Hadron-Deuteron Correlations and Production of Light Nuclei in Relativistic Heavy-Ion Collisions

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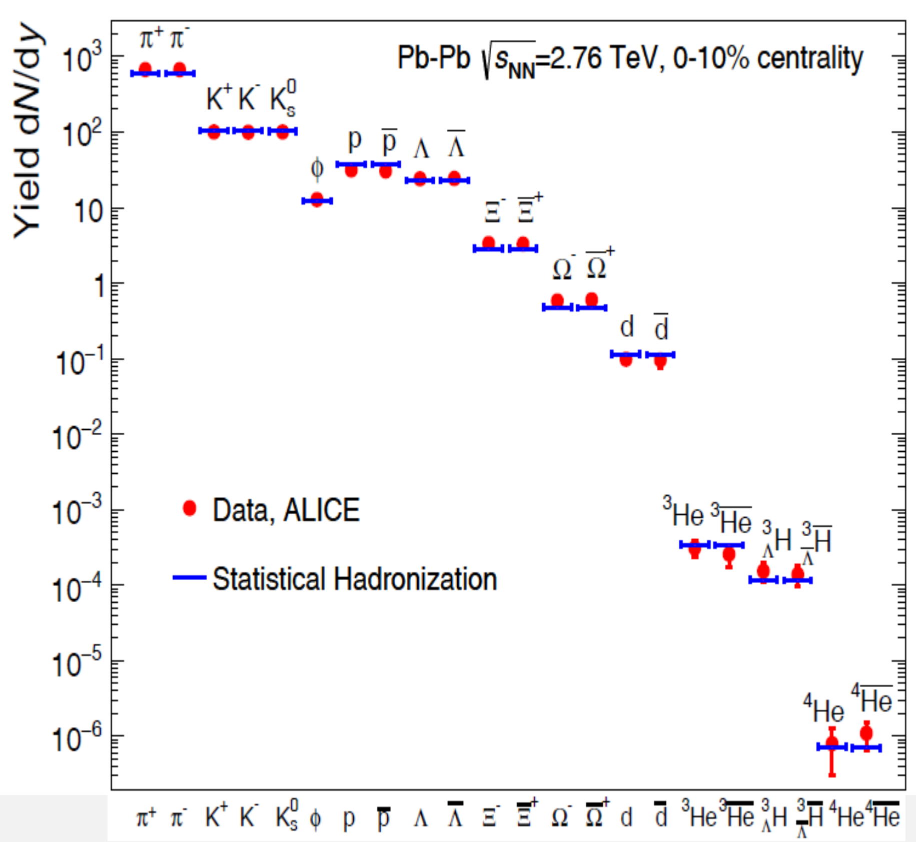
Motivation

- Production of ^{2}H, $^{2}\overline{H}$, ^{3}H, $^{3}\overline{H}$, ^{3}He, $^{3}\overline{He}$, ^{4}He, $^{4}\overline{He}$, $^{3}_{\Lambda}H$, $^{3}_{\overline{\Lambda}}\overline{H}$ is observed in midrpidity at RHIC & LHC.
- Thermal model properly describes yields of light nuclei.



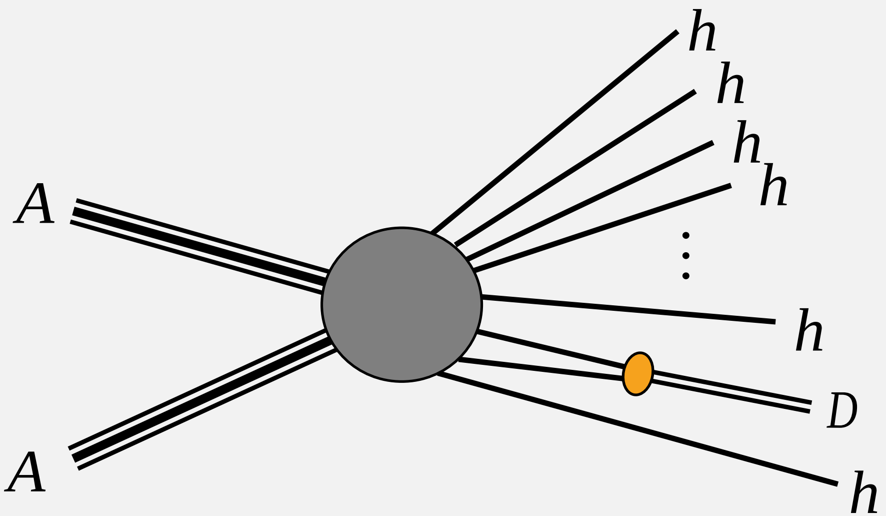
A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature **561**, 321 (2018)

Can light nuclei exist in a fireball?

- Interparticle spacing in a hadron gas is about 1.5 fm at T = 156 MeV.
- Root mean square radius of a deuteron is 2.0 fm.
- Binding energy of a deuteron is 2.2 MeV.

Coalescence model

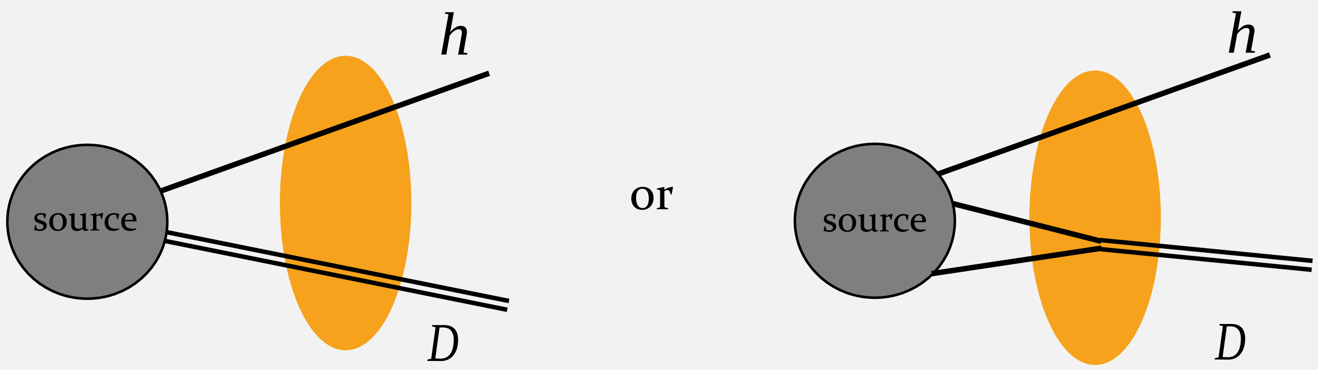
- In the coalescence model light nuclei are produced due to final state interactions among produced nucleons.



- The coalescence model also properly describes the yields of light nuclei.

How to falsify one of the models?

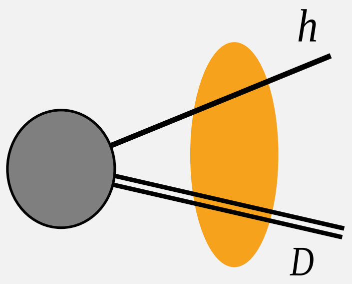
- Hadron-deuteron correlations carry information about a source of deuterons.
- A measurement of K^--D or p-D correlation functions is suggested to falsify the thermal or coalescence model.



Hadron-deuteron correlation function

1. Deuteron treated as an elementary particle

- Experimental definition of the correlation function *R*



$$\frac{dN_{hD}}{d\mathbf{p}_h d\mathbf{p}_D} = R(\mathbf{p}_h, \mathbf{p}_D)\ \frac{dN_h}{d\mathbf{p}_h}\frac{dN_D}{d\mathbf{p}_D}$$

- Theoretical formula

$$R(\mathbf{p}_h, \mathbf{p}_D) = \int d^3r_h\, d^3r_D D(\mathbf{r}_h) D(\mathbf{r}_D) |\psi(\mathbf{r}_h, \mathbf{r}_D)|^2$$

$D(\mathbf{r})$ – probability distribution of emission points

$\psi(\mathbf{r}_h, \mathbf{r}_D)$ – wave function

S.E. Koonin, Phys. Lett. B **70**, 43 (1977)
R. Lednicky and V.L. Lyuboshitz, Yad. Fiz. **35**, 1316 (1982)

Hadron-deuteron correlation function

1. Deuteron treated as an elementary particle cont.

- Center-of-mass variables

$$\begin{cases} \mathbf{R} = \dfrac{m_h \mathbf{r}_h + m_D \mathbf{r}_D}{m_h + m_D} \\ \mathbf{r}_{hD} = \mathbf{r}_h - \mathbf{r}_D \end{cases} \qquad \begin{cases} \mathbf{P} = (\mathbf{p_1} + \mathbf{p_2}) \\ \mathbf{q} = \dfrac{m_h \mathbf{p}_D - m_D \mathbf{p}_h}{m_h + m_D} \end{cases} \qquad \psi(\mathbf{r}_h, \mathbf{r}_D) = e^{i\mathbf{PR}} \phi_{\mathbf{q}}(\mathbf{r}_{hD})$$

$$R(\mathbf{q}) = \int d^3\, r_{hD} D_r(\mathbf{r}_{hD}) \left| \phi_{\mathbf{q}}(\mathbf{r}_{hD}) \right|^2$$

- „Relative” source

$$D_r(\mathbf{r}_{hD}) \equiv \int d^3\mathbf{R}\, D\left(\mathbf{R} - \frac{m_h}{m_h + m_D}\mathbf{r}_{hD}\right) D\left(\mathbf{R} + \frac{m_D}{m_h + m_D}\mathbf{r}_{hD}\right)$$

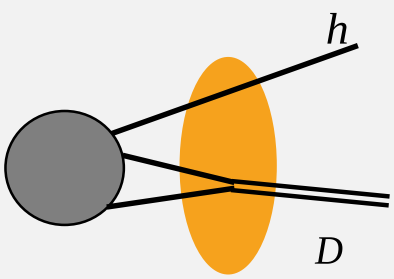
$$D(\mathbf{r}) = \left(\frac{1}{2\pi R^2}\right)^{3/2} \exp\left(-\frac{\mathbf{r}^2}{2R^2}\right) \quad \Rightarrow \quad D_r(\mathbf{r}) = \left(\frac{1}{4\pi R^2}\right)^{3/2} \exp\left(-\frac{\mathbf{r}^2}{4R^2}\right)$$

Hadron-deuteron correlation function

2. Deuteron treated as a bound state of neutron and proton

- Experimental definition

$$\frac{dN_{hD}}{d\mathbf{p}_h d\mathbf{p}_D} = R(\mathbf{p}_h, \mathbf{p}_D)\ A\ \frac{dN_h}{d\mathbf{p}_h}\frac{dN_n}{d\mathbf{p}_n}\ \frac{dN_p}{d\mathbf{p}_p}$$



- Deuteron formation rate

$$\frac{dN_D}{d\mathbf{p}_D} = A\ \frac{dN_n}{d\mathbf{p}_n}\ \frac{dN_p}{d\mathbf{p}_p} \qquad \boldsymbol{p}_n = \boldsymbol{p}_p = \frac{1}{2}\boldsymbol{p}_d$$

$$A = \frac{3}{4}(2\pi)^3 \int d^3\, \mathbf{r}_n d^3 \mathbf{r}_p D(\mathbf{r}_n) D(\mathbf{r}_p) \left|\psi_D(\mathbf{r}_n, \mathbf{r}_p)\right|^2 = \frac{3}{4}(2\pi)^3 \int d^3\, r_{np} D_r(\mathbf{r}_{np}) \left|\phi_D(\mathbf{r}_{np})\right|^2$$

$$\psi_D(\mathbf{r}_n, \mathbf{r}_p) = e^{i\mathbf{PR}} \phi_D(\mathbf{r}_{np})$$

Hadron-deuteron correlation function

2. Deuteron treated as a bound state of neutron and proton cont.

- Theoretical formula

$$R(\mathbf{p}_h, \mathbf{p}_D) = \frac{1}{A}\int d^3r_h d^3r_n\, d^3r_p D(\mathbf{r}_h)D(\mathbf{r}_n)D(\mathbf{r}_p)\left|\psi_{hD}(\mathbf{r}_h, \mathbf{r}_n, \mathbf{r}_p)\right|^2$$

- Center-of-mass (Jacobi) variables

$$\begin{cases} \mathbf{R} = \dfrac{m_h\mathbf{r}_h + m_n\mathbf{r}_n + m_p\mathbf{r}_p}{m_h + m_n + m_p} \\ \mathbf{r}_{np} = \mathbf{r}_n - \mathbf{r}_p \\ \mathbf{r}_{hD} = \mathbf{r}_h - \dfrac{m_n\mathbf{r}_n + m_p\mathbf{r}_p}{m_n + m_p} \end{cases}$$

$$\psi_{hD}(\mathbf{r}_h, \mathbf{r}_n, \mathbf{r}_p) = e^{i\mathbf{PR}}\phi_{\mathbf{q}}(\mathbf{r}_{hD})\phi_D(\mathbf{r}_{np})$$

$$D_{3r}(\mathbf{r}_{hD})D_r(\mathbf{r}_{np}) \equiv \int d^3\mathbf{R}\, D(\mathbf{r}_h)D(\mathbf{r}_n)D(\mathbf{r}_p)$$

$$D_{3r}(\mathbf{r}) = \left(\frac{1}{3\pi R^2}\right)^{3/2} \exp\left(-\frac{\mathbf{r}^2}{3R^2}\right)$$

Deuteron formation rate cancels out.

$$R(\mathbf{q}) = \int d^3\, r_{hD} D_{3r}(\mathbf{r}_{hD})\left|\phi_{\mathbf{q}}(\mathbf{r}_{hD})\right|^2$$

Thermal vs. coalescence model

- **Thermal model**

$$R(\mathbf{q}) = \int d^3\, r_{hD} D_r(\mathbf{r}_{hD}) \left|\phi_{\mathbf{q}}(\mathbf{r}_{hD})\right|^2$$

- **Coalescence model**

$$R(\mathbf{q}) = \int d^3\, r_{hD} D_{3r}(\mathbf{r}_{hD}) \left|\phi_{\mathbf{q}}(\mathbf{r}_{hD})\right|^2$$

$$D(\mathbf{r}) = \left(\frac{1}{2\pi R^2}\right)^{3/2} \exp\left(-\frac{\mathbf{r}^2}{2R^2}\right)$$

$$D_r(\mathbf{r}) = \left(\frac{1}{4\pi R^2}\right)^{3/2} \exp\left(-\frac{\mathbf{r}^2}{4R^2}\right)$$

$$D_{3r}(\mathbf{r}) = \left(\frac{1}{3\pi R^2}\right)^{3/2} \exp\left(-\frac{\mathbf{r}^2}{3R^2}\right)$$

Computation of correlation function

$$R(\mathbf{q}) = \int d^3 r_{hD} D_r(\mathbf{r}_{hD}) \left|\phi_{\mathbf{q}}(\mathbf{r}_{hD})\right|^2$$

- Source function

$$D_r(\mathbf{r}) = \left(\frac{1}{4\pi R^2}\right)^{3/2} \exp\left(-\frac{\mathbf{r}^2}{4R^2}\right) \quad \text{or} \quad D_{3r}(\mathbf{r}) = \left(\frac{1}{3\pi R^2}\right)^{3/2} \exp\left(-\frac{\mathbf{r}^2}{3R^2}\right)$$

- Wave function

$$\phi_{\mathbf{q}}(\mathbf{r}) = e^{i\mathbf{qr}} + f(q)\frac{e^{iqr}}{r}$$

- Coulomb effect

$$R(\mathbf{q}) \to G(\mathbf{q})R(\mathbf{q})$$

- S-wave amplitude

$$f(q) = -\frac{a}{1 + iqa}$$

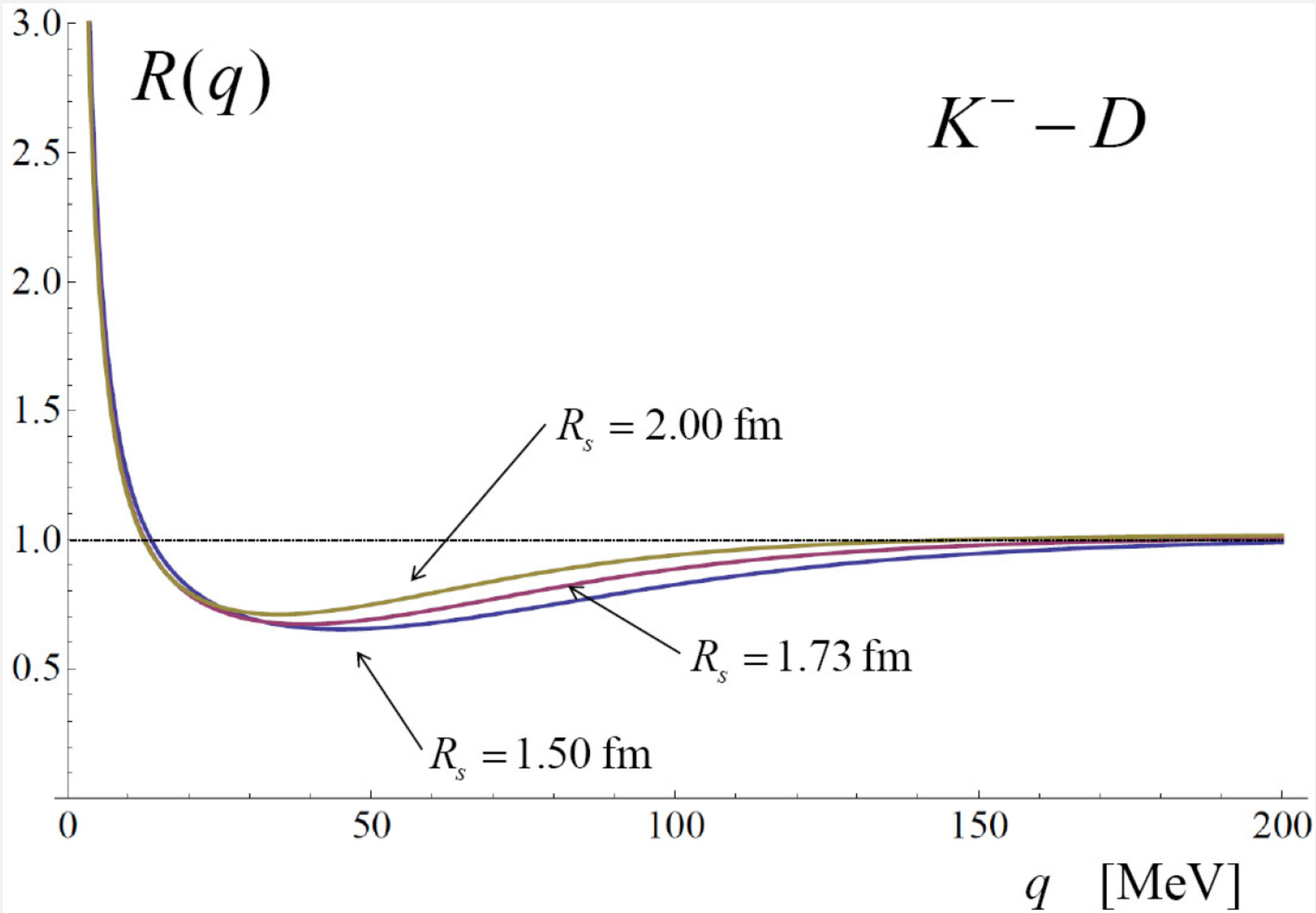
- Gamov factor

$$G(\mathbf{q}) = \pm\frac{2\pi}{a_B q}\frac{1}{\exp\left(\frac{2\pi}{a_B q}\right) - 1}$$

a - scattering length

Bohr radius - $a_B = \frac{1}{\mu\alpha}$

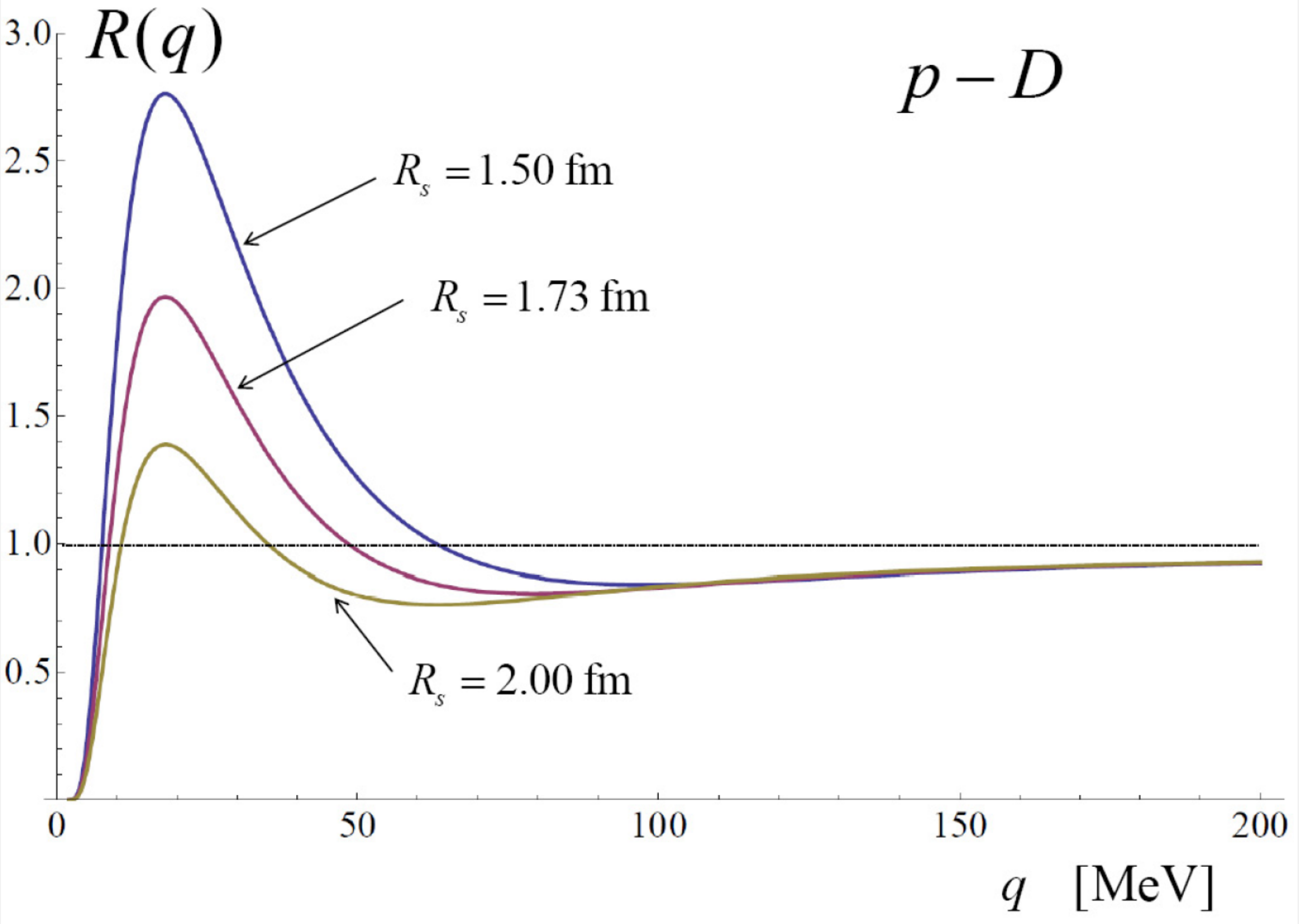
K^--D correlation functions



$a = (1.46 - 1.08i)\ \mathrm{fm}$

$$2.00 = \sqrt{\frac{4}{3}}1.73 = \frac{4}{3}1.50$$

p-*D* correlation functions



$a_{1/2} = 4.0$ fm

$a_{3/2} = 11.0$ fm

$$R(q) = \frac{1}{3} R_{1/2}(q) + \frac{2}{3} R_{3/2}(q)$$

$$2.00 = \sqrt{\frac{4}{3}} 1.73 = \frac{4}{3} 1.50$$

Conclusions

- Hadron-deuteron correlations carry information about source of deuterons.
- Measurement of *h-D* correlation function can tell us whether deuterons are directly emitted from a fireball or deuterons are formed due to final state interactions.
- *p-D* correlation function shows a sufficient sensitivity to a size of particle source to falsify the thermal or coalescence model.