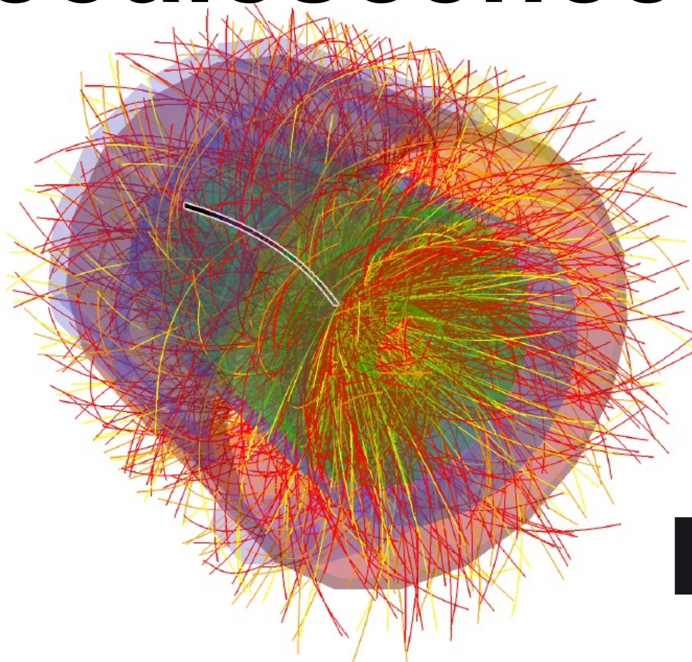
Hypertriton production in the coalescence model



09.04.2024

EMMI RRTF

„Understanding light (anti-)nuclei production at RHIC and LHC“

Benjamin Dönigus

Institut für Kernphysik

Goethe Universität Frankfurt

Content

- Hypertriton
- Approaches
  - Box coalescence
  - Wave-function based
  - Analytical approach
- Summary

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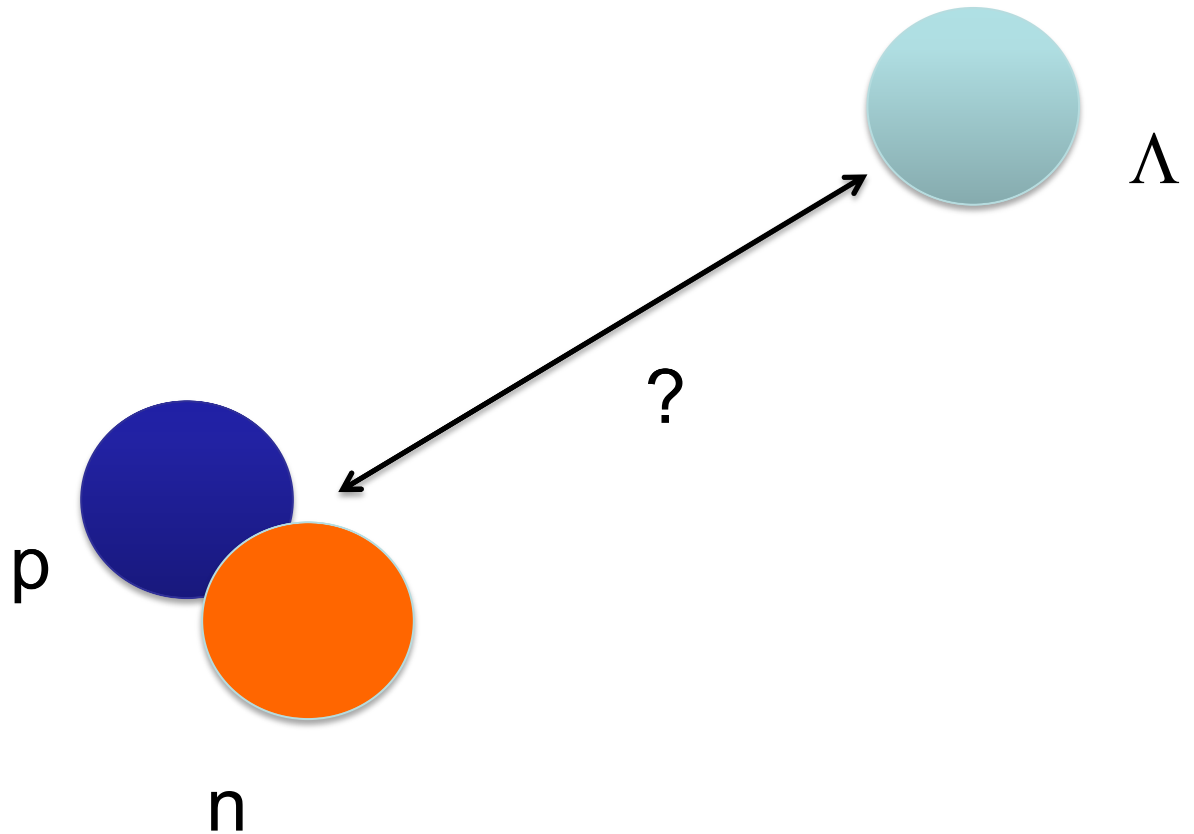
Hypertriton

Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)



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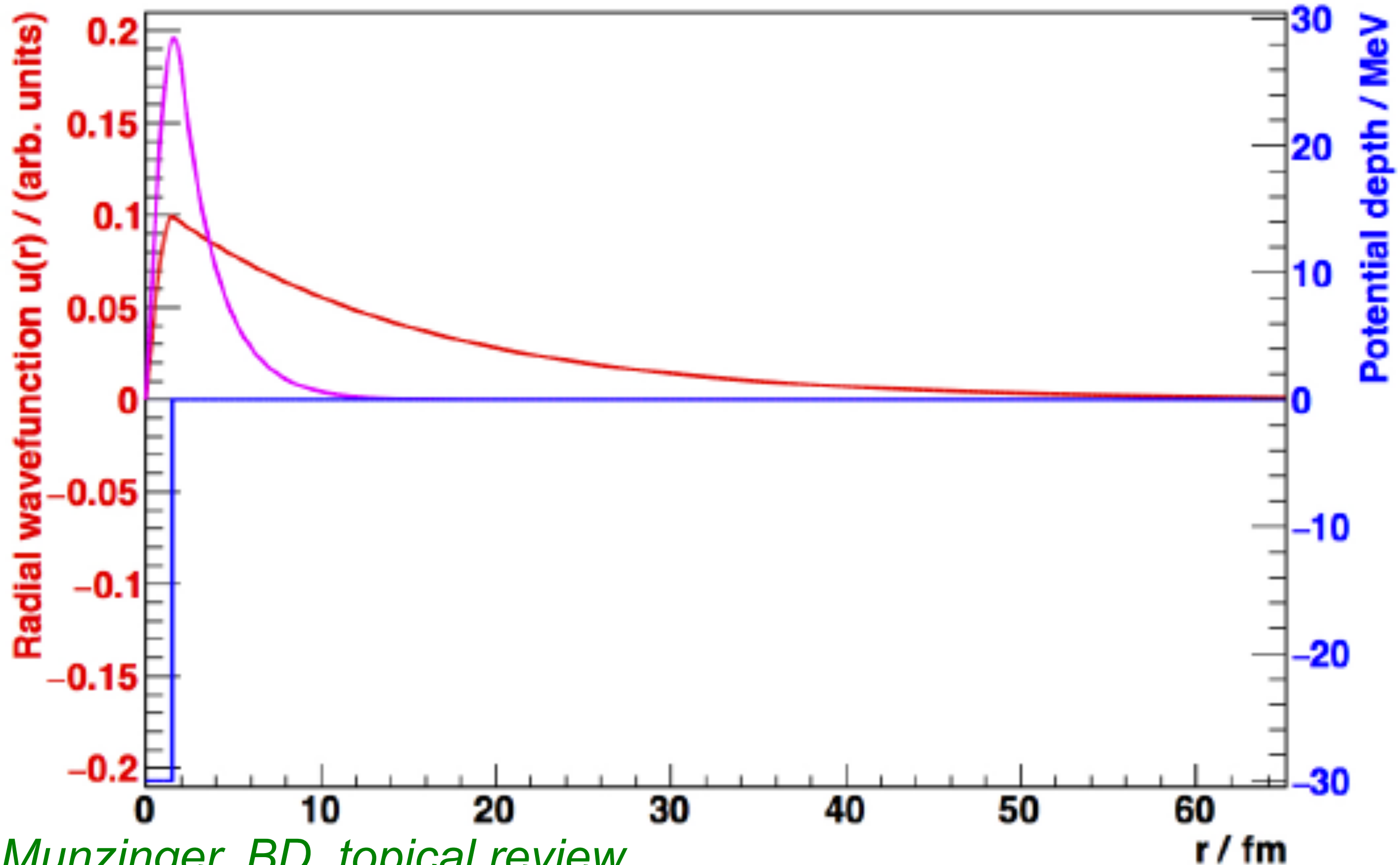

P. Braun-Munzinger, BD, topical review, NPA 987, 144 (2019), arXiv:1809.04681

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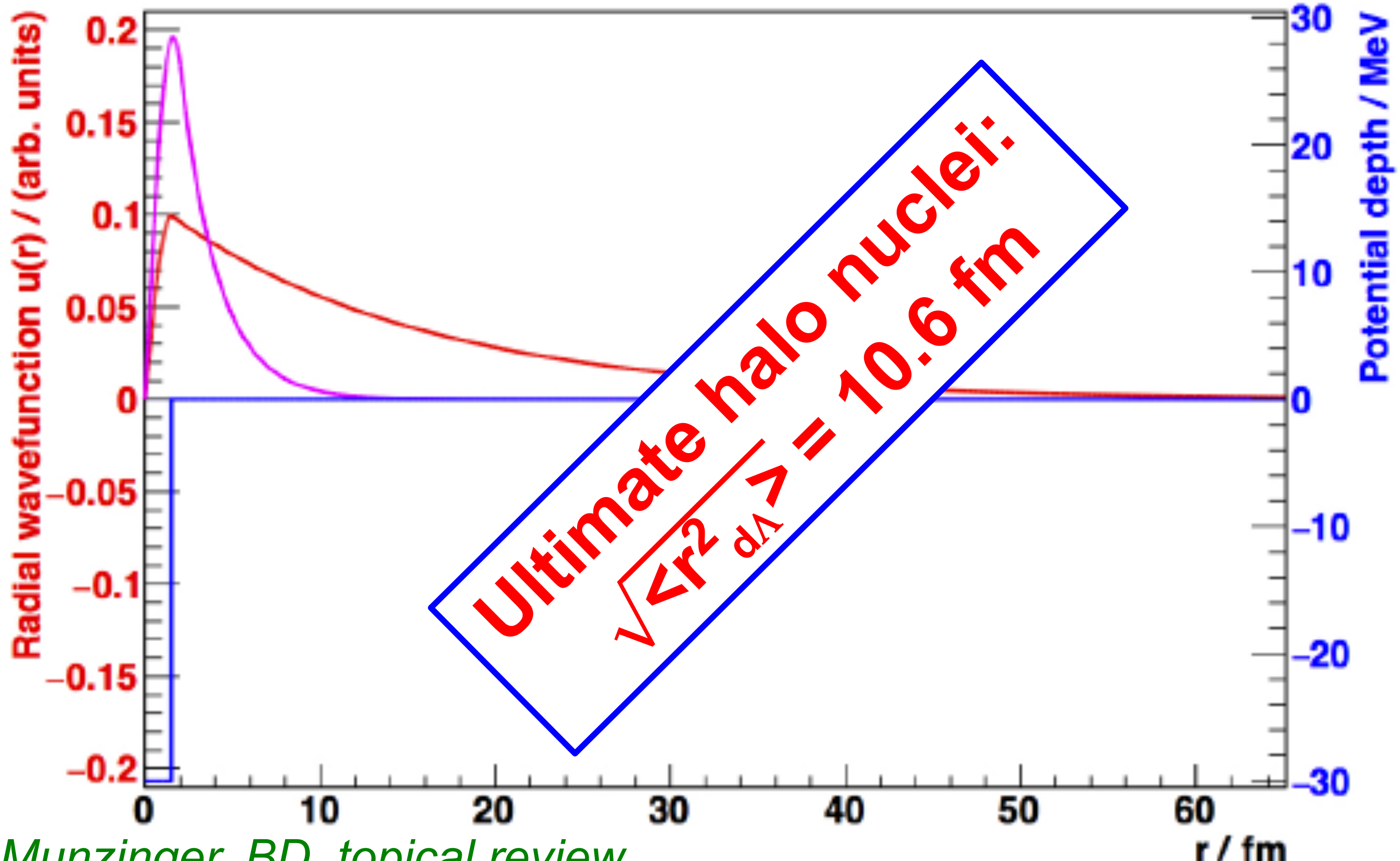
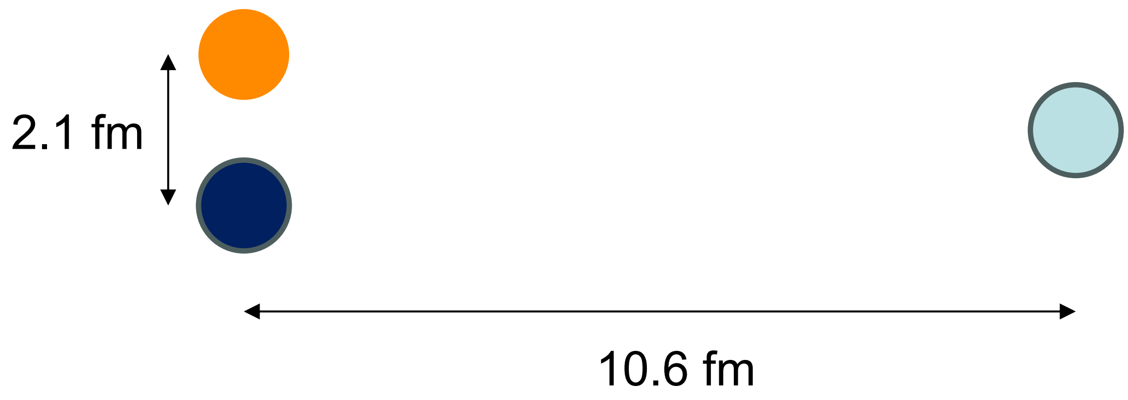


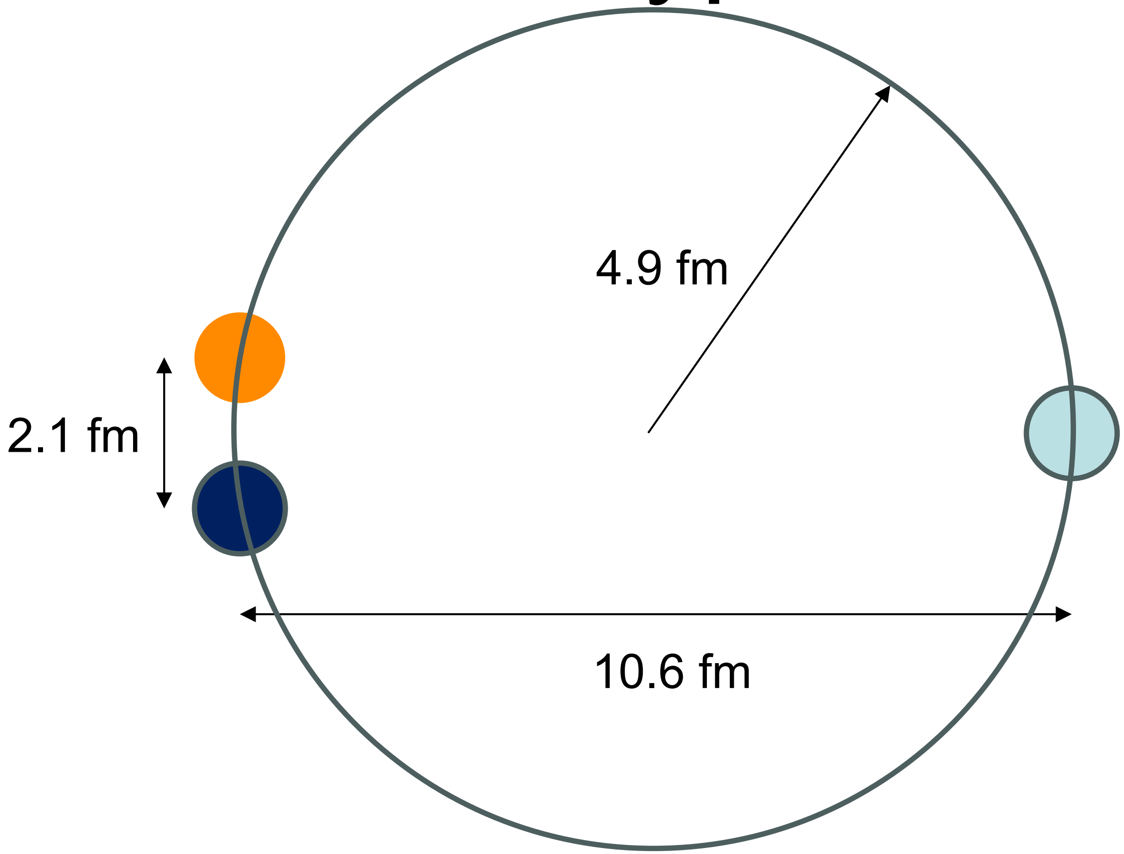
P. Braun-Munzinger, BD, topical review, NPA 987, 144 (2019), arXiv:1809.04681

Hypertriton

- Putting the rms „radii“ into scale



Hypertriton



- Putting the rms „radii“ into scale

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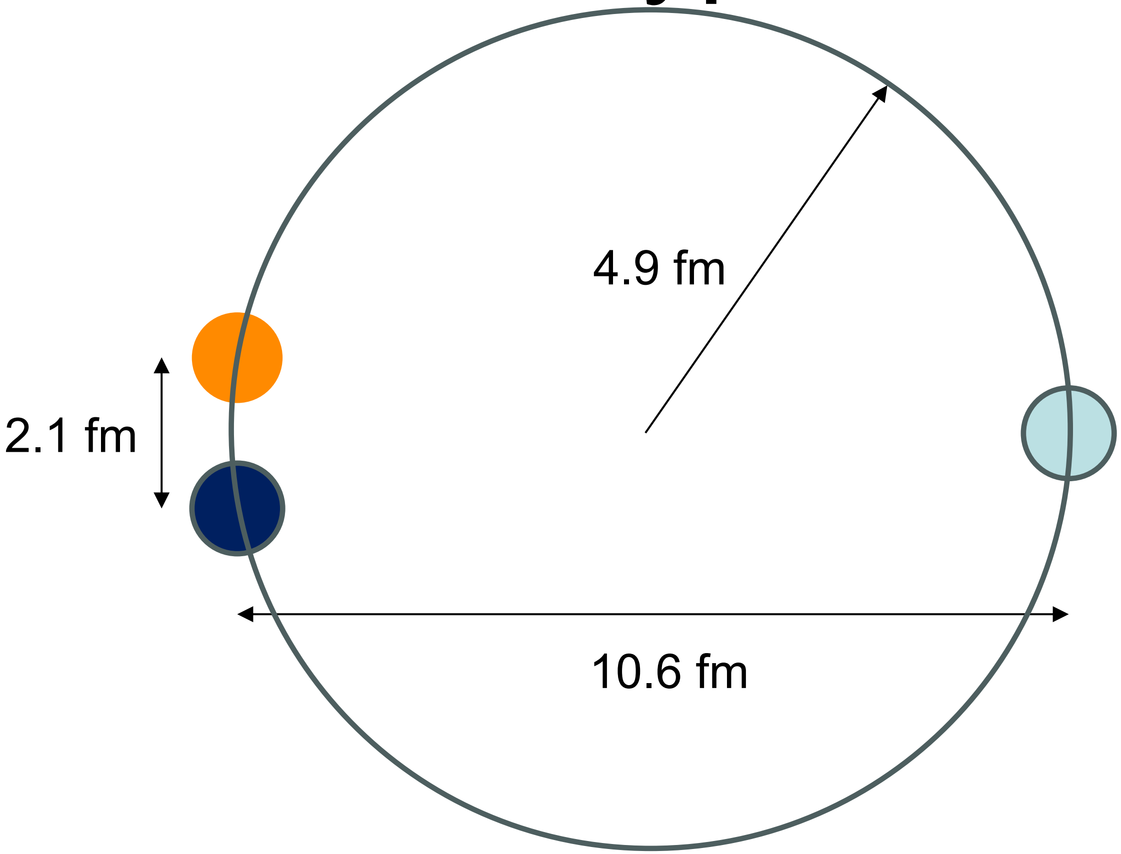
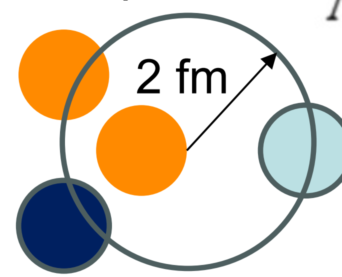
Hypertriton

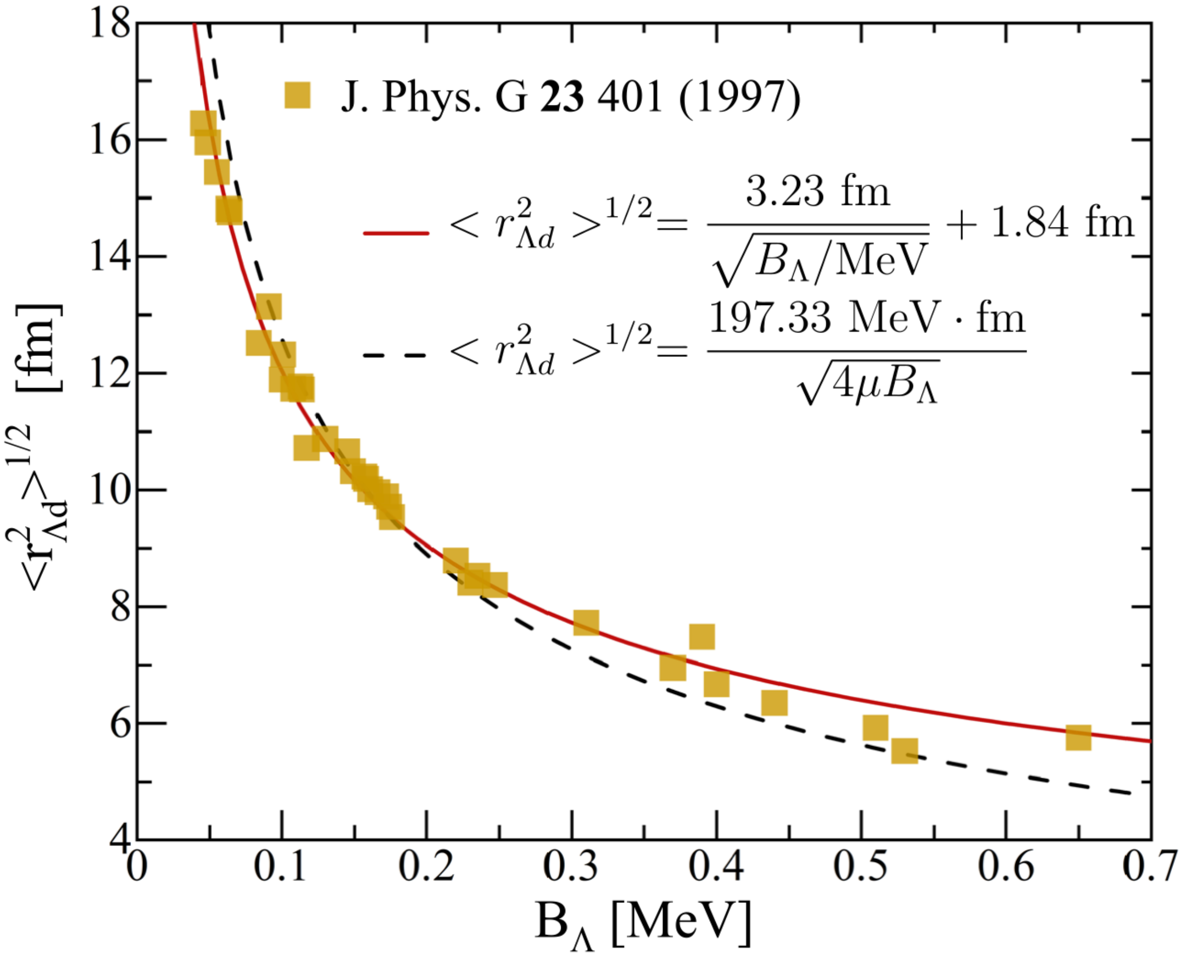


- Putting the rms „radii“ into scale

For comparison: ${}^{4}_{\Lambda}H$



Hypertriton



- Putting the rms „radii“ into scale

D.-N. Liu et al., arXiv:2404.02701

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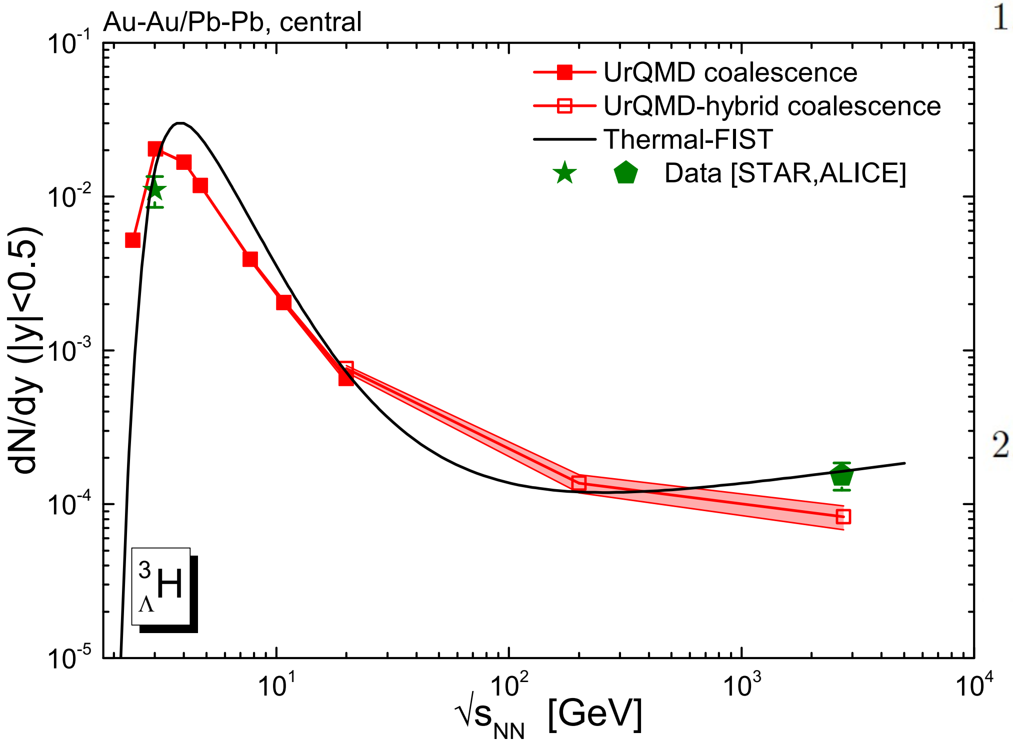
„Box coalescence“



	NN	ΛΛ	ΞN	NNN	$(NN\Lambda)_a$	$(NN\Lambda)_b$	NNΞ
spin-isospin	3/8	3/16	3/8	1/12	1/12	1/12	1/12
Δr_{max} [fm]	3.575	9.5	9.5	4.3	9.5	4.3	9.5
Δp_{max} [GeV]	0.285	0.135	0.135	0.33	0.135	0.25	0.135

1. Using the list of freeze-out coordinates from the UrQMD model, the relative coordinates of all nucleon (hyperon) pairs in their respective center of mass frame is calculated. If their relative distance $\Delta r = |\vec{r}_{n_1} - \vec{r}_{n_2}| < \Delta r_{max,nn}$ and momentum distance $\Delta p = |\vec{p}_{n_1} - \vec{p}_{n_2}| < \Delta p_{max,nn}$, a two nucleon state is potentially formed with the combined momenta $\vec{p}_{nn} = \vec{p}_{n_1} + \vec{p}_{n_2}$ at position $\vec{r}_{nn} = (\vec{r}_{n_1} + \vec{r}_{n_2})/2$.
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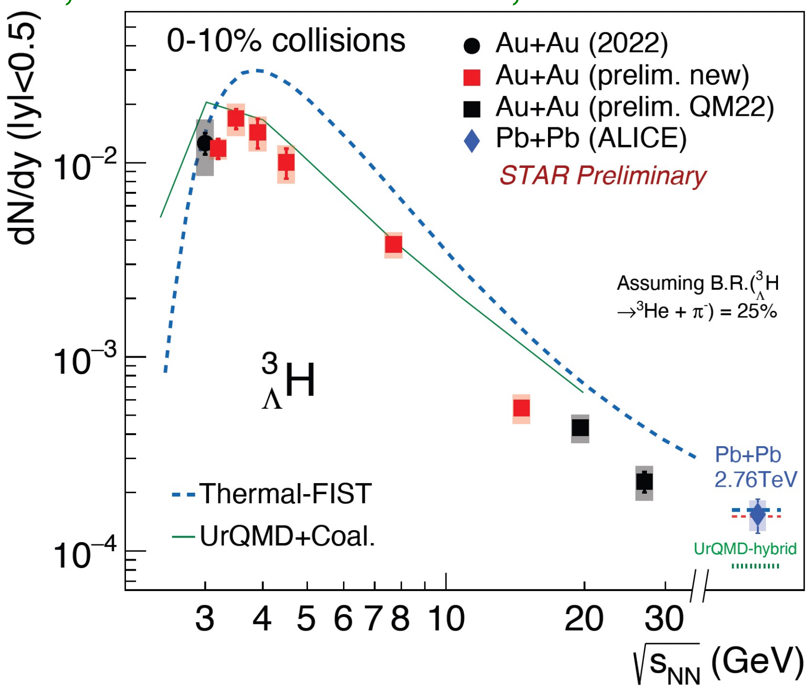
3. If no third particle is found, a dibaryon can be formed with the appropriate probability given by the spin-isospin-coupling.

T. Reichert et al., Phys.Rev.C 107 (2023) 014912, arXiv:2210.11876

„Box coalescence“

Y. Ji, STAR Collaboration, arXiv:2312.15768



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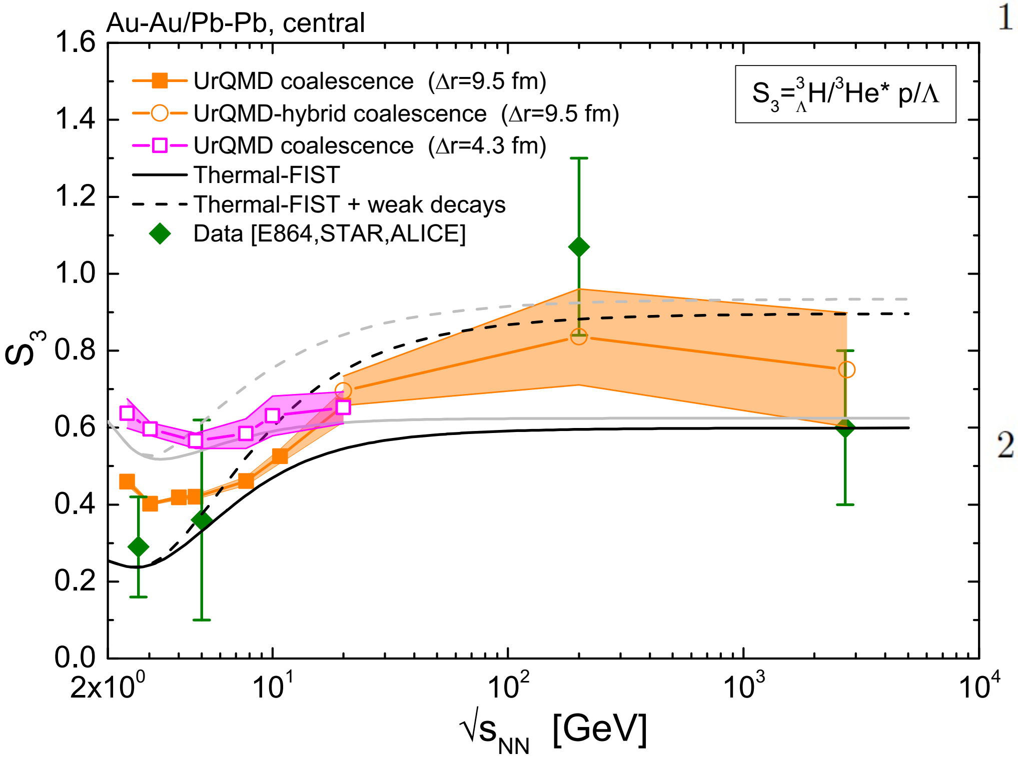

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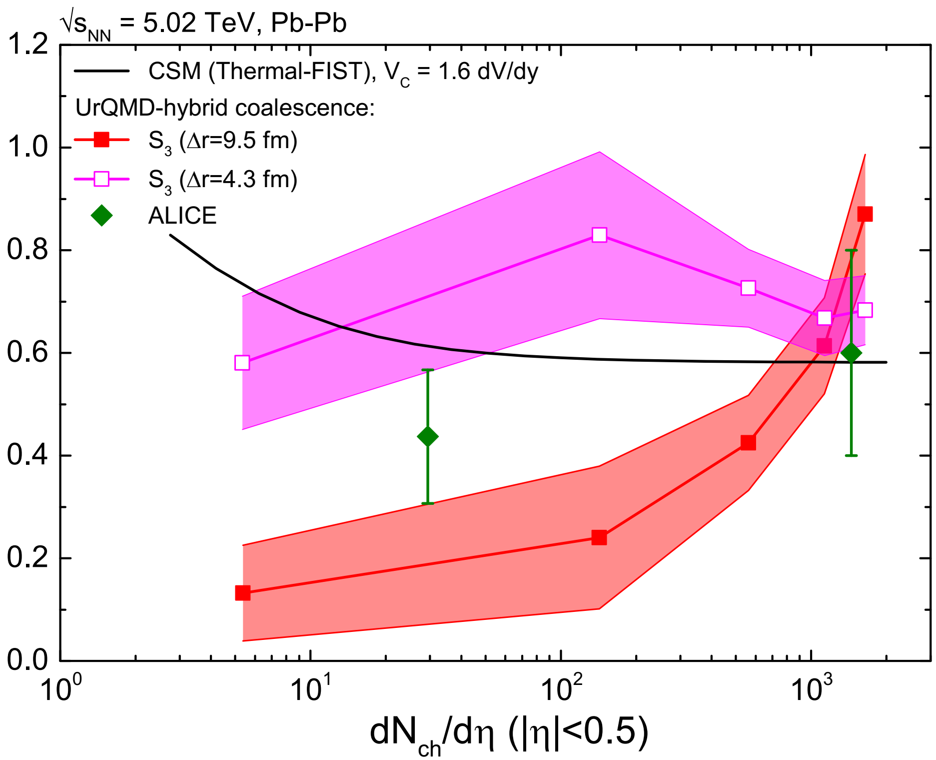

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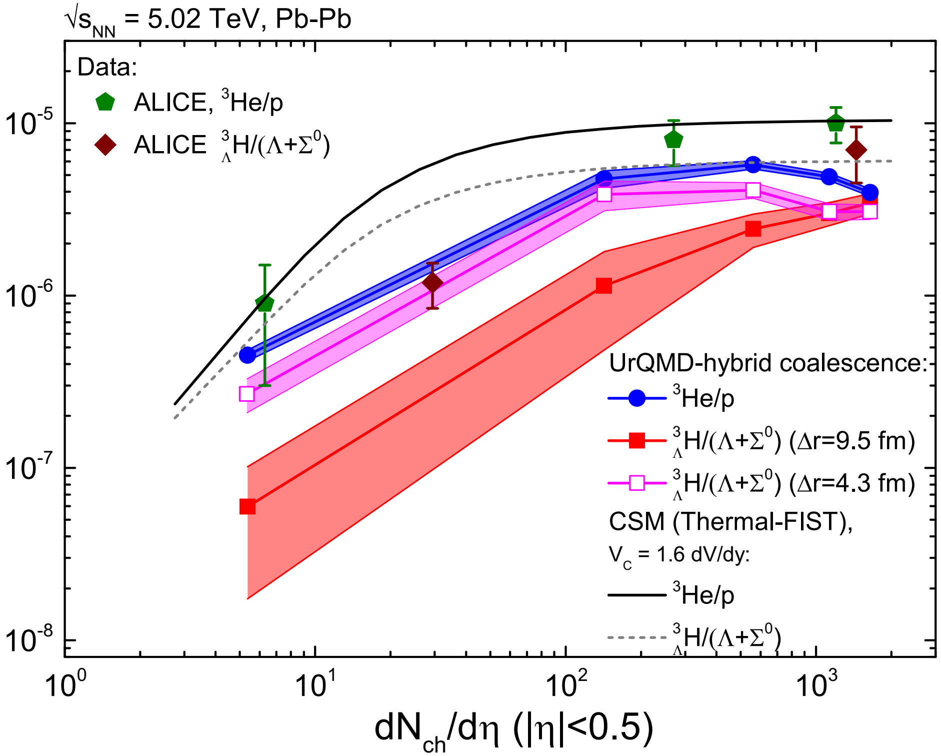

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T. Reichert et al., Phys.Rev.C 107 (2023) 014912, arXiv:2210.11876

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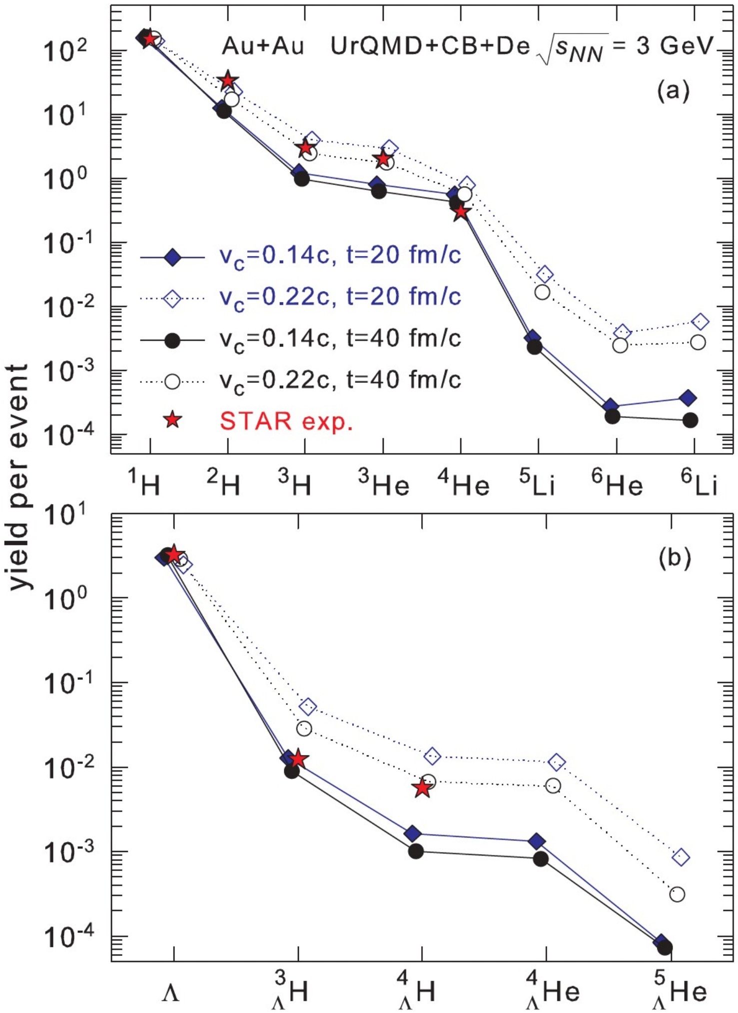
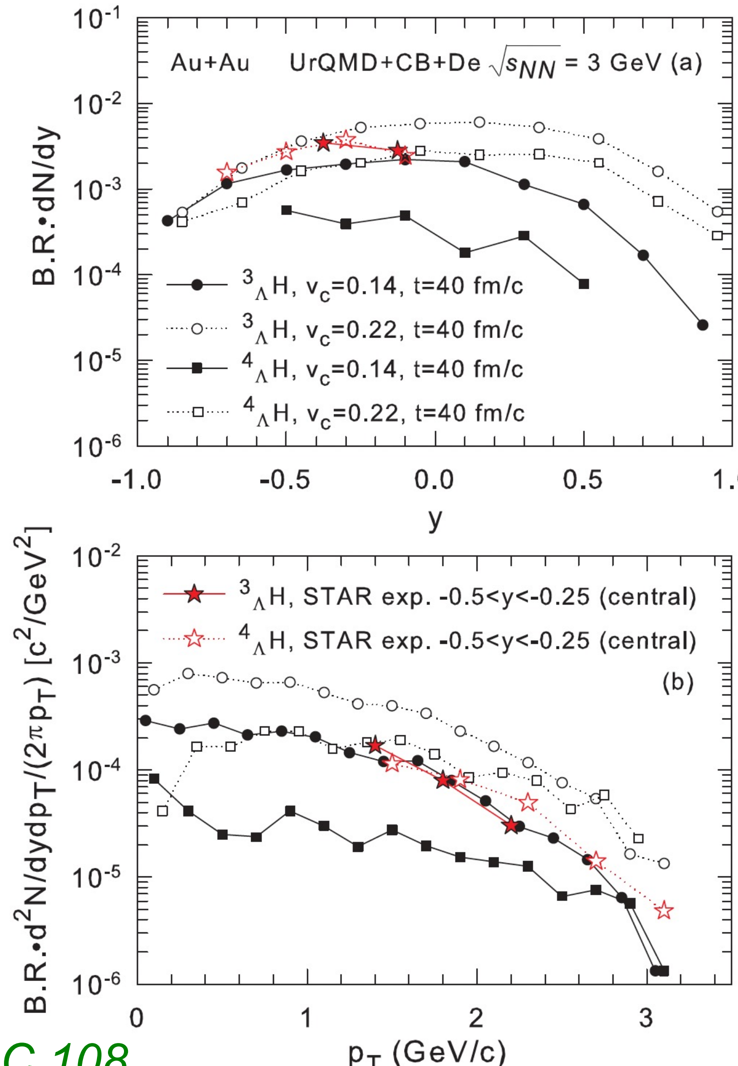
„Box coalescence“





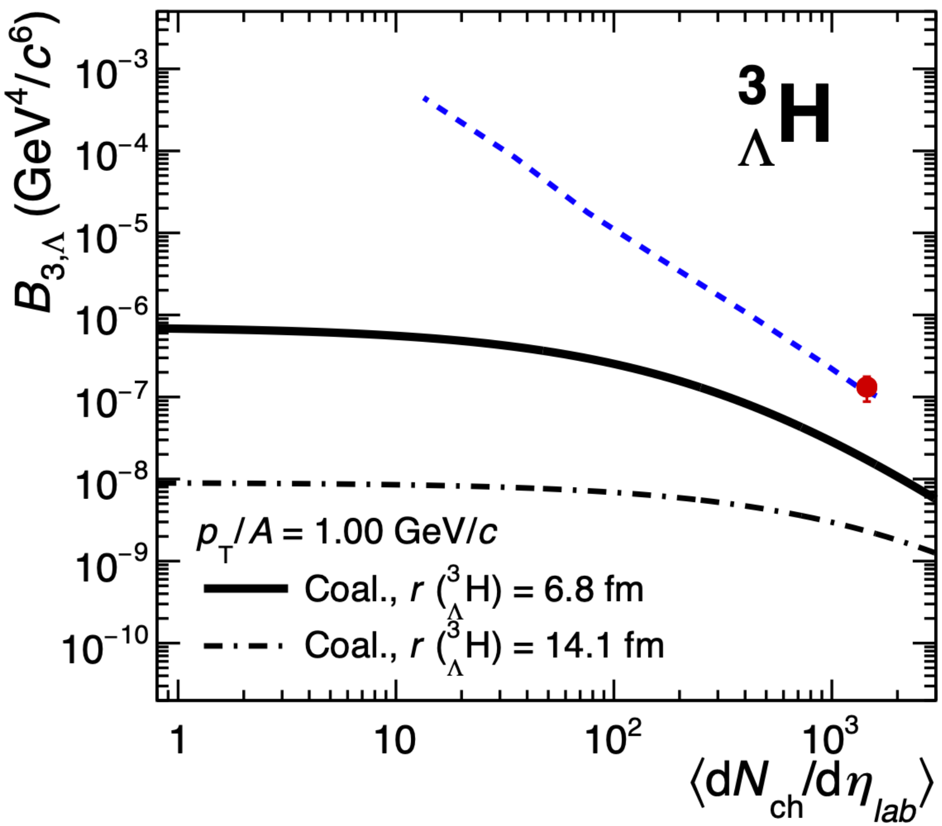
Similar approach (coalescence of baryons CB) using maximum variance between velocities of baryons as main criterium – was applied to Dubna Cascade Model in the past

N. Buyukcizmeci et al., Phys.Rev.C 108 (2023) 054904, arXiv:2306.17145

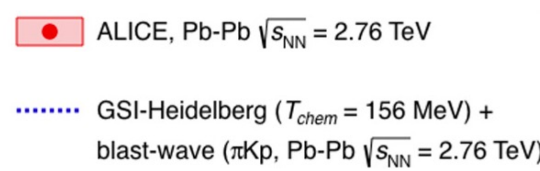
Wigner formalism

Mostly exercised on the deuteron, see talks by Chiara and Maximilian
Discussions with Uli Heinz led to involvements of experimentalists

$$N_c = \frac{2J_c+1}{(2J_a+1)(2J_b+1)} \int \frac{dx_a dk_a}{(2\pi)^3} \frac{dx_b dk_b}{(2\pi)^3} f_a(x_a,k_a) f_b(x_b,k_b) W_c(x,k)$$



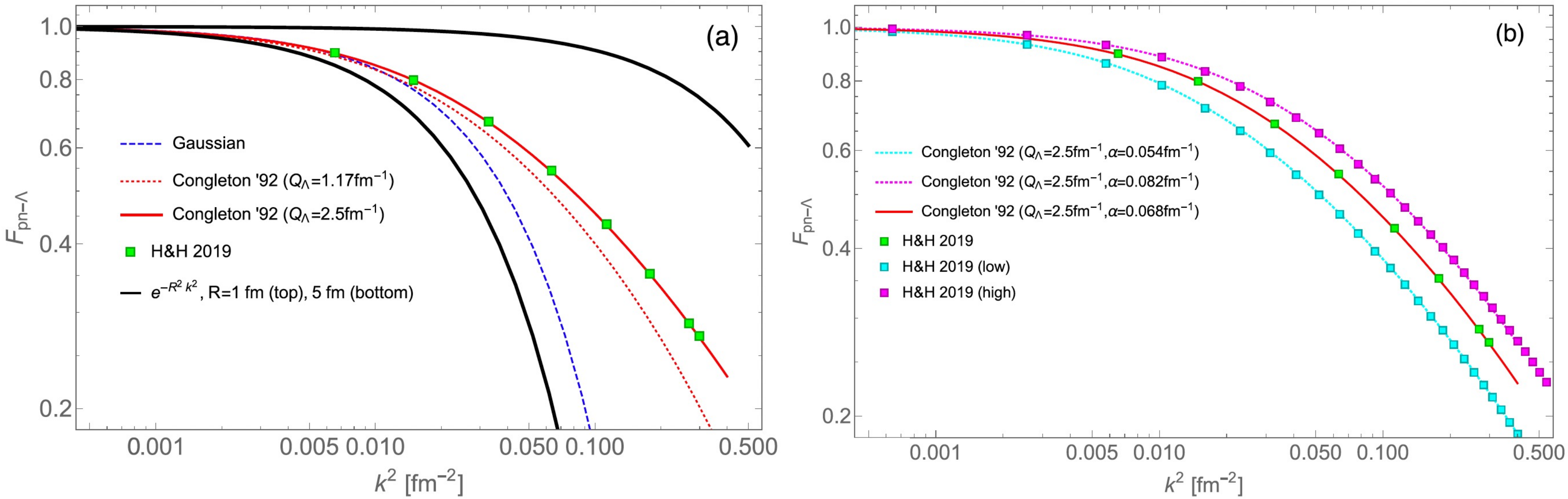
Predictions for coalescence parameters B_A done using the formalism by Scheibl, Heinz using paramterization of the π HBT measurements of ALICE and Gaussian WF



F. Bellini, A. Kalweit, Phys.Rev.C 99 (2019) 054905, Acta Phys.Polon.B 50 (2019) 991

Wigner formalism

Matching the most recent three-body wave function by Hildenbrand & Hammer in a pionless EFT approach to a two body wave function, e.g. Congleton



F. Bellini et al., Phys.Rev.C 103 (2021) 014907

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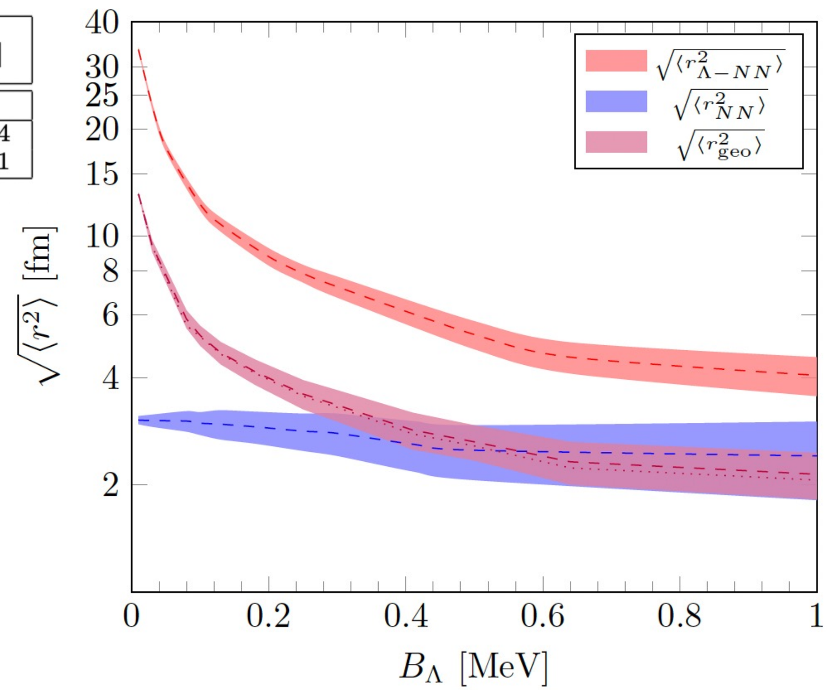
$\sqrt{\langle r^2_{\Lambda-NN'}\rangle}$[fm]	$\sqrt{\langle r^2_{N'-\Lambda N}\rangle}$[fm]	$\sqrt{\langle r^2_{N-N'\Lambda}\rangle}$[fm]	$\sqrt{\langle r^2_{NN'}\rangle}$[fm]	$\sqrt{\langle r^2_{geo}\rangle}$[fm]
10.79	3.96	4.02	2.96	4.66
$+3.04/-1.53$	$+0.40/-0.25$	$+0.41/-0.25$	$+0.06/-0.05$	$+1.19/-0.54$
$+0.03/-0.02$	$+0.03/-0.03$	$+0.03/-0.03$	$+0.03/-0.04$	$+0.01/-0.01$

Compared to shallow two-body calculation:

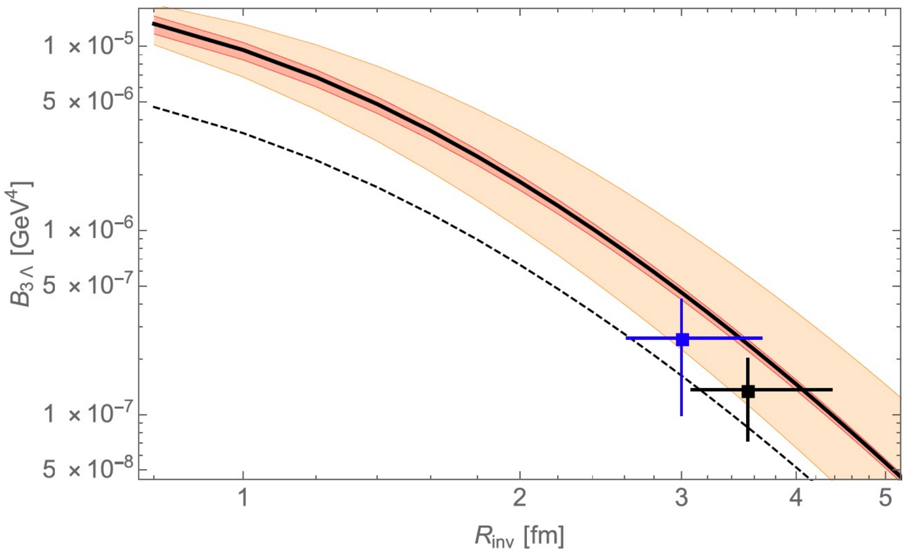
$$\sqrt{\langle r^2_{\Lambda d}\rangle} \approx 10.34\,\text{fm}$$

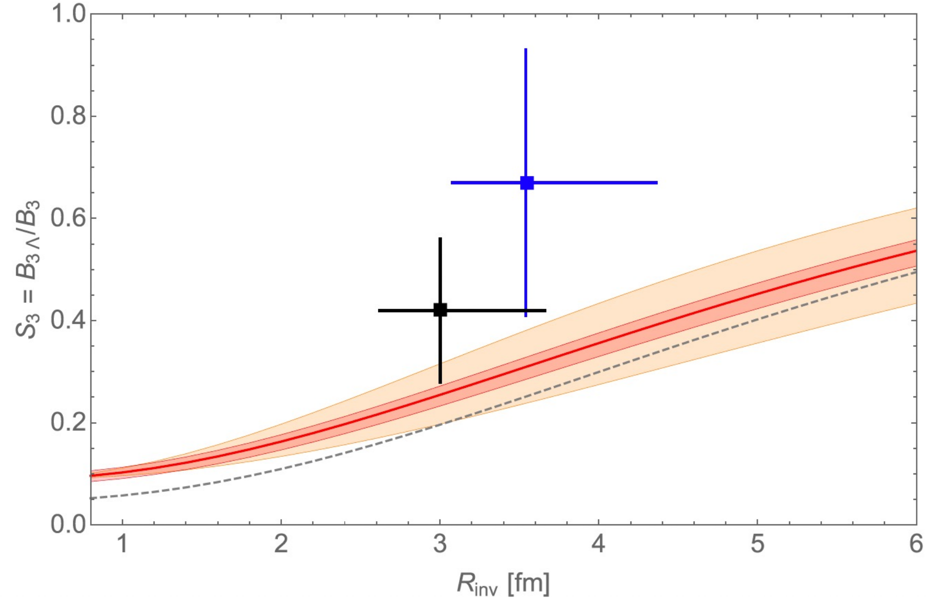


F. Hildenbrand, HFHF Colloquium 2023

Wigner formalism

Matching the most recent three-body wave function by Hildenbrand & Hammer in a pionless EFT approach, the same approach can describe the data





F. Bellini et al., Phys.Rev.C 103 (2021) 014907

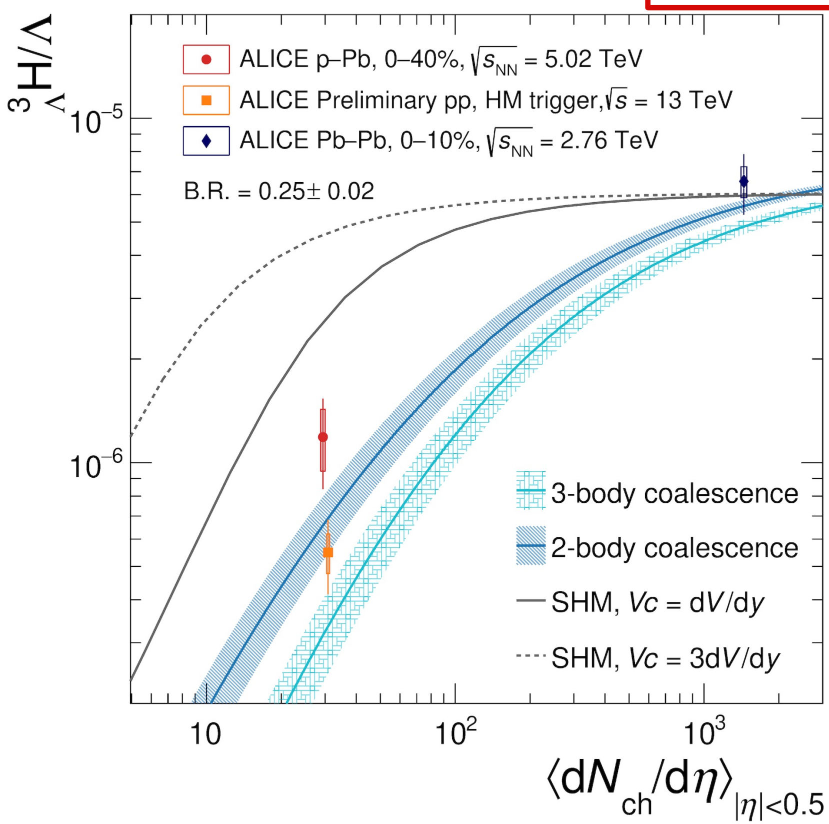
Analytical approach

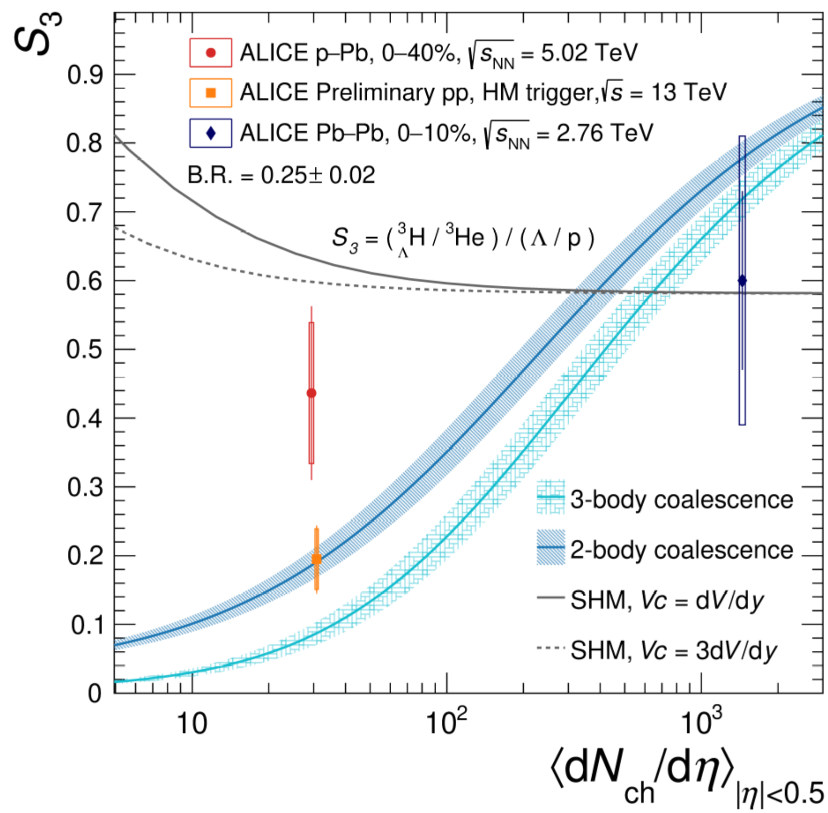
$$N_c = \frac{2J_c+1}{(2J_a+1)(2J_b+1)} \int \frac{dx_a dk_a}{(2\pi)^3} \frac{dx_b dk_b}{(2\pi)^3} f_a(x_a,k_a) f_b(x_b,k_b) W_c(x,k)$$

$$\approx \frac{2J_c+1}{(2J_a+1)(2J_b+1)} \frac{N_a N_b}{\left(\frac{m_a m_b T}{m_a+m_b}(R_a^2+R_b^2)\right)^{3/2}} \times \boxed{\frac{1}{\left(1+\frac{\sigma^2}{R_a^2+R_b^2}\right)^{3/2}}}$$

$$f_a = \frac{N_a}{(m_a T R_a^2)^{3/2}} e^{-\frac{k_a^2}{2m_aT} - \frac{x_a^2}{2R_a^2}}$$

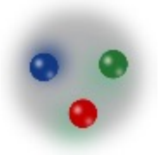
$$N_a = \int \frac{dx_a dk_a}{(2\pi)^3} f_a(x_a,k_a) \quad W_c = 8e^{-x^2/\sigma^2 - \sigma^2 k^2}$$



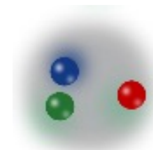


K.-J. Sun, C.-M. Ko, BD, Phys. Lett. B 792 (2019) 132, arXiv:1812.05175

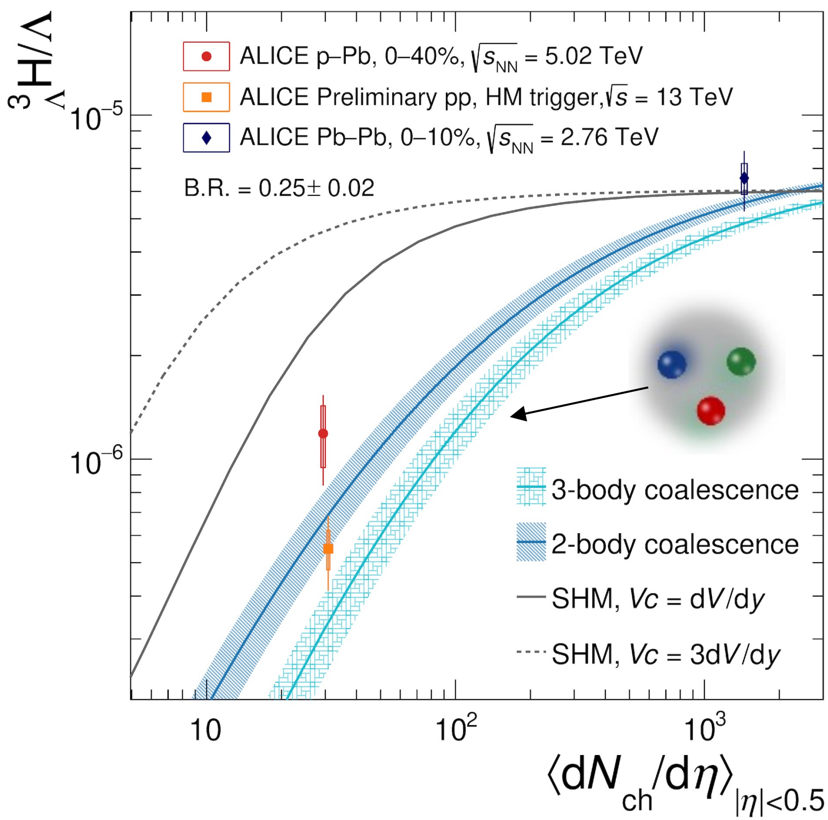
Analytical approach

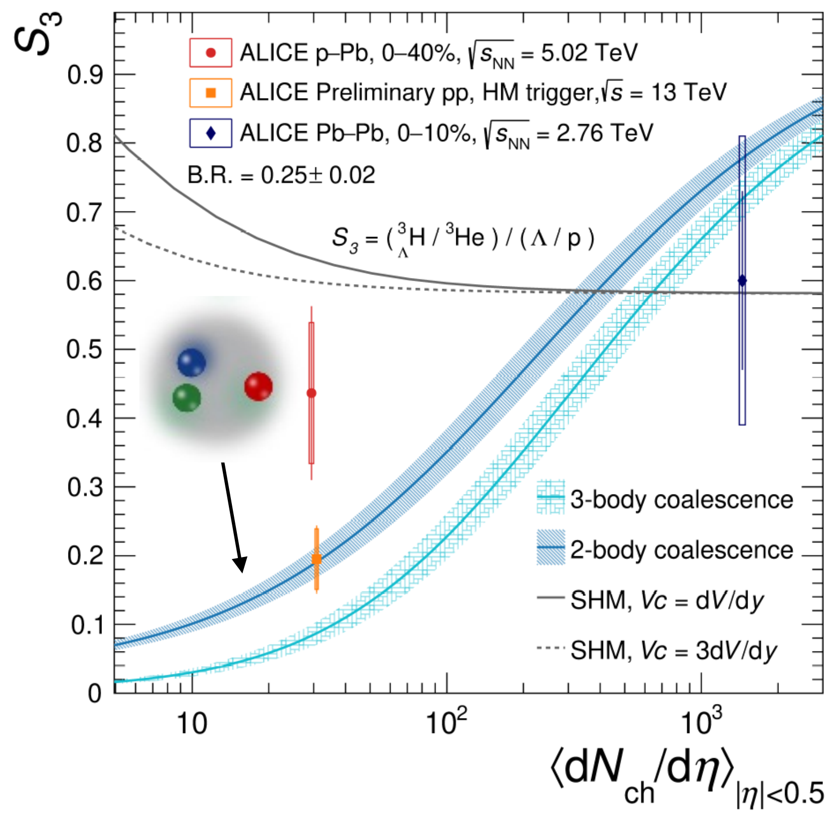


$$\frac{N_{^3_\Lambda H}}{N_\Lambda} \approx \frac{7.1\times10^{-6}}{[1+\frac{r^2_{^3_\Lambda H}}{2R^2}]^3}$$



$$\frac{N_{^3_\Lambda H}}{N_\Lambda} \approx \frac{7.1\times10^{-6}}{[1+k\frac{r^2_{d\Lambda}}{R^2}]^{3/2}[1+\frac{r^2_{d}}{2R^2}]^{3/2}}$$





K.-J. Sun, C.-M. Ko, BD, Phys. Lett. B 792 (2019) 132, arXiv:1812.05175

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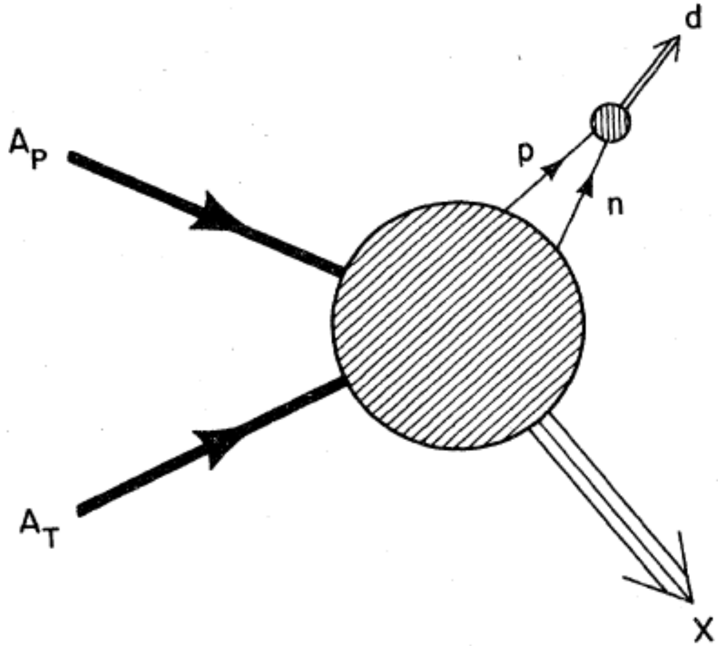
Summary

- The structure of the hypertriton reflects its loosely-bound state nature
- The coalescence models has several incarnations
- All do rather well in the description of the production of the hypertriton in the investigated phase space
- More and precise data is needed to test the different versions

Backup

Coalescence



J. I. Kapusta, PRC 21, 1301 (1980)

Nuclei are formed by protons and neutrons which are nearby and have similar velocities (after kinetic freeze-out)

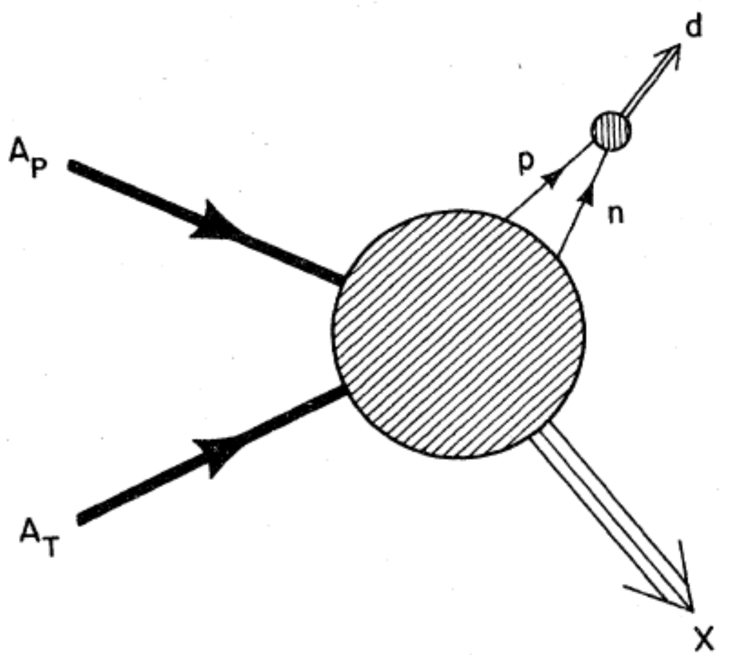
Produced nuclei

→ can break apart

→ created again by final-state coalescence

→ Different implementations on the market

Coalescence: basics



J. I. Kapusta, PRC 21, 1301 (1980)

- Alternative approach to thermal model already suggested in the first occurence of the thermal model application on nuclei in 1965 (Hagedorn contra Butler/Pearson)

- Nuclei are formed by protons and neutrons which are nearby in space and have similar velocities (after kinetic freeze-out)

- Produced nuclei

→ can break apart

→ created again by final-state coalescence

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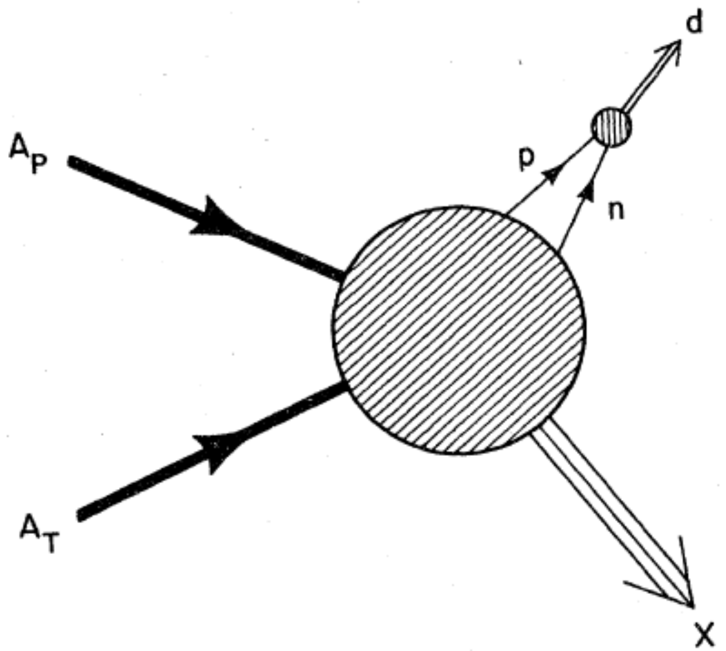

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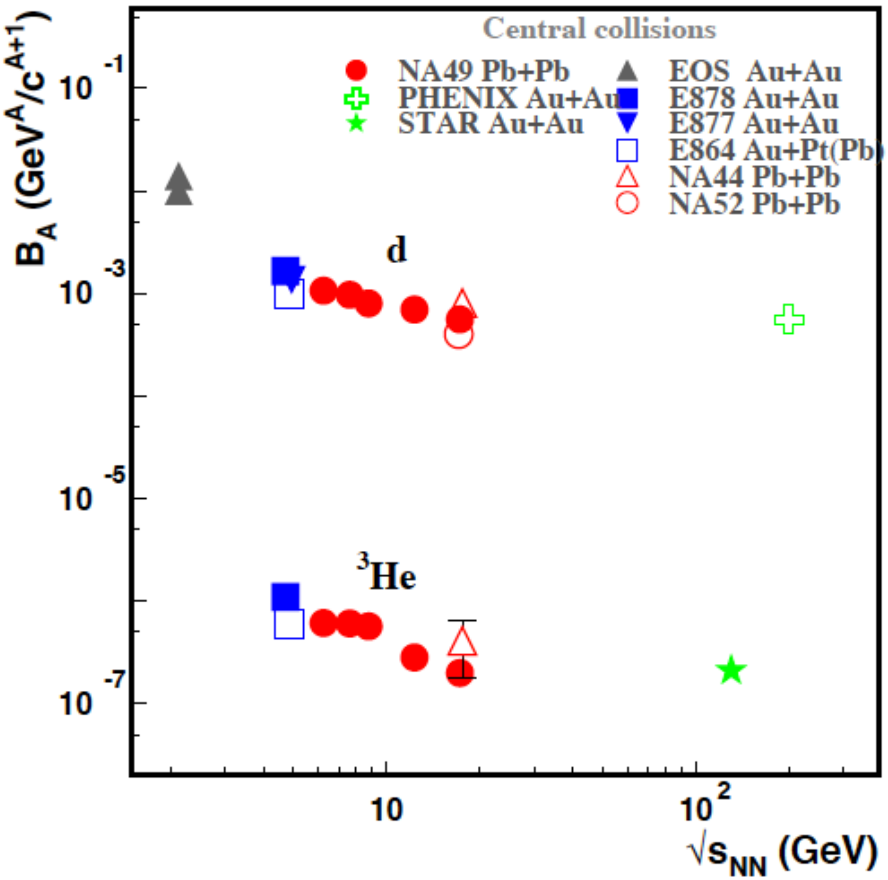
→ many different approaches – not one single coalescence model!

Coalescence: empirical



T. Anticic et al. (NA49 Collaboration)
PRC 94, 044906 (2016)

- Production probability of nuclei is usually quantified through a coalescence parameter B_A using

$$E_A \frac{dN_A}{d^3P_A} = B_A \left(E_p \frac{dN_p}{d^3P_p} \right)^Z \left(E_n \frac{dN_n}{d^3P_n} \right) \Bigg|^N_{P_p = P_n = P_A/A}$$

- B_A often connected to the coalescence volume (in momentum space p_0)

$$B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{A-1} \frac{M}{m^A}$$

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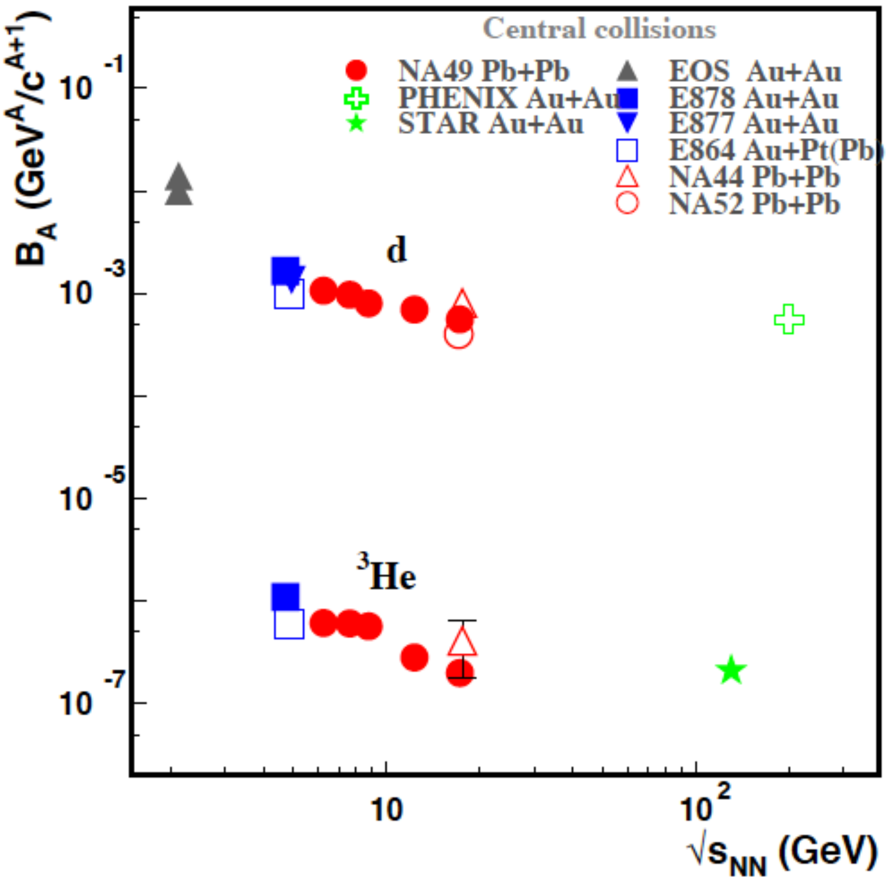

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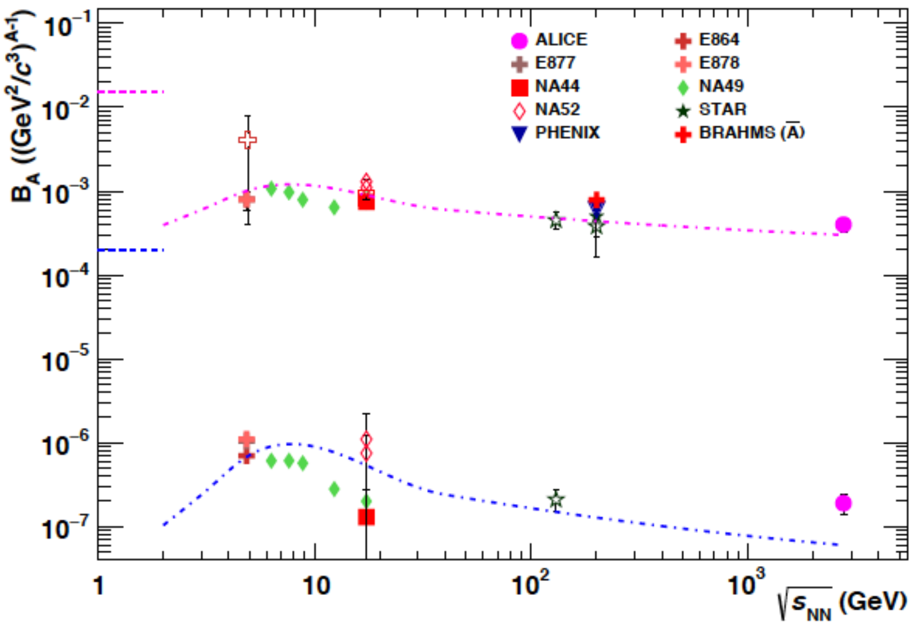

P. Braun-Munzinger, bd, invited review, NPA 987, 144 (2019), arXiv:1809.04681

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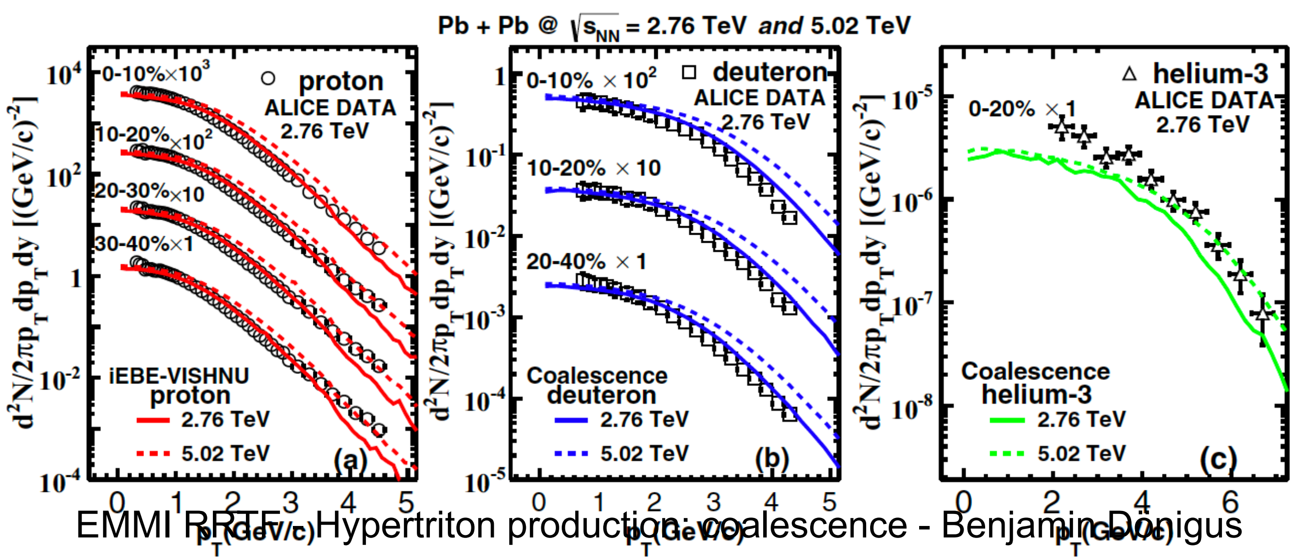
- In particular in HICs B_A described by replacing coalescence volume by HBT „volume"

$$B_A \propto \left(\frac{1}{V}\right)^{(A-1)}$$

Coalescence: improved

- An improved model has to involve quantum mechanics: For the deuteron this means involving the wave functions of the different particles, i.e. proton and neutron wave functions have to overlap with the wave function of the deuteron itself
- Typically done by using Gaussian wave packages for all particles and the Wigner formalism to calculate the overlap

SPECTRA AND FLOW OF LIGHT NUCLEI IN … PHYSICAL REVIEW C **98**, 054905 (2018)



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$$\frac{dN_d}{d^3\mathbf{p}} = \mathcal{A}\frac{dN_p}{d^3\left(\frac{1}{2}\mathbf{p}\right)}\frac{dN_n}{d^3\left(\frac{1}{2}\mathbf{p}\right)}, \qquad \mathcal{A} = \frac{3}{4}\frac{\pi^{3/2}}{(R_{\mathrm{kin}}^2 + R_d^2)^{3/2}}$$

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$$B_2 = \frac{3\pi^{3/2}\langle \mathcal{C}_d \rangle}{2m_t \mathcal{R}_\perp^2(m_t)\mathcal{R}_\parallel(m_t)} e^{2(m_t - m)(1/T_p^* - 1/T_d^*)}$$

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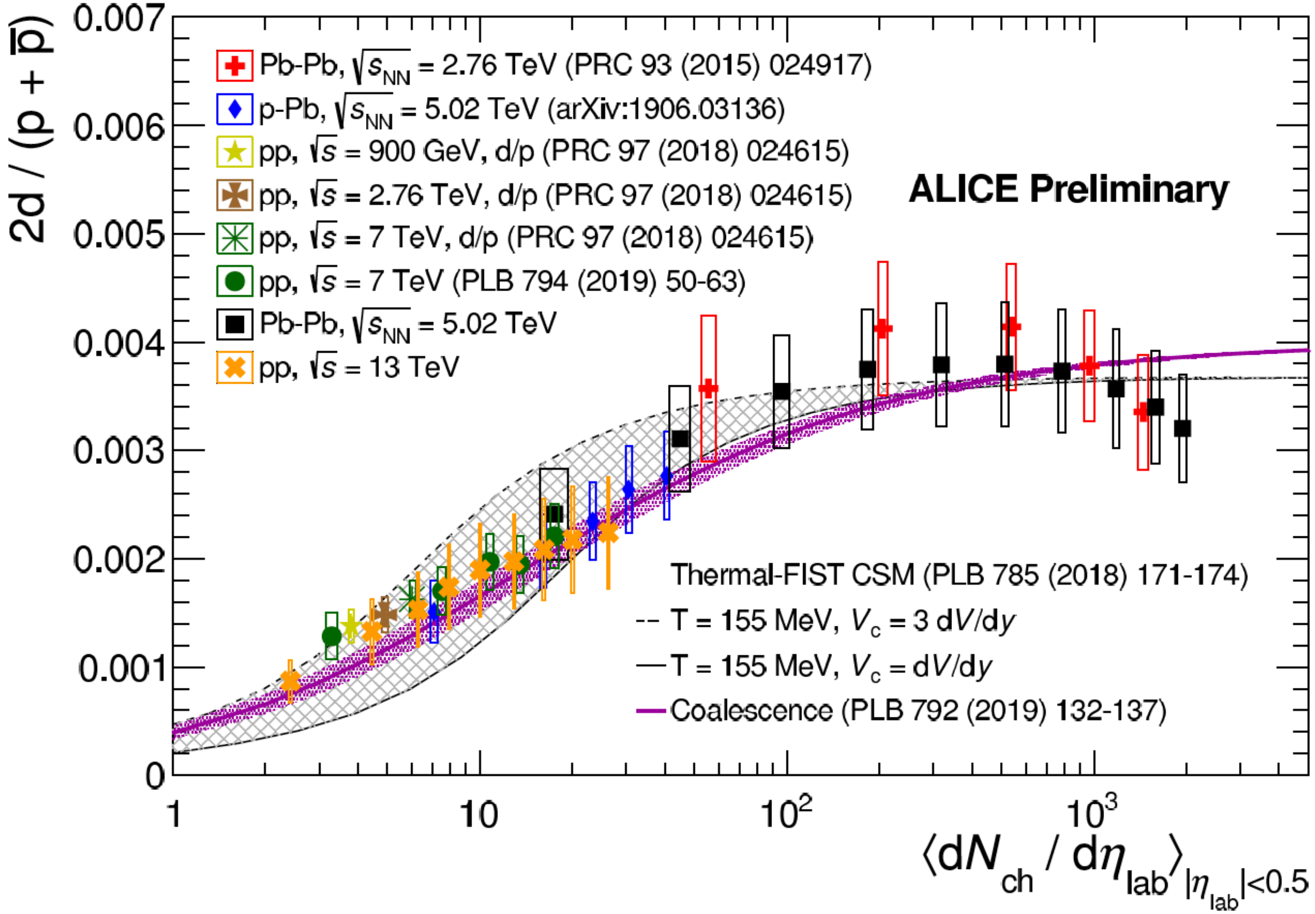
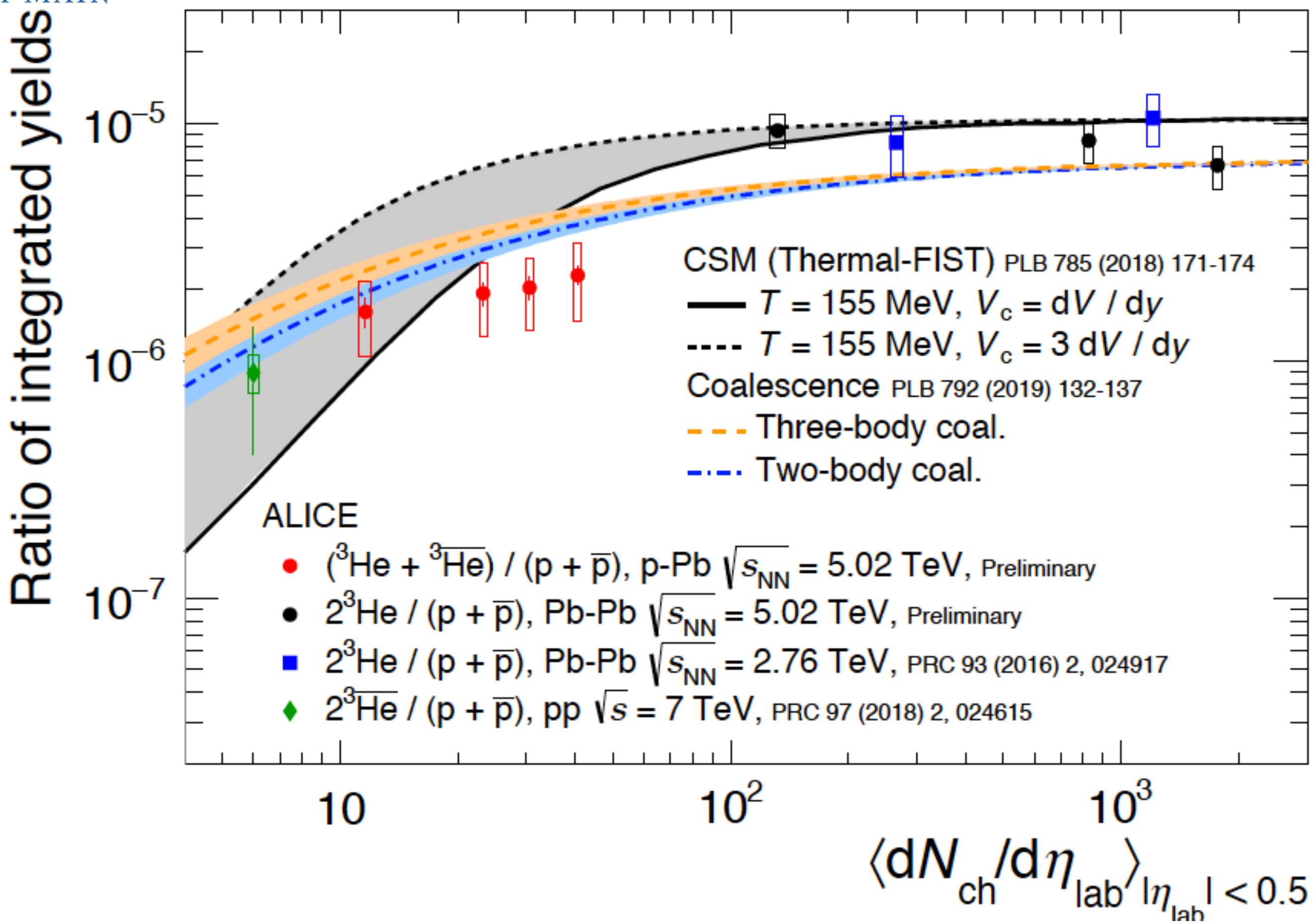
$$\mathcal{B}_2(p) \approx \frac{3}{2\,m}\int d^3q\,\mathcal{D}(\vec{q})\,\mathcal{C}_2^{\mathrm{PRF}}\,(\vec{p},\vec{q})$$

d/p vs. multiplicity



d/p ratio rather well described by using a coalescence approach, from an analytical coalsecence formula or a canonical treatment

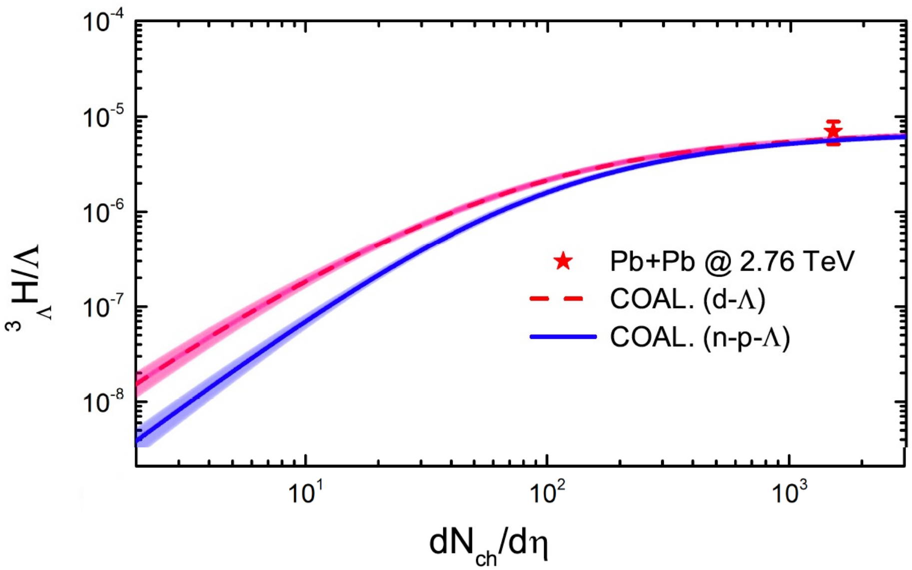
^{3}He/p vs. multiplicity

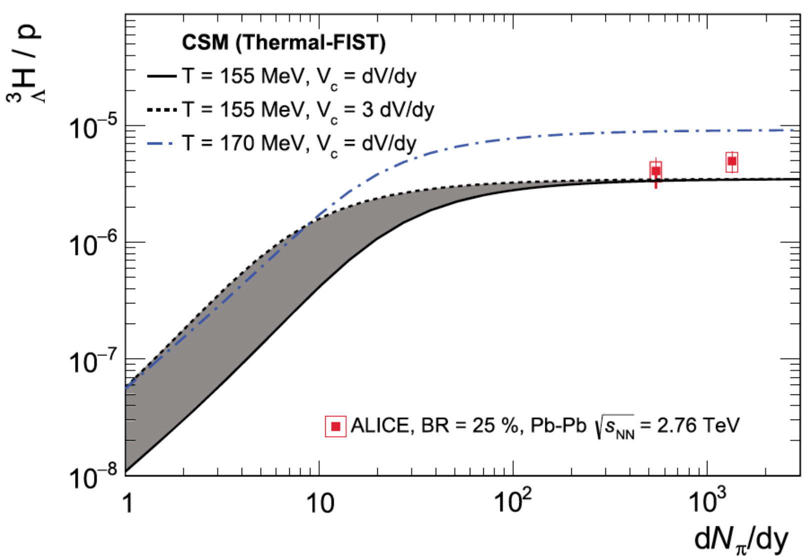


^{3}He/p ratio rather well described by using a coalescence approach, from an analytical coalsecence formula or a canonical treatment in the thermal model

Expectations

- Hypertriton production predictions vs. multiplicity: strong suppression in pp collisions from both models





K.-J. Sun, C.-M. Ko, BD
PLB 792 (2019) 132

V. Vovchenko, BD, H. Stöcker
PLB 785 (2018) 171

Special ratio S3: First appearance

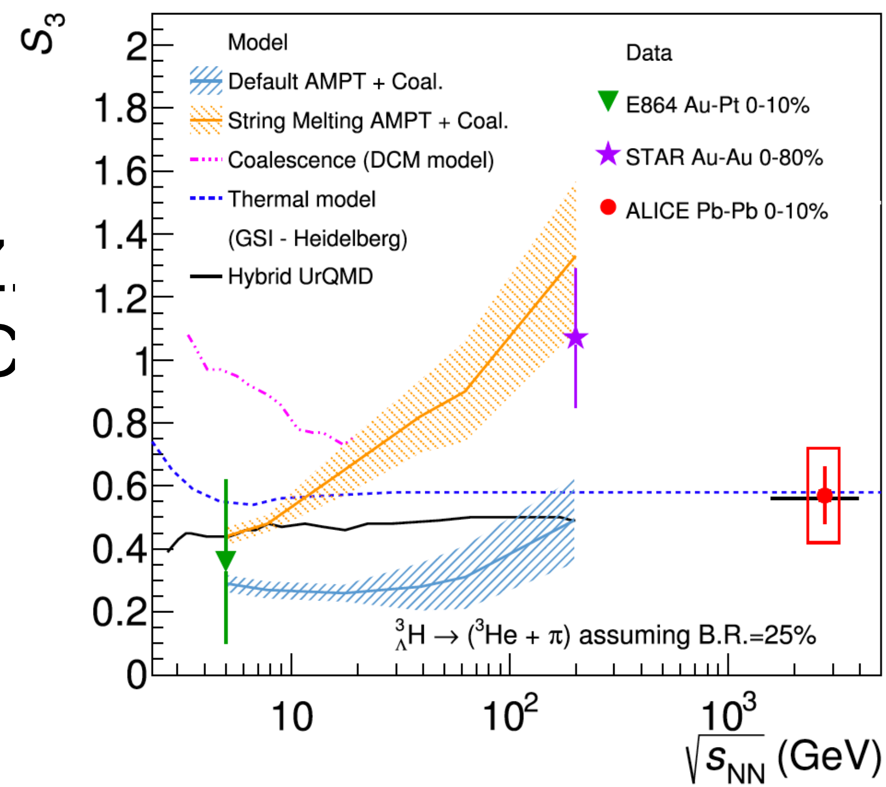
- S3: Strangeness population factor was introduced as measure for the baryon-strangeness correlations

V. Koch, A. Majumder, and J. Randrup, PRL 95 (2005) 182301

$$C_{BS} \equiv -3\frac{\sigma_{BS}}{\sigma_S^2} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2} = -3\frac{\langle BS\rangle}{\langle S^2\rangle}$$

- First used in E864 (Thesis Z.
- Followed by STAR and ALIC
- Defined as $S_3 = ({}^3_\Lambda H/{}^3He) / (\Lambda/p)$

T. Armstrong et al. (E864 Collab.), PRC 70 (2004) 024902
Zhang et al., PLB 684 (2010) 224

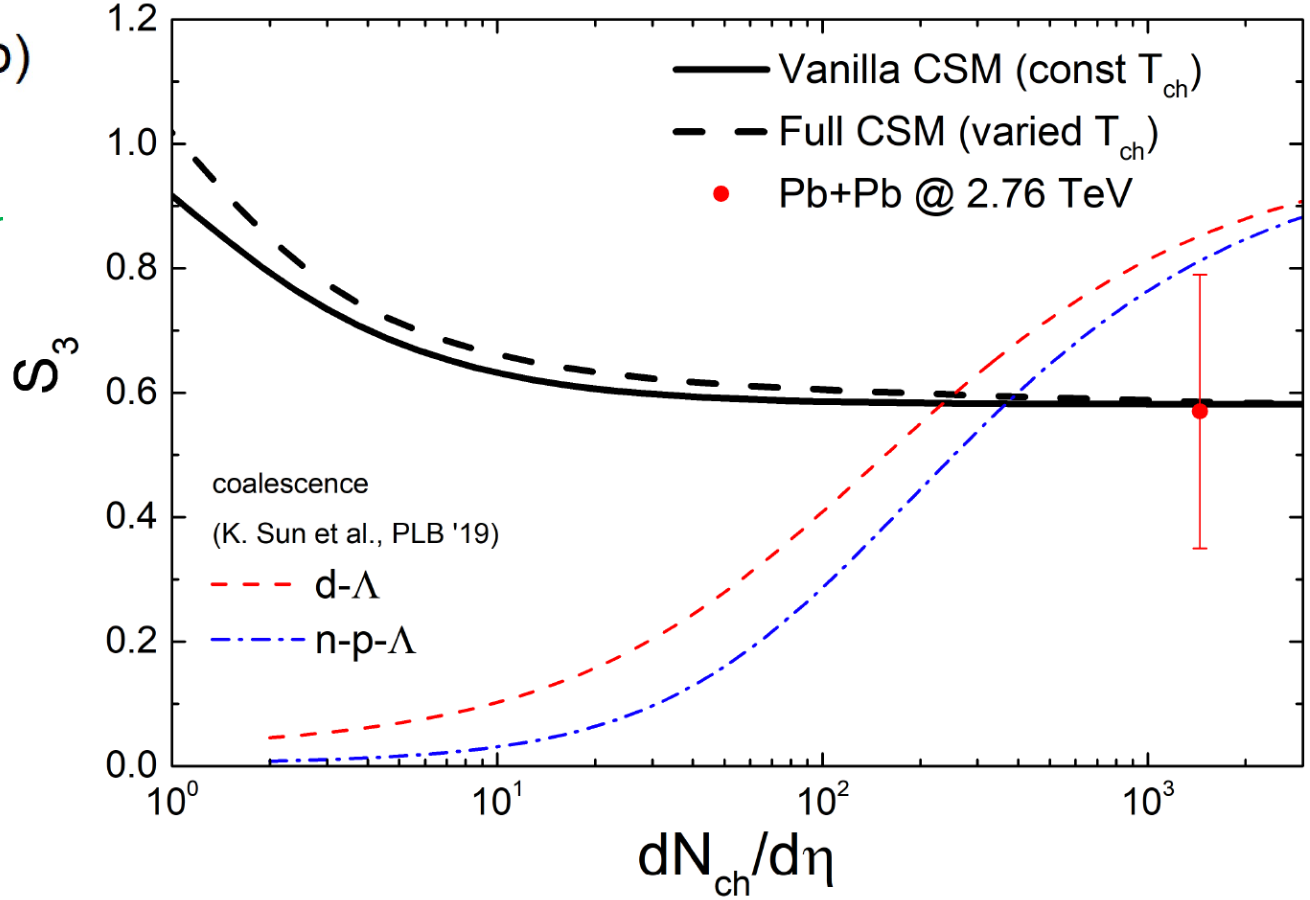


Situation at LHC vs. Multiplicity

$S_3 = ({}^3_\Lambda H/{}^3He) / (\Lambda/p)$

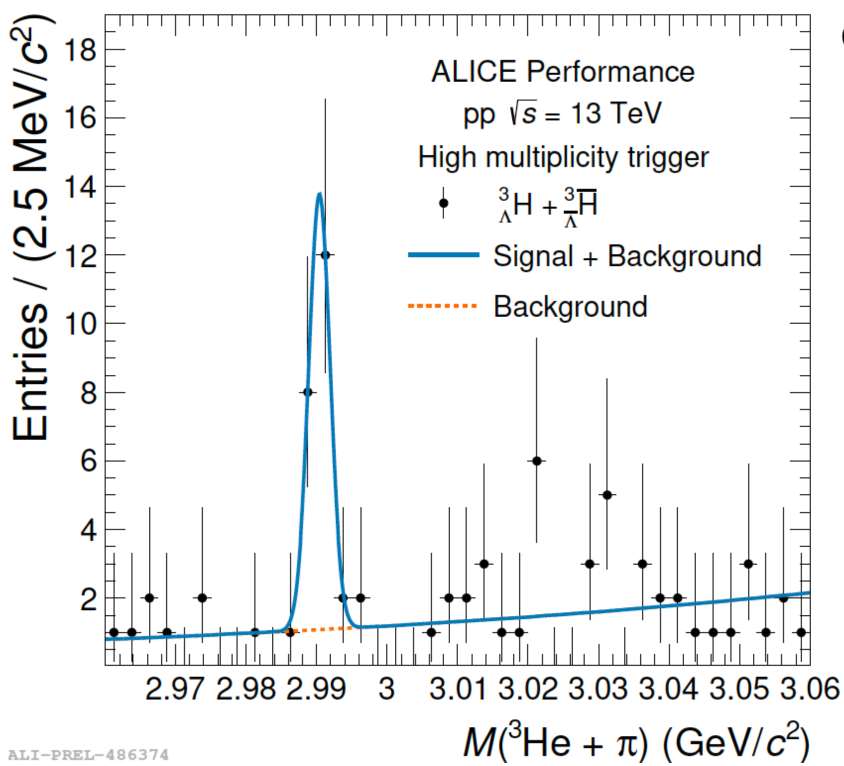
Thermal model (CSM):
V. Vovchenko, BD, H. Stöcker
PLB 785 (2018) 171
PRC 100 (2019) 054906

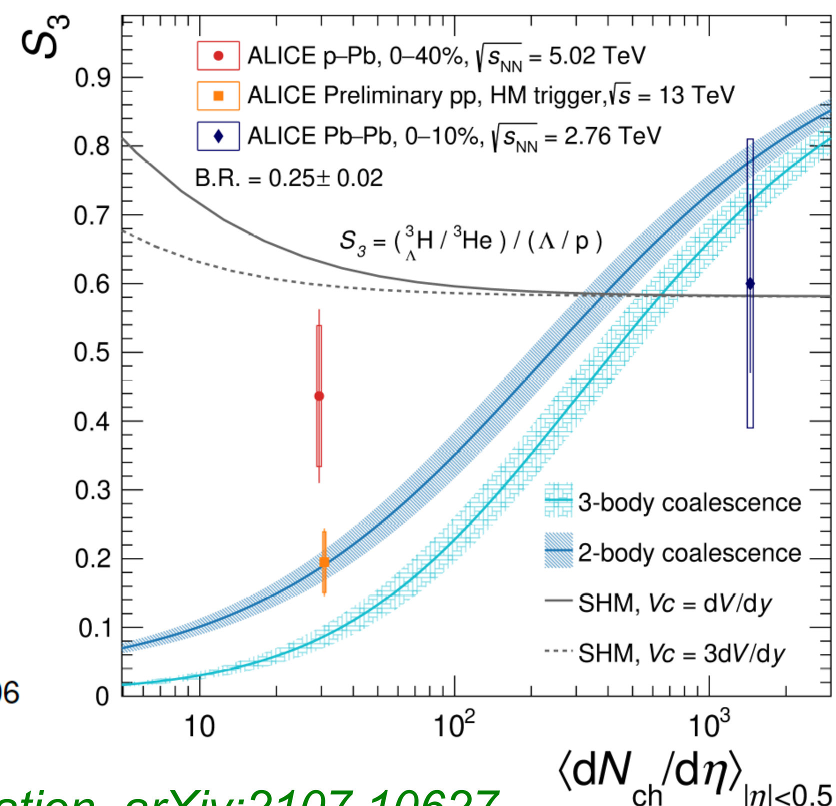
Coalescence:
K.-J. Sun, C.-M. Ko, BD
PLB 792 (2019) 132



Hypertriton in pp & p-Pb

- Hypertriton signal recently also extracted in pp and p-Pb collisions
- Stronger separation between models as for other particle ratios, mainly due to the size of the hypertriton

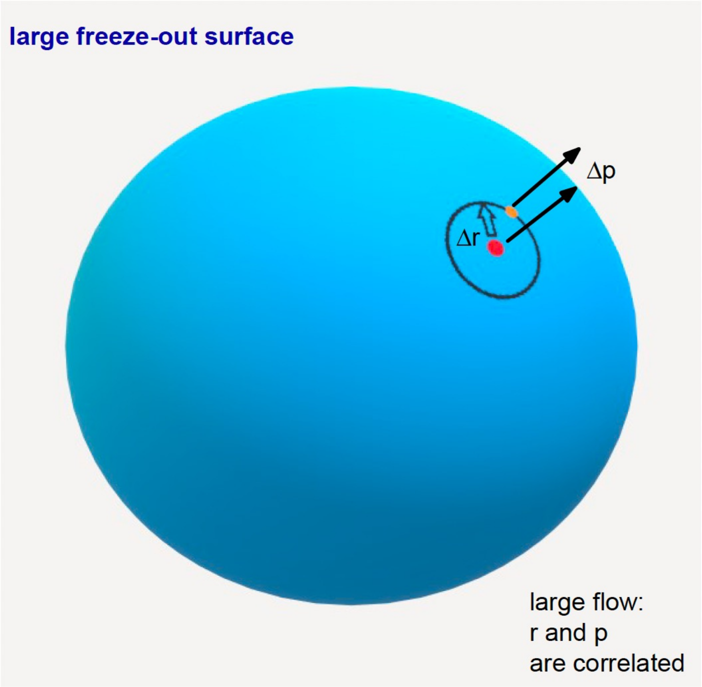


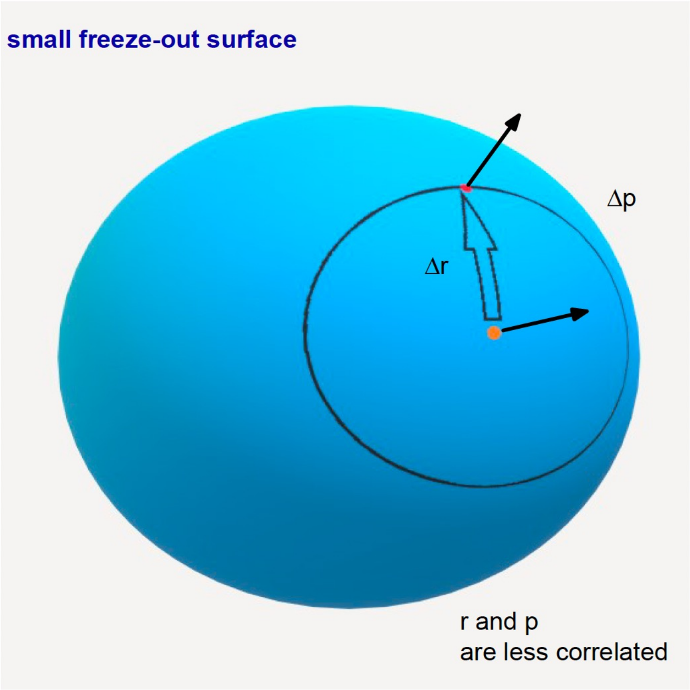


V. Vovchenko, BD, H. Stoecker, PLB 785 (2018) 171
K.-J. Sun, C.-M. Ko, BD, PLB 792 (2019) 132

ALICE Collaboration, arXiv:2107.10627

How to understand the source volume



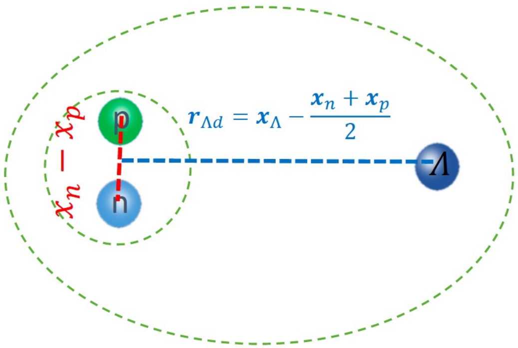


From Tom Reichert

How about the spectrum? (7)

MUSIC + UrQMD + Coalescence

Due to small lambda separation energy, the hypertriton can be well approximated as a bound state of deuteron and lambda hyperon.



$$W_{ht} = 8^2 e^{-\frac{x_1^2}{\sigma_1^2} - k_1^2\sigma_1^2 - \frac{x_2^2}{\sigma_2^2} - k_2^2\sigma_2^2}$$

$$x_1 = \frac{x_n - x_p}{\sqrt{2}}$$

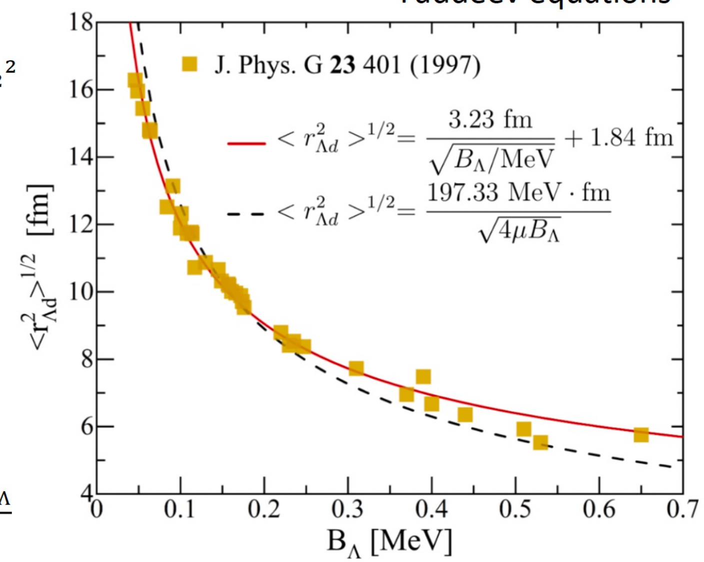
$$k_1 = \sqrt{2}\frac{m_p k_n - m_n k_p}{m_n + m_p}$$

$$x_2 = \sqrt{\frac{2}{3}}\left(\frac{m_n x_n - m_p x_p}{m_n + m_p} - x_\Lambda\right)$$

$$k_2 = \sqrt{\frac{3}{2}}\frac{m_\Lambda(k_n + k_p) - (m_n + m_p)k_\Lambda}{m_n + m_p + m_\Lambda}$$

$$\Lambda - d \text{ distance: } \sqrt{< r_{\Lambda d}{}^2 >} = \frac{3}{2}\sigma_2$$

Faddeev equations



Taking $B_\Lambda = 0.13$ MeV

$\sqrt{< r_{\Lambda d}{}^2 >} \approx 10$ fm $\quad \sigma_2 \approx 6.7$ fm

A. Cobis, A. S. Jensen, and D. V. Fedorov, J. Phys. G 23, 401 (1997)

From Kai-Jia's talk