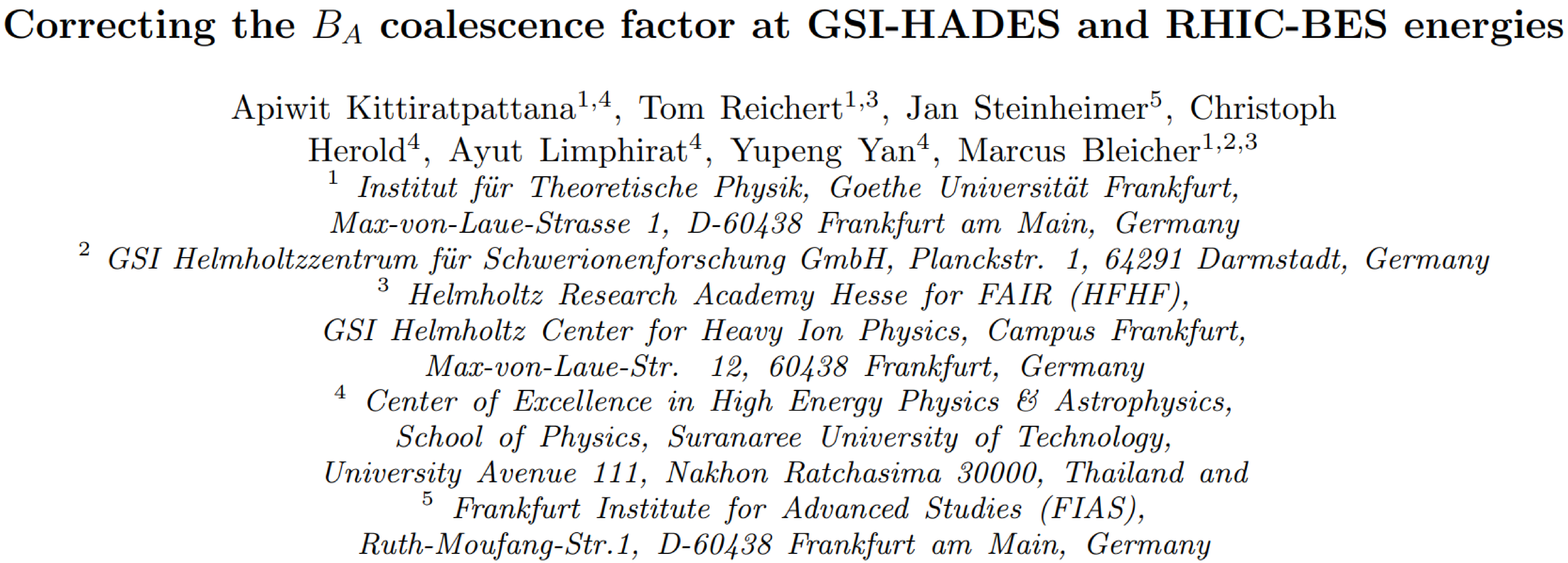
HFHF Theory Retreat 2022

Outlines

- Heavy-Ion Collisions
  - Light nuclei
  - Problems
- Methodology
  - Estimation for primordial state
  - UrQMD simulations
- Results
- Conclusion



Correcting the B_A coalescence factor at GSI-HADES and RHIC-BES energies

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Present by: Apiwit Kittiratpattana

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Heavy-ion Collisions

QCD Phase Diagram

- **Equations of State (EoS), Phase Transition**
- **Beam Energy Scan:** Early Universe, Neutron Stars
- **Dark matter**

Light nuclei are currently one of the most active and interesting topics that can study all the mentioned above.

[1] Nayak, Tapan K., *Journal of Physics,* 2020.

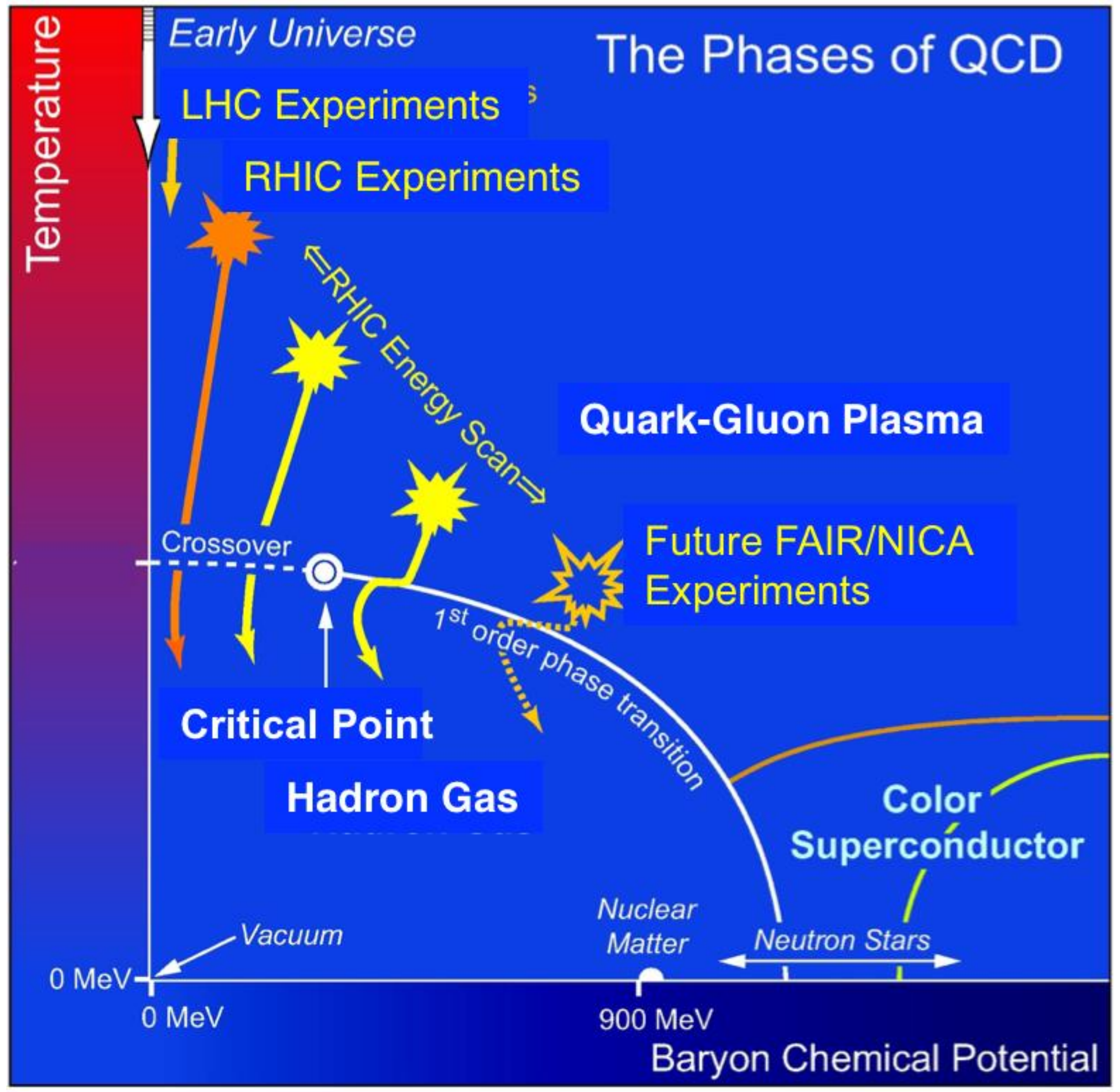

Figure 1 QCD Phase Diagram [1]

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Light nuclei

At the Early Universe

- Big bang nucleosynthesis
- $p + n \rightarrow d + \gamma$
  - **This reaction cannot take place in a hot universe!**
  - **Deuteron Bottleneck ($T \sim 10^{10}$K)**
- After the $T \sim 10^9$, these reaction died down where the lighter clusters are feed into heavier nuclei

[2] Hou, S. Q., et al (2017). Non-extensive statistics to the cosmological lithium problem. *The Astrophysical Journal*, *834*(2), 165.

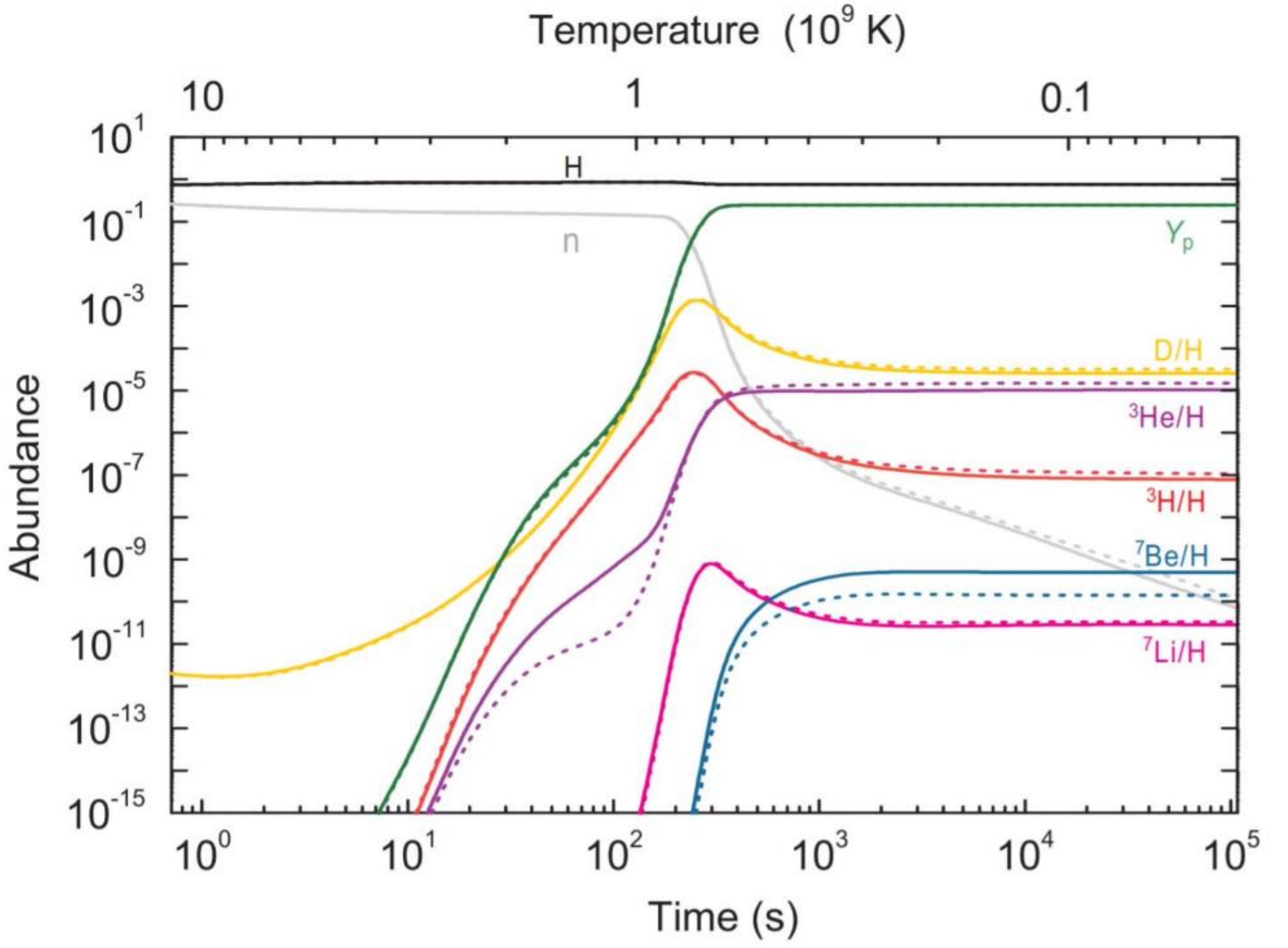

Figure 2 The abundance of light elements in the early universe as a function of time and temperature [2].

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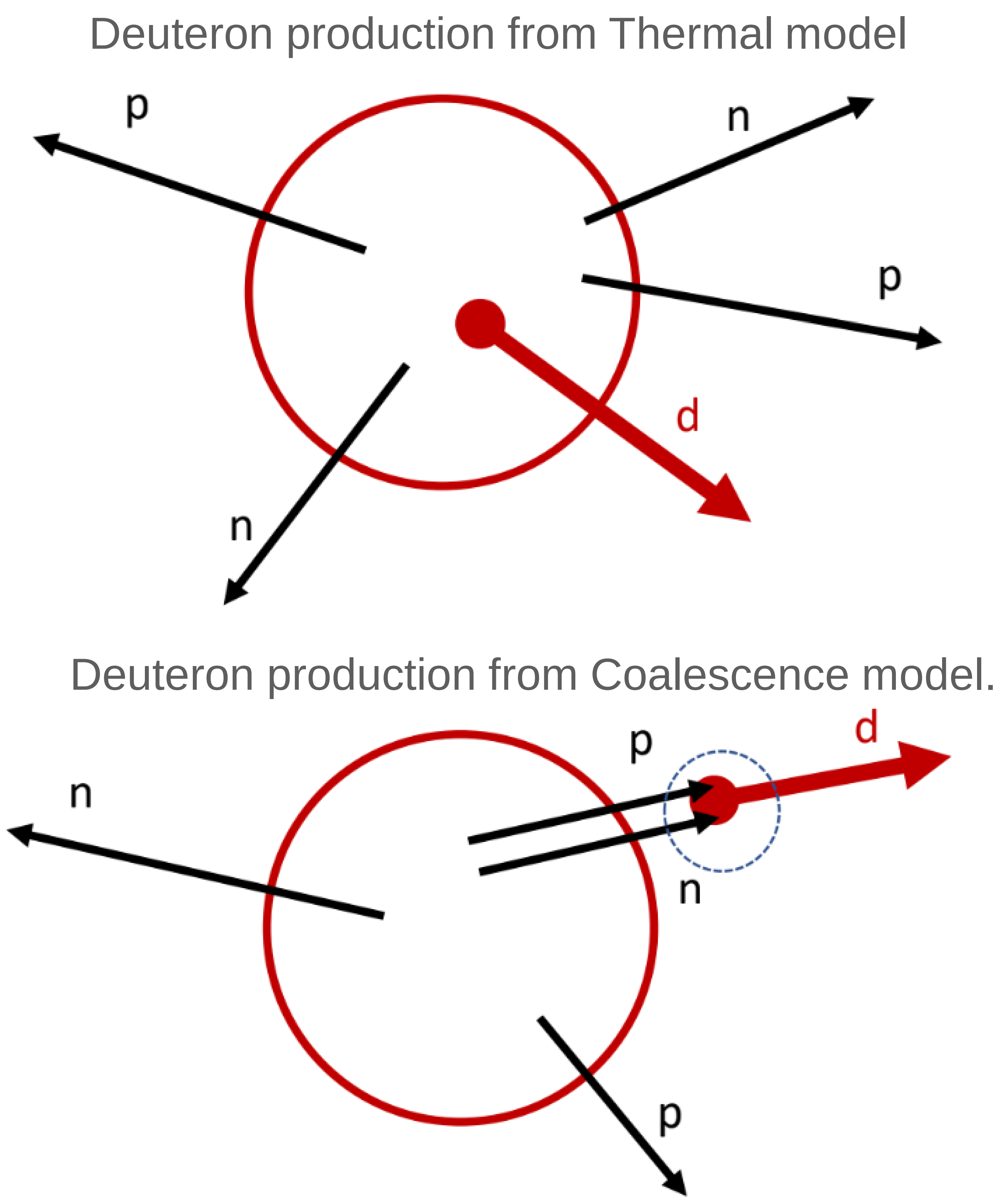
Light nuclei

In Heavy-ion collisions

- The study of formation of light nuclei can be done statistically by two approaches
  - ✗ **Thermal model**
    - Snow-ball-in-hell
  - ☑ **Coalescence model**
    - Phase-space coalescence

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3}\right)^Z \left(E_n \frac{d^3N_n}{dp_n^3}\right)^N \quad \text{(Eq. 1)}$$


Deuteron production from Thermal model

Deuteron production from Coalescence model.

Figure 3 The deuteron formation mechanisms.

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Light nuclei

Signal for Dark Matter (AMS on ISS)

- $\bar{p}$ and $\bar{n}$ are produced by WIMP annihilations **(Signals)**
- Random $p + p \to \bar{p} + X$ in galaxy **(BG – very small)**
- $\bar{\boldsymbol{d}}$ and $\overline{{}^{3}\mathbf{He}}$ are produced via coalescence mechanism.
- We need an understanding on the cluster formation process in detail via coalescence method.

[3] [Aperitivo Scientifico] Cosmic Antinucle by Francesca Bellini (BO)

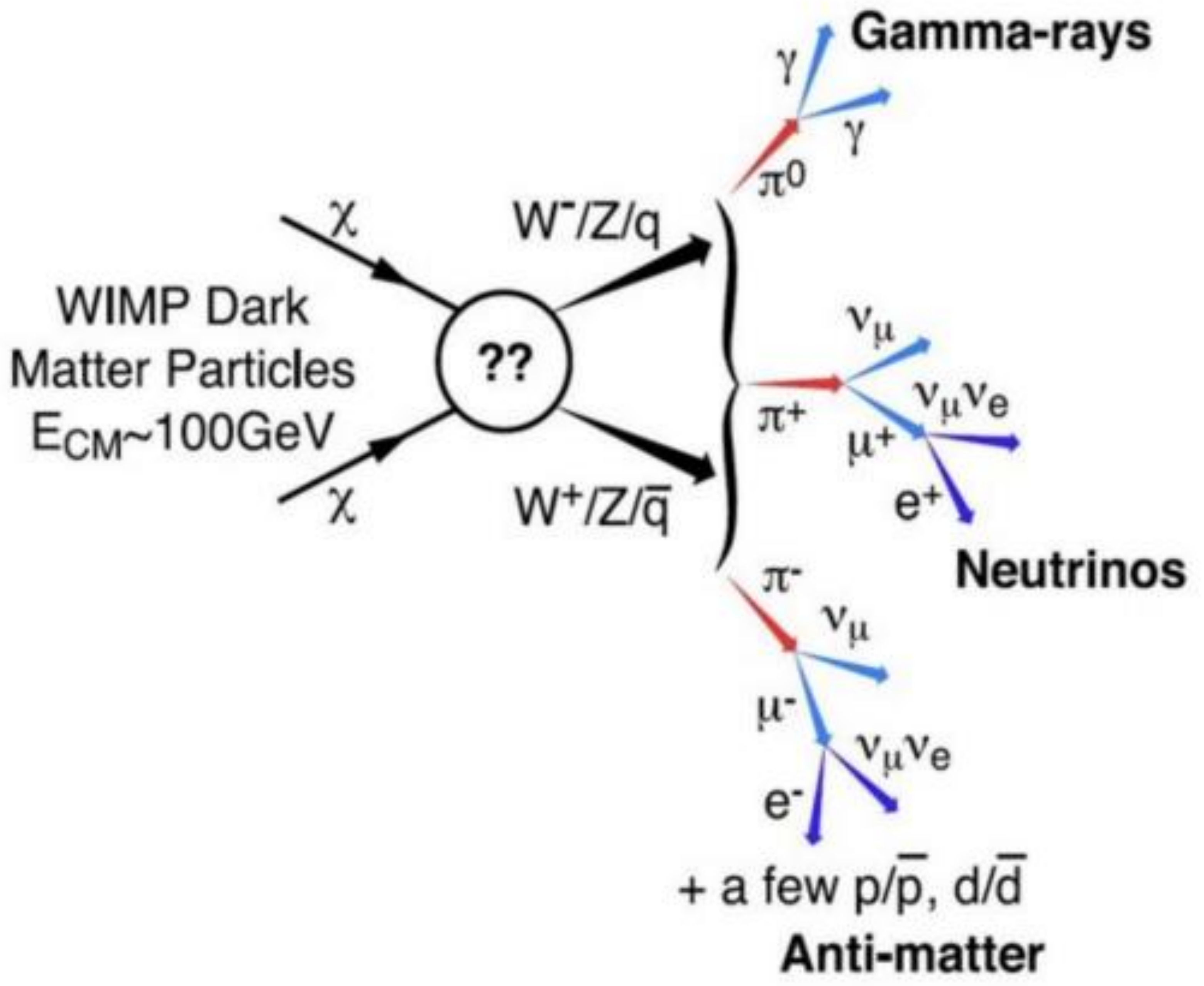

Figure 4 The WIMPs annihilation process [3].

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Problems with B_A

At low energy

- $\mathrm{B_A}$ is the probability of having light nuclei per $(p^Z \cdot n^{A-Z})$ and is usually inferred as Vol^{-1}
- $\mathrm{B_A} \propto Vol^{-1}$
  - $Vol_{\mathrm{HBT}} \uparrow$ vs $Vol_{\mathrm{EXP}} \downarrow$ (Why?)

Probability …

- $B_2 \sim \frac{d}{p_f^2}$ …. Final state protons?

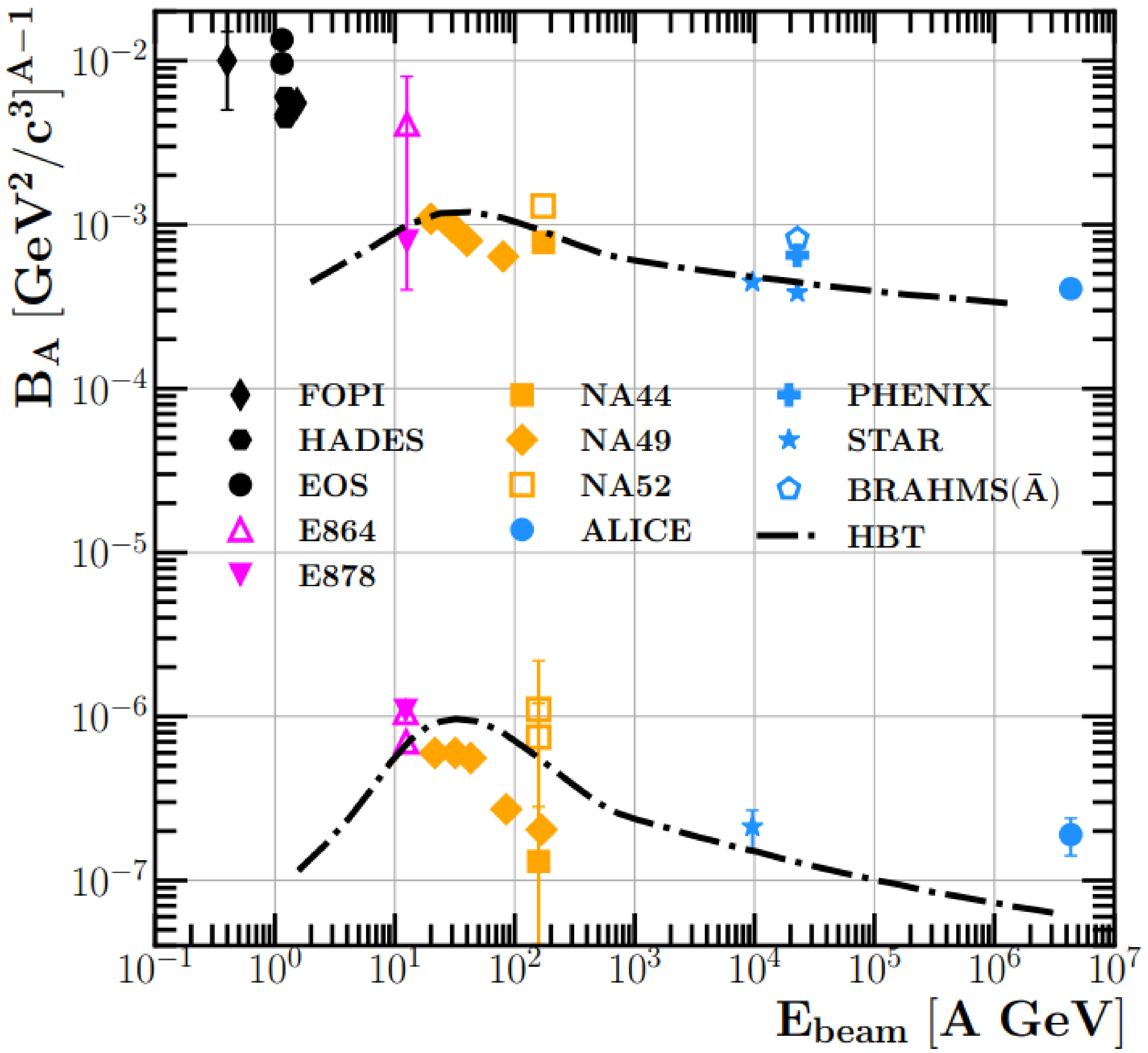

Figure 5 B_A as a function of E_{beam}

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Probability …

- $B_2 \sim \frac{d}{p_f^2} \Rightarrow B_2' \sim \frac{d}{p_i^2}$ with $p_i > p_f$
  - All the protons before coalescence

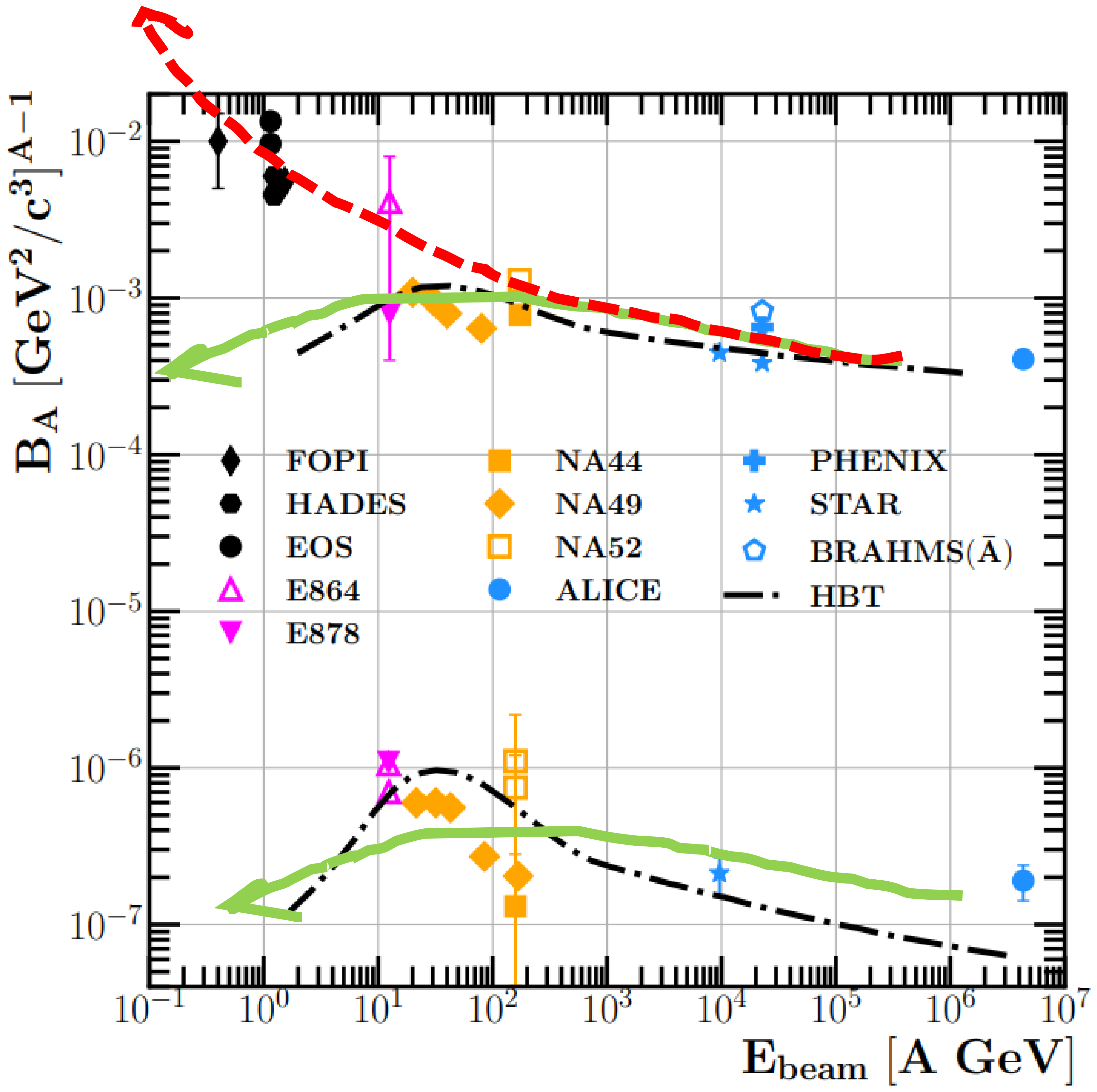

Figure 5 B_A as a function of E_{beam}

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Problems with B_A

Experimental problems!

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3}\right)^Z \left(E_n \frac{d^3N_n}{dp_n^3}\right)^N \dashrightarrow B_2 \sim d/p_f^2$$

1. Only **final state** protons and estimated neutrons (after coalescence) are used.

2. The **neutrons** are usually not measured, and the neutron distribution is often assumed to be the same as the proton distribution.

   - At low energy, the system has no enough energy and time to equilibrate the iso-spin), $N_n \neq N_p$.

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Estimation for Primordial state

Protons and Neutrons before “Coalescence”

Before Coalescence

$$p \rightarrow n + \pi^{+}$$
$$n \rightarrow p + \pi^{-}$$

$$p_{prim} = p_{part} + (\pi^{-} - \pi^{+})$$
$$n_{prim} = n_{part} - \Delta\pi$$

After Coalescence

$$p_{final} = p_{prim} - Z_i \times Cluster_i$$
$$n_{final} = n_{prim} - N_i \times Cluster_i$$

- ☑ $p_{prim} = p_{final} + Z_i \times Cluster_i$ (Eq. 2)
- ☑ $n_{prim} = p_{prim} \left[\frac{\overbrace{(p_{prim} - \Delta\pi)\left(\frac{N_{Au}}{Z_{Au}} + 1\right)\frac{N_{Au}}{A} - \Delta\pi}^{\boxed{\delta_{iso}^{prim}}}}{(p_{prim} - \Delta\pi)\left(\frac{N_{Au}}{Z_{Au}} + 1\right)\frac{Z_{Au}}{A} + \Delta\pi} \right]$ (Eq. 3)

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UrQMD Simulations

Ultra-relativistic Quantum Molecular Dynamics

- Microscopic transport theory (Boltzmann transport)
- Quark and gluon degree of freedom
- The information/history on all collisions, decays, produced resonances, and all stable particles, 4-momentum, charge, and quantum numbers at all time-steps

---

- ☑ $p_{prim} = p_{final} + Z_i \times Cluster_i$
- ☑ $n_{prim} = p_{prim} \delta_{iso}^{prim}$

We will implement UrQMD output to our formulars

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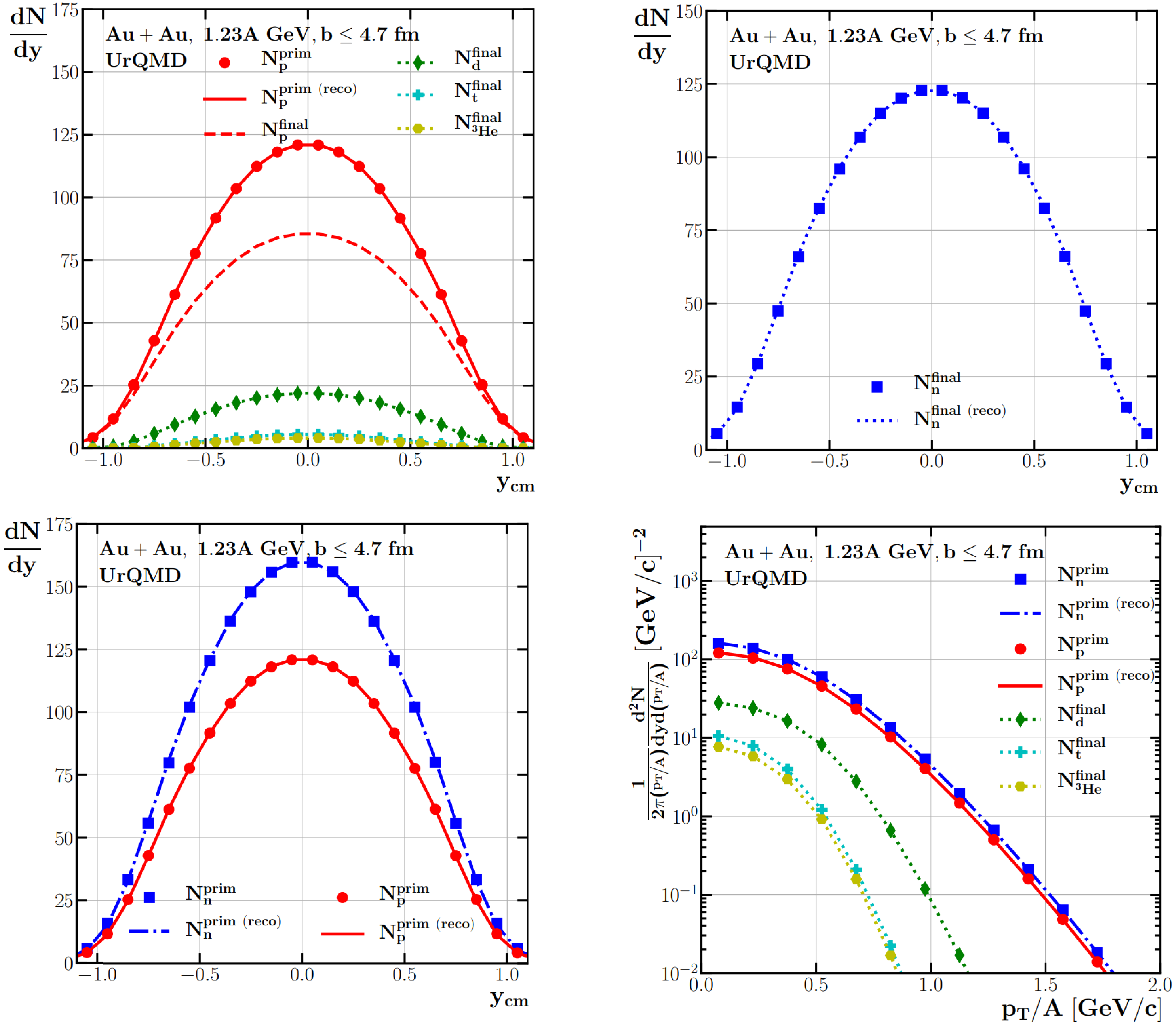

Figure 6 Particle distribution

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Corrected B_A estimation

Primordial state vs final state at 1.23A GeV

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Reminders:

1. The **final state** protons (after coalescence) are used.

- **Final vs Primordial**
- A factor of 1-3 (r-r, b-b)
  - Deuterons are more likely to coalesce at $p_T \approx 0$ (see Fig. 3)
  - The primordial protons are fed into clusters (lesser final protons)

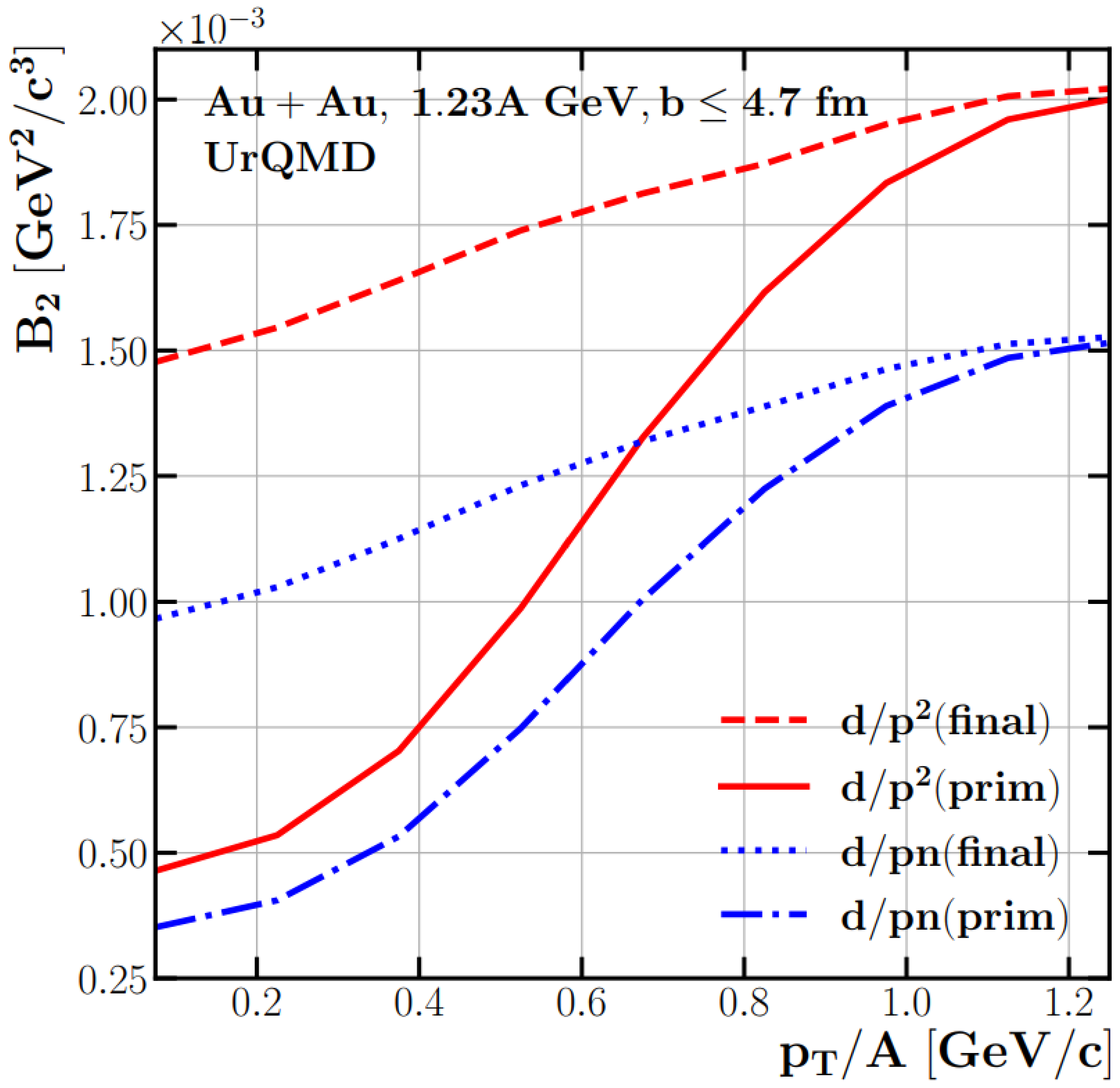

Figure 7 B_2 as a function of transverse momentum p_T

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Corrected B_A estimation

Primordial state vs final state at 1.23A GeV

Reminders:

2. The **neutron** distribution is often assumed to be the same as the proton distribution.

- d/p^2 **vs** d/pn
    - A factor of 1.5 for final (n/p~1.5 similar to N_{Au}/Z_{Au} of gold nucleus).

☑ From both effects, B_2 is reduced by a factor of ~4

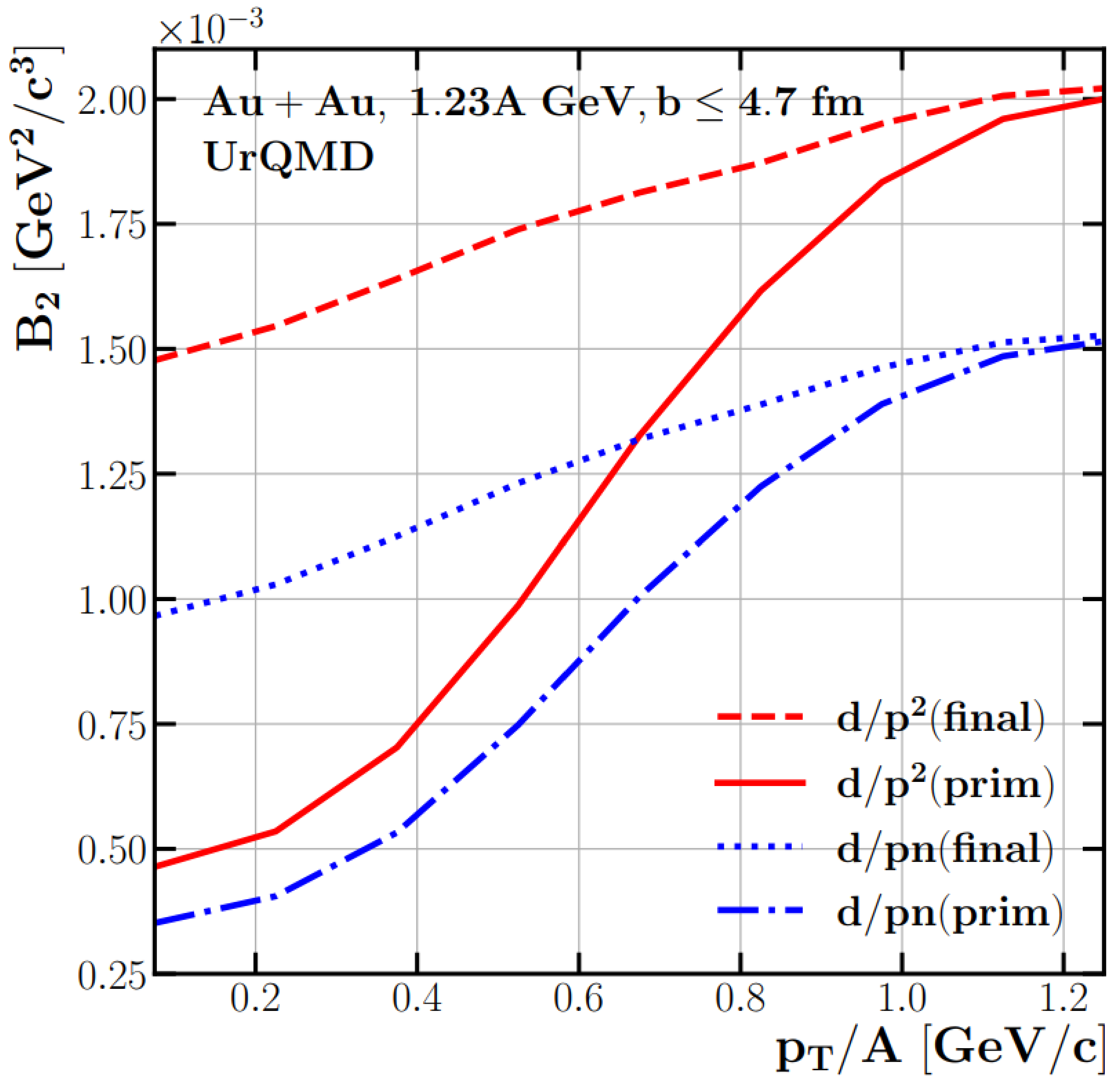

Figure 7 B_2 as a function of transverse momentum p_T

Corrected B_A estimation

B_2 and B_3 as a function of energy

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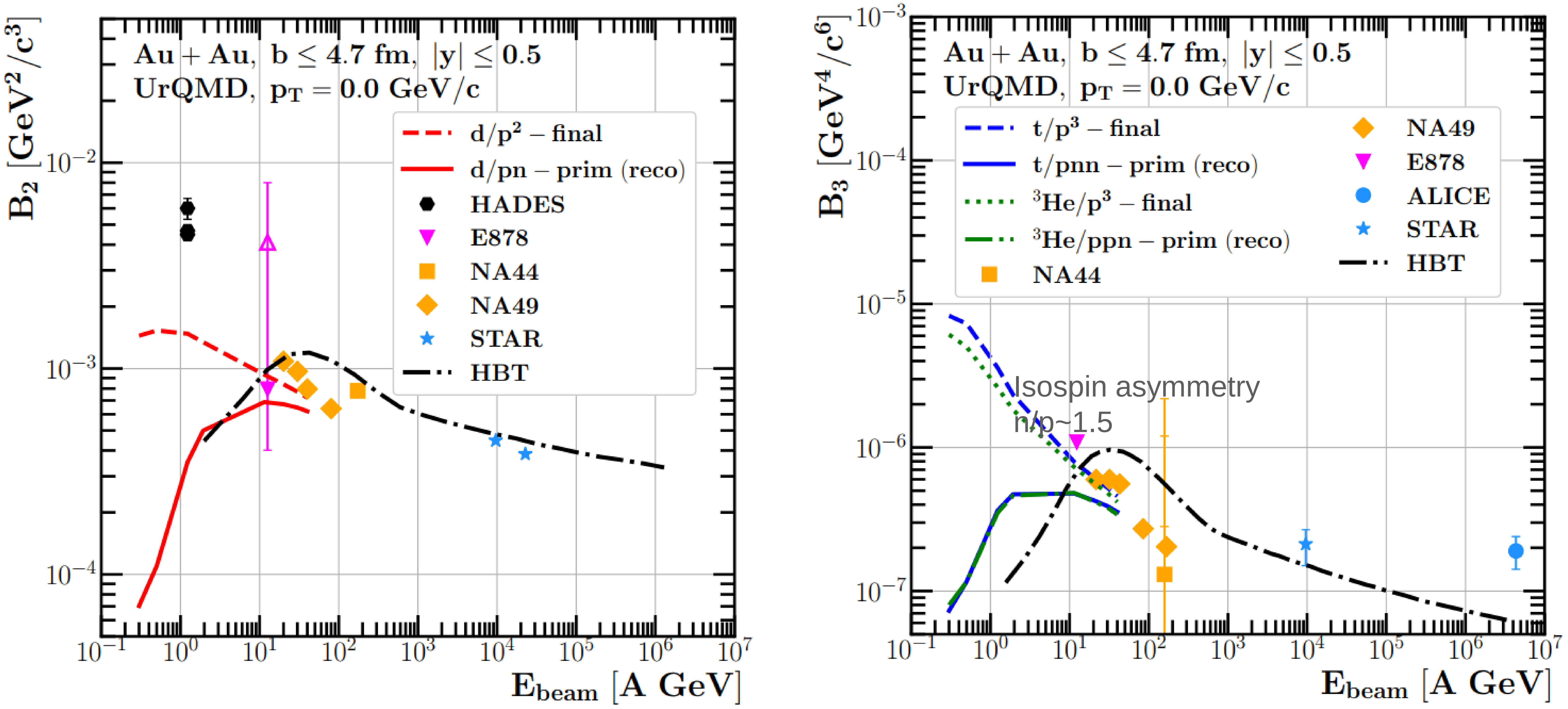

Figure 8 B_A as a function of beam energy

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Conclusion

Correction of B_A

- We clarify the interpretation for the B_A equation
- We shows that B_A is affected by **primordial and final** state protons and neutrons. (First problems).
- We shows that B_A is also affected by using proton square instead of proper **estimated neutron** (Second problems).
- The corrected B_A is now made sense and **drops** at low energy in agreement with HBT result.

[redacted]

apiwitkitti
(Dated: May 2022)

I. EQUATION PER STAGE

A. t=0

$2 \times 118 = n_{initial}$

$2 \times 79 = p_{initial}$

B. before π-emission

$n_{part} = \frac{A_{part}}{2A} 2N$

$p_{part} = \frac{A_{part}}{2A} 2Z$

$A_{part} = p_{part} + n_{part}$

C. after isospin eq./before cluster

$\Delta\pi = \pi^{-} - \pi^{+}$

$p_{prim} = p_{part} + \Delta\pi$

$n_{prim} = n_{part} - \Delta\pi$

D. after cluster

$p_{final} = p_{prim} - C$

$n_{final} = n_{prim} - C$

II. WE WANT n_{prim}

$n_{prim} = n_{part} - \Delta\pi$

now we put in n_{part},

$n_{prim} = \frac{A_{part}}{2A} 2N - \Delta\pi$

But, we know

$\frac{n_{part}}{p_{part}} = \frac{\frac{A_{part}}{2A} 2Z}{\frac{A_{part}}{2A} 2N} = \frac{N}{Z}$

which means,

$n_{part} = \frac{N}{Z} p_{part}$

Then this is equal to,

$n_{part} = \frac{N}{Z}(p_{prim} - \Delta\pi)$

NOW A_{part} is,

$A_{part} = p_{part} + n_{part}$

$A_{part} = (p_{prim} - \Delta\pi) + (\frac{N}{Z}(p_{prim} - \Delta\pi))$

$$A_{part} = (p_{prim} - \Delta\pi) \times (\frac{N}{Z} + 1) \quad (1)$$

put back to n_{prim}

$n_{prim} = \frac{A_{part}}{2A} 2N - \Delta\pi$

$n_{prim} = \frac{(p_{prim} - \Delta\pi) \times (\frac{N}{Z} + 1)}{2A} 2N - \Delta\pi$

Then, we know $p_{prim} = p_{final} + C$

$n_{prim} = \frac{(p_{final} + C - \Delta\pi) \times (\frac{N}{Z} + 1)}{2A} 2N - \Delta\pi$

$$n_{prim} = (p_{final} + C - \Delta\pi) \times [1 + \frac{(A-Z)^2 - Z^2}{ZA}] - \Delta\pi \quad (2)$$

III. JANS STUFF

Somehow the idea was to get n_{final} without A_{part} which can be used also to do a consistency check for A_{part} since $A_{part} = n_{final} + p_{final}$, assuming all measured nucleons are participants. So I started from:

$n_{prim} = n_{part} - \Delta\pi$

$n_{prim} = p_{part} \left(\frac{A-Z}{Z}\right) - \Delta\pi$

$n_{prim} = (p_{prim} + \Delta\pi) \cdot \left(\frac{A-Z}{Z}\right) - \Delta\pi$

$n_{prim} = p_{prim} \left(\frac{A-Z}{Z}\right) - \Delta\pi \left(1 - \left(\frac{A-Z}{Z}\right)\right)$

New version with $(p_{prim} - \Delta\pi)$*:*

$n_{prim} = (p_{prim} - \Delta\pi) \cdot \left(\frac{A-Z}{Z}\right) - \Delta\pi$

$n_{prim} = p_{prim} \left(\frac{A-Z}{Z}\right) - \Delta\pi \left(1 + \left(\frac{A-Z}{Z}\right)\right)$