Nuclear clusters in an off-equilibrium thermal model

Volodymyr Vovchenko (LBNL)

Mini-workshop "Origin of nuclear clusters in hadronic collisions"

May 19, 2020

- Nucleosynthesis in heavy-ion collisions via the Saha equation
  V.V., K. Gallmeister, J. Schaffner-Bielich, C. Greiner, *Phys. Lett. B* ***800,*** *135131 (2020)*
- Off-equilibrium light nuclei production with rate equations
  V.V., D. Oliinychenko, V. Koch, *to appear*

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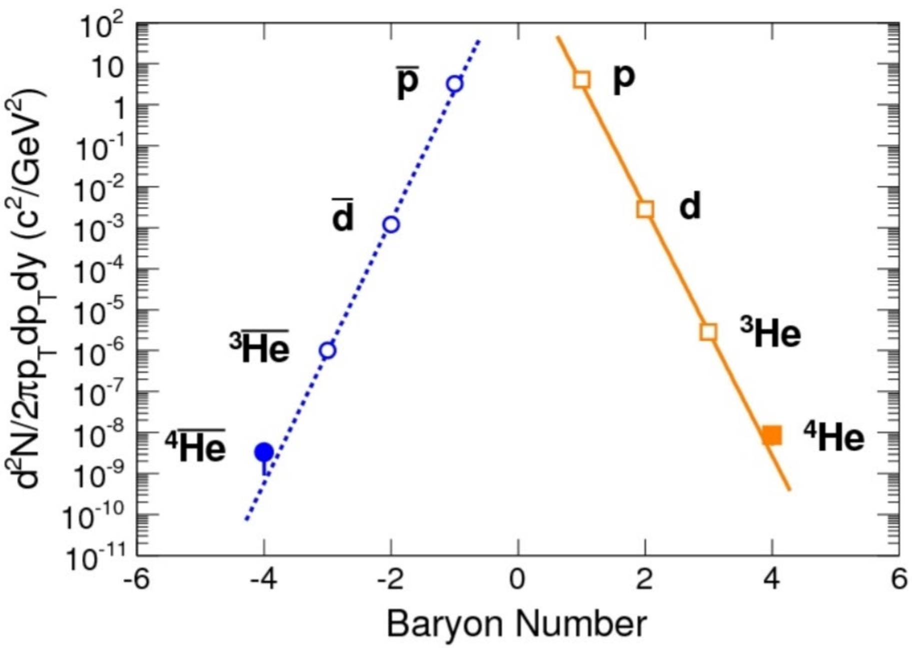
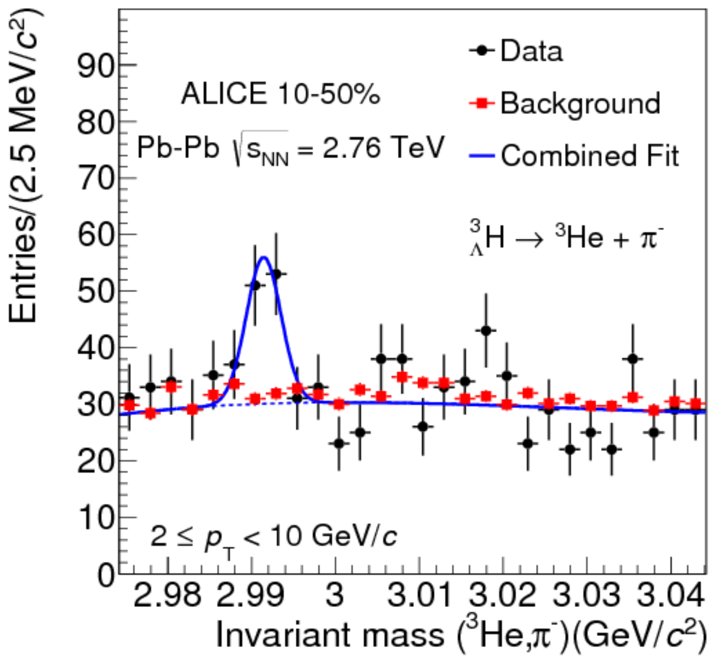
Alexander von Humboldt Stiftung/Foundation

Loosely-bound objects in heavy-ion collisions



[STAR collaboration, Nature **473**, 353 (2011)]



[ALICE Collaboration, PLB **754**, 360 (2016)]

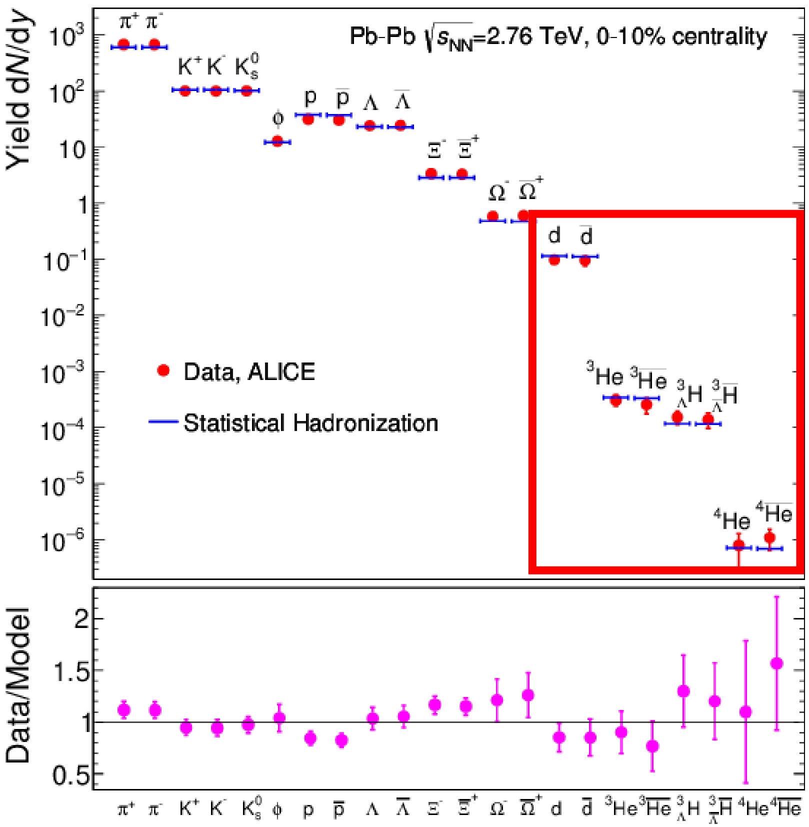
binding energies: ^{2}H, ^{3}He, ^{4}He, $^3_\Lambda$H: 2.22, 7.72, 28.3, 0.130 MeV $\ll T\sim 150$ MeV

“snowballs in hell”

The production mechanism is not established. Common approaches include **thermal** nuclei emission together with hadrons [Andronic et al., PLB ’11;...] or final-state **coalescence** of nucleons close in phase-space [Butler, Pearson, PRL ’61; Scheibl, Heinz, PRC ’99;...]

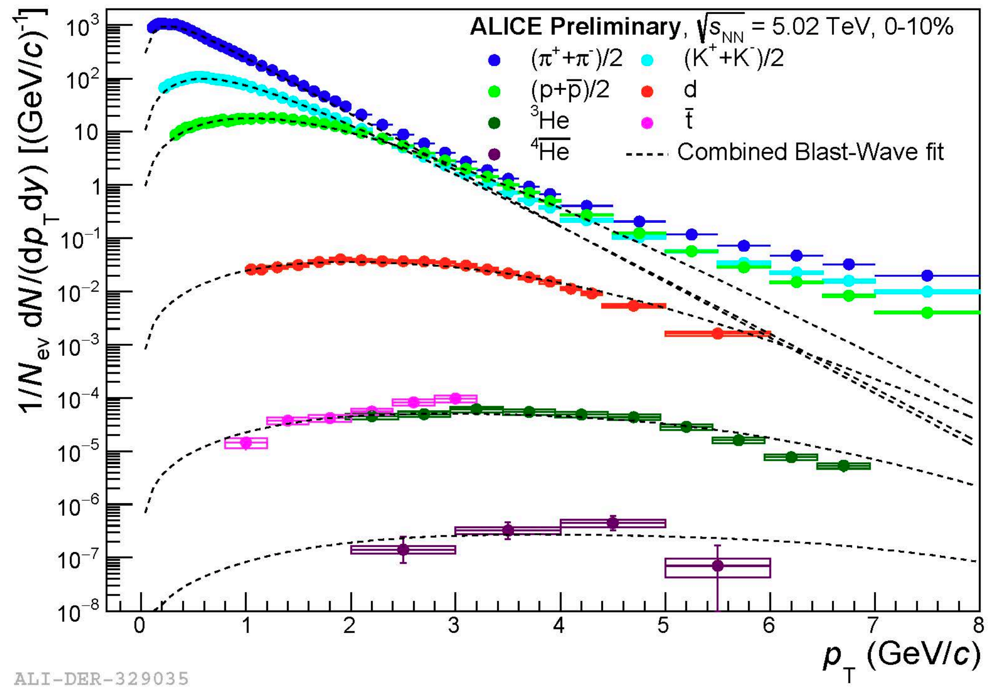
Two experimental observations at the LHC

1. Measured yields are described by thermal model at $T_{ch} \approx 155$ MeV



[A. Andronic et al., Nature **561**, 321 (2018)]

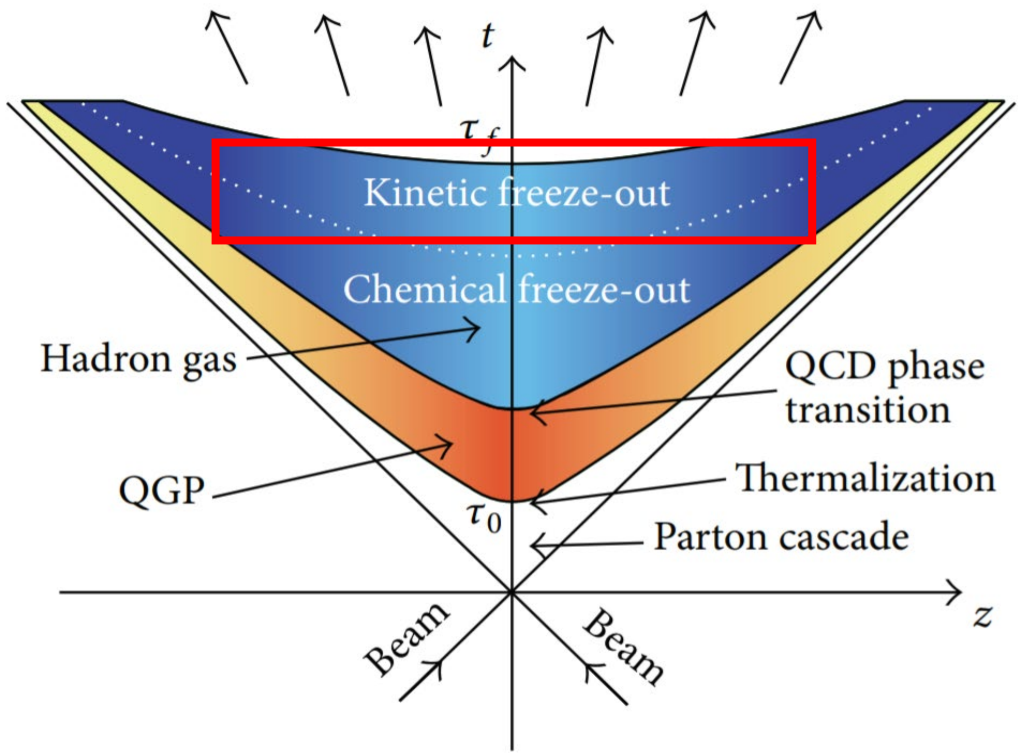
2. Spectra described by blast-wave model at $T_{kin} \approx 100 - 120$ MeV



[E. Bartsch (ALICE Collaboration), QM2019]

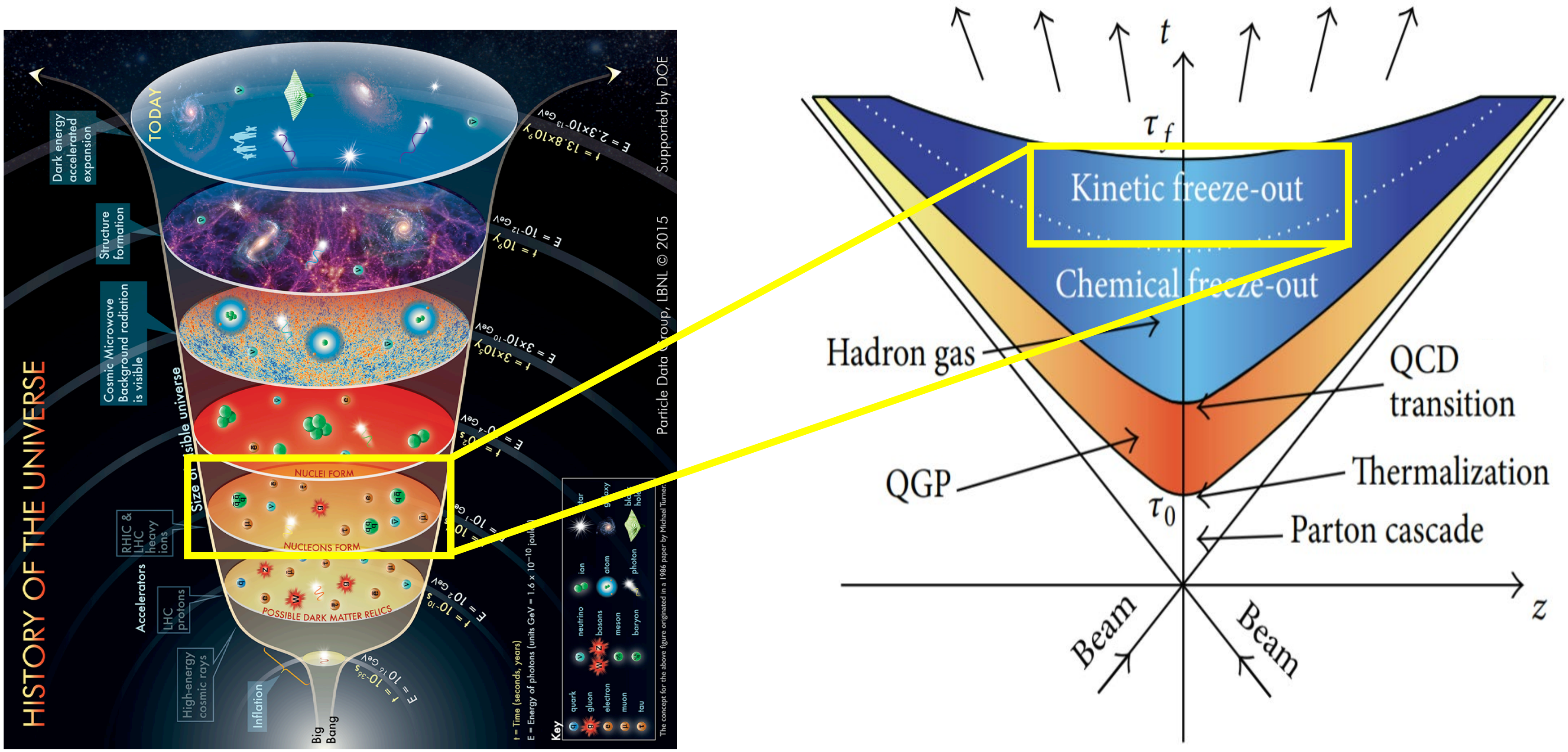
What happens between T_{ch} and T_{kin}?

Hadronic phase in central HICs



- At $T_{ch} \approx 150 - 160$ MeV inelastic collisions cease, yields of hadrons frozen
- Kinetic equilibrium maintained down to $T_{kin} \approx 100 - 120$ MeV through (pseudo)elastic scatterings

Big Bang vs LHC “Little Bangs”



- Hadrons (nucleons) form and “freeze-out” chemically before nuclei
- Bosons (photons or pions) catalyse nucleosynthesis

e.g. $p + n \leftrightarrow d + \gamma$ vs $p + n + \pi \leftrightarrow d + \pi$

Saha equation (1920)

- Ionization of a gas (one level)

$$X \longleftrightarrow X^+ + e^-$$

$$\frac{n_e^2}{n_0} = \frac{2}{\lambda_e^3}\frac{g_1}{g_0}\exp(-\epsilon/T) \qquad n_1 = n_e \qquad \lambda_e : \text{ deBroglie}$$

Megh Nad Saha, Phil. Mag. Series 6 40:238 (1920) 472

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Nuclear equivalent: detailed balance in an expanding system (early universe/HIC)

Deuteron number evolution through $pnX \leftrightarrow dX$, in kinetic equilibrium

gain **loss**

$$\frac{dN_d}{d\tau} = \langle \sigma_{dX} v_{rel} \rangle N_d^0 n_x^0 e^{\mu_p/T} e^{\mu_n/T} e^{\mu_X/T} - \langle \sigma_{dX} v_{rel} \rangle N_d^0 n_x^0 e^{\mu_d/T} e^{\mu_X/T}$$

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gain $\approx$ loss $\quad\rightarrow\quad$ $\mu_d \approx \mu_p + \mu_n$

Saha equation

= detailed balance

= law of mass action

LHC nucleosynthesis: BBN-like setup

- Chemical equilibrium lost at $T_{ch} = 155$ MeV, abundances of nucleons are frozen and acquire effective fugacity factors: $n_i = n_i^{eq} e^{\mu_N/T}$

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$$\frac{n_A}{\prod_i n_{A_i}} = \frac{n_A^{\text{eq}}}{\prod_i n_{A_i}^{\text{eq}}}, \quad \Leftrightarrow \quad \mu_A = \sum_i \mu_{A_i}, \qquad \text{e.g. } \mu_d = \mu_p + \mu_n, \; \mu_{^3\text{He}} = 2\mu_p + \mu_n, \; \ldots$$

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Saha equation

$$\boxed{X_A = d_A \left[(d_M)^{A-1} \zeta(3)^{A-1} \pi^{\frac{1-A}{2}} 2^{-\frac{3+A}{2}}\right] A^{5/2} \left(\frac{T}{m_N}\right)^{\frac{3}{2}(A-1)} \eta_B^{A-1} \exp\left(\frac{B_A}{T}\right)}$$

$d_M \sim 11 - 13$, $\eta_B \simeq 0.03$ fixed at $T_{\rm ch}$

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BBN: $$X_A = d_A \left[\zeta(3)^{A-1} \pi^{\frac{1-A}{2}} 2^{\frac{3A-5}{2}}\right] A^{\frac{5}{2}} \left(\frac{T}{m_N}\right)^{\frac{3}{2}(A-1)} \eta^{A-1} X_p^Z X_n^{A-Z} \exp\left(\frac{B_A}{T}\right)$$

[E. Kolb, M. Turner, “The Early Universe” (1990)]

(BBN-like) Saha equation vs thermal model

Saha equation:

$$\frac{N_A(T)}{N_A(T_{\rm ch})} \simeq \left(\frac{T}{T_{\rm ch}}\right)^{\frac{3}{2}(A-1)} \exp\left[B_A\left(\frac{1}{T}-\frac{1}{T_{\rm ch}}\right)\right]$$

$B_A \ll T$

Thermal model:

$$\left[\frac{N_A(T)}{N_A(T_{\rm ch})}\right]_{\rm eq.} \simeq \left(\frac{T}{T_{\rm ch}}\right)^{-\frac{3}{2}} \exp\left[-m_A\left(\frac{1}{T}-\frac{1}{T_{\rm ch}}\right)\right]$$

$m_A \gg T$

Strong exponential dependence on the temperature is eliminated in the Saha equation approach

Further, quantitative applications require numerical treatment of full spectrum of *massive* mesonic and baryonic resonances

Partial chemical equilibrium (PCE)

Expansion of hadron resonance gas in partial chemical equilibrium at $T < T_{ch}$

[H. Bebie, P. Gerber, J.L. Goity, H. Leutwyler, Nucl. Phys. B '92; C.M. Hung, E. Shuryak, PRC '98]

Chemical composition of stable hadrons is fixed, kinetic equilibrium maintained through pseudo-elastic resonance reactions $\pi\pi \leftrightarrow \rho$, $\pi \mathrm{K} \leftrightarrow \mathrm{K}^*, \pi N \leftrightarrow \Delta$, etc.

E.g.: $\pi + 2\rho + 3\omega + \cdots = const$, $\mathrm{K} + \mathrm{K}^* + \cdots = const$, $N + \Delta + N^* + \cdots = const$,

Effective chemical potentials:

$$\tilde{\mu}_j = \sum_{i \in \text{stable}} \langle n_i \rangle_j \, \mu_i, \qquad \langle n_i \rangle_j \text{ – mean number of hadron } i \text{ from decays of hadron } j, \qquad j \in \text{HRG}$$

Conservation laws:

$$\sum_{j \in \text{hrg}} \langle n_i \rangle_j \, n_j(T, \tilde{\mu}_j) \, V = N_i(T_{\text{ch}}), \quad i \in \text{stable}$$

$$\sum_{j \in \text{hrg}} s_j(T, \tilde{\mu}_j) \, V = S(T_{\text{ch}})$$

$$\xrightarrow{\textit{numerical solution}} \quad \{\mu_i(T)\}, V(T)$$

Numerical implementation within (extended) **Thermal-FIST** package

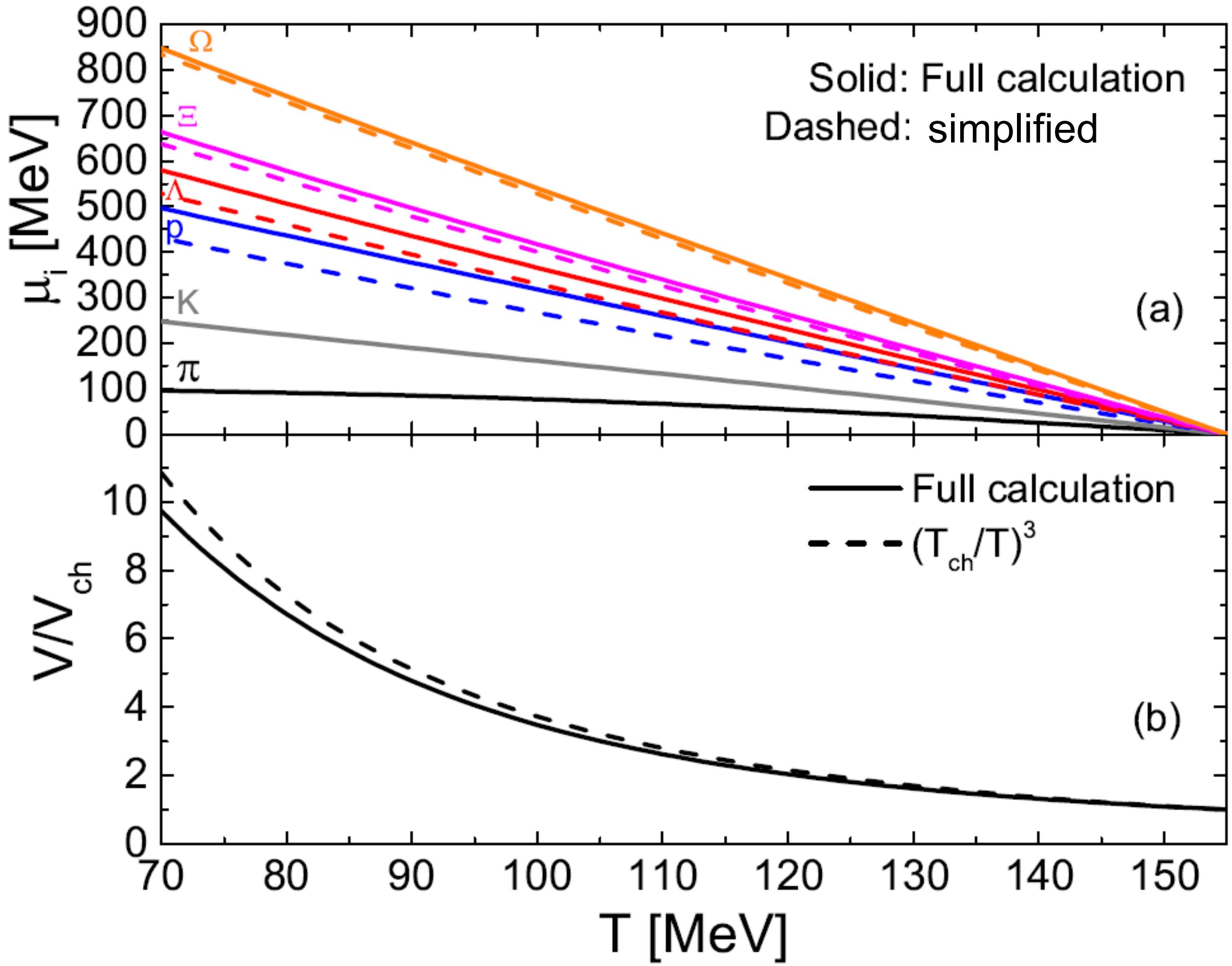
[**V.V.**, H. Stoecker, *Comput. Phys. Commun.* ***244***, *295 (2019)*]

open source: https://github.com/vlvovch/Thermal-FIST

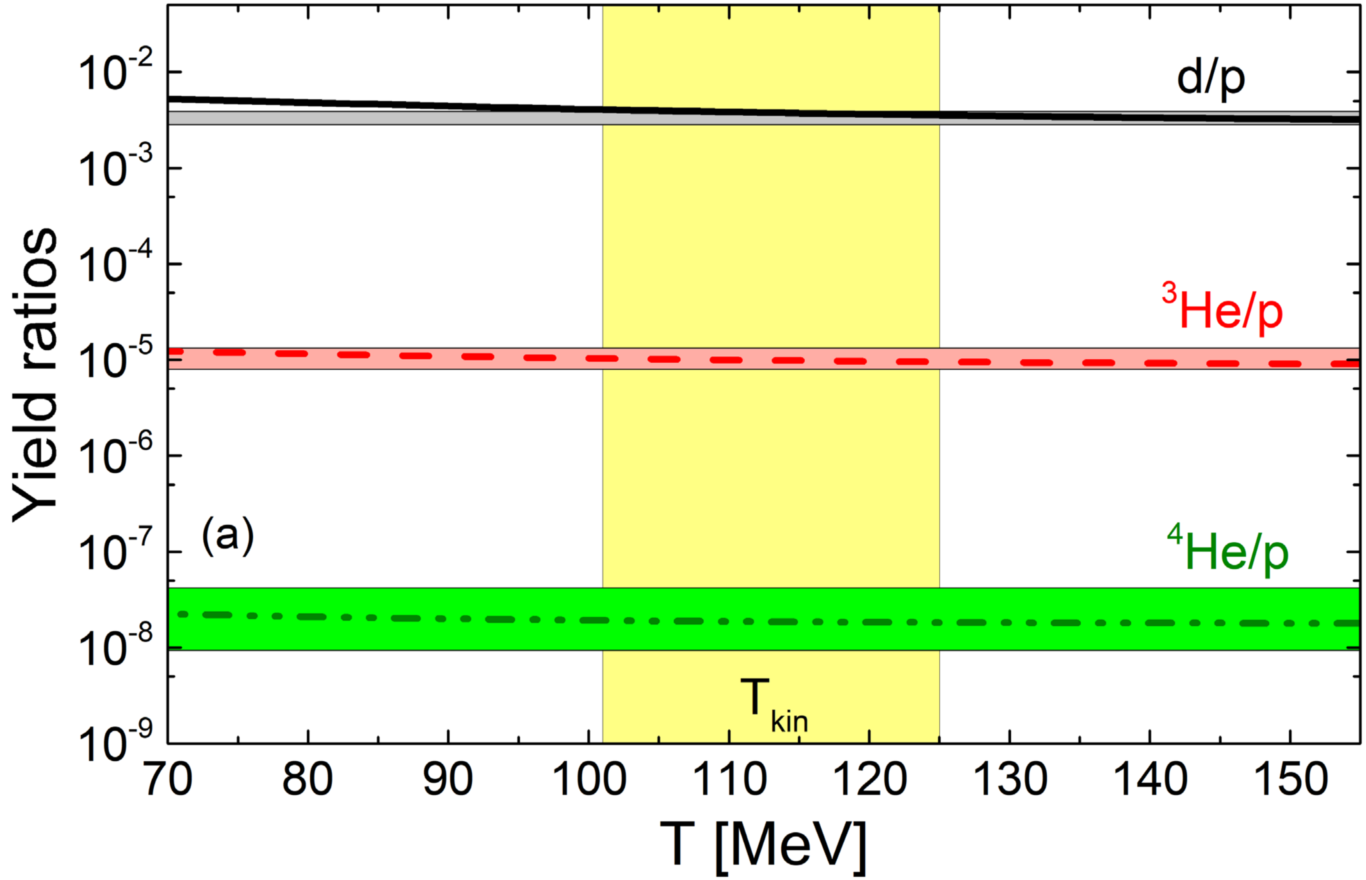
Full calculation: parameters

"Initial conditions": $T_{ch} = 155$ MeV, $V_{ch} = 4700$ fm^3 (chemical freeze-out)

values from **V.V.**, Gorenstein, Stoecker, 1807.02079



Full calculation: nuclei

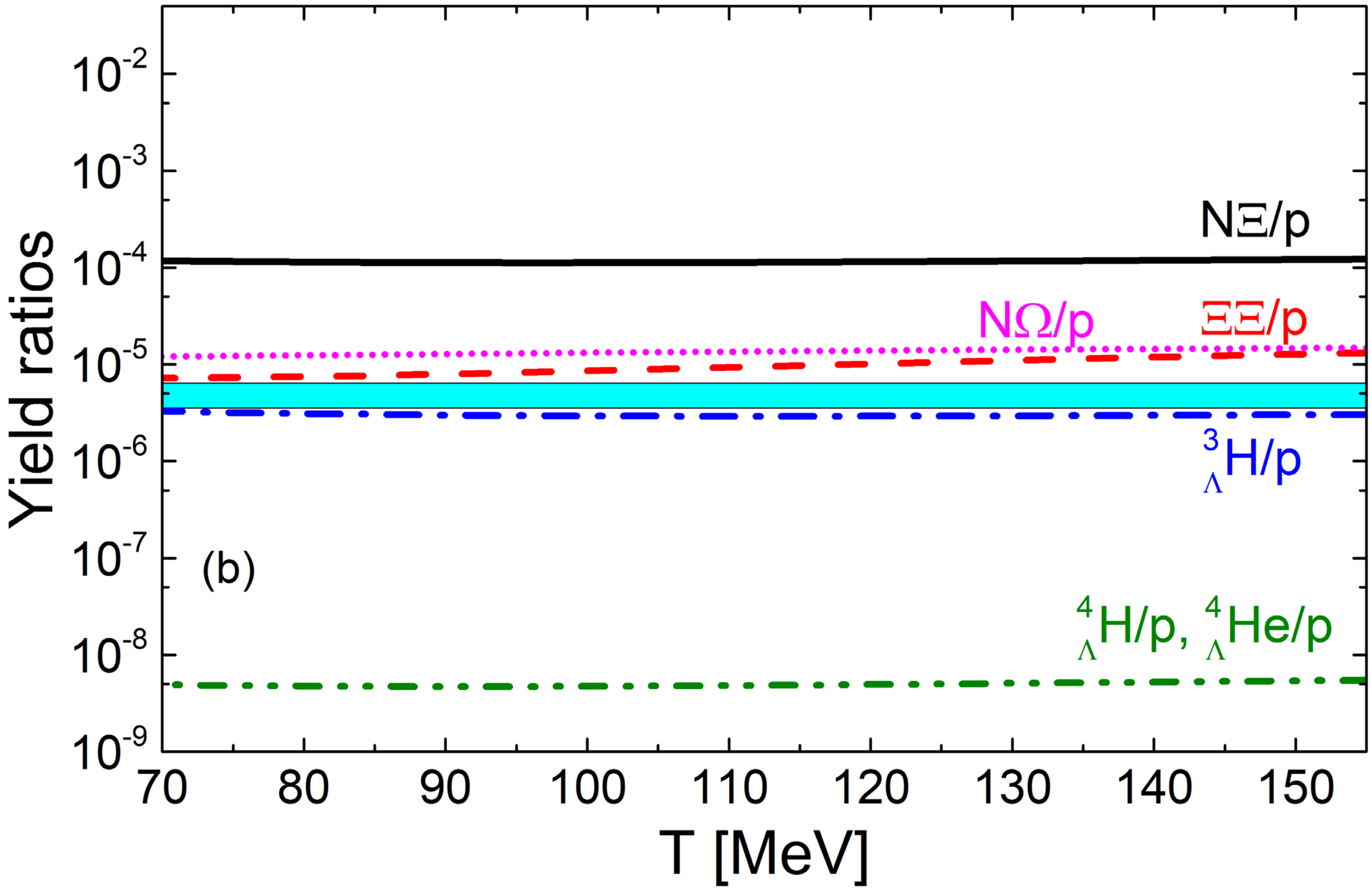


Deviations from thermal model predictions are moderate despite significant cooling and dilution. Is this the reason for why thermal model works so well?

Echoes earlier transport model conclusions for d [D. Oliinychenko, et al., PRC 99, 044907 (2019)]

For $T = T_{kin}$ similar results reported in [X. Xu, R. Rapp, EPJA 55, 68 (2019)]

Full calculation: hypernuclei



Hypernuclei stay close to the thermal model prediction. An exception is a hypothetical $\Xi\Xi$ state ← *planned measurement in Runs 3 & 4 at the LHC*

[LHC Yellow Report, 1812.06772]

Light nuclei production with rate equations

with D. Oliinychenko and V. Koch, *to appear*

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$$\underbrace{\frac{dN_d}{d\tau}}_{\textit{small}} = \overbrace{\underbrace{\langle \sigma_{dX} v_{rel} \rangle N_d^0 \, n_X^0 \, e^{\mu_p/T} e^{\mu_n/T} e^{\mu_X/T}}_{\textit{big}}}^{\textbf{gain}} - \overbrace{\underbrace{\langle \sigma_{dX} v_{rel} \rangle N_d^0 \, n_X^0 \, e^{\mu_d/T} e^{\mu_X/T}}_{\textit{big}}}^{\textbf{loss}}$$

Saha equation

gain $\approx$ loss $\quad \rightarrow \quad \mu_d \approx \mu_p + \mu_n$ $\quad$ = detailed balance

= law of mass action

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~~***small***~~ ~~***big***~~ ~~***big***~~

~~**Saha equation**~~

~~gain $\approx$ loss $\rightarrow$ $\mu_d = \mu_p + \mu_n$ $=$ detailed balance $=$ law of mass action~~

Relax the assumption of equilibrium for $AX \leftrightarrow \sum_i A_i X$ reactions

Light nuclei production with rate equations

- Pion catalysis of light nuclei reactions. Destruction through $A\pi \to \sum_i A_i\pi$ and creation through $\sum_i A_i\pi \to A\pi$. Detailed balance principle respected but *relative chemical equilibrium not enforced*
- Bulk hadron matter evolves in partial chemical equilibrium, unaffected by light nuclei

$$\frac{dN_A}{d\tau} = \langle \sigma^{\text{in}}_{A\pi} v_{rel} \rangle n^{\text{pce}}_{\pi} \left(N^{\text{saha}}_A - N_A \right)$$

Static fireball: $n^{\text{pce}}_{\pi}, N^{\text{saha}}_A, \langle \sigma^{\text{in}}_{A\pi} v_{rel} \rangle = const$

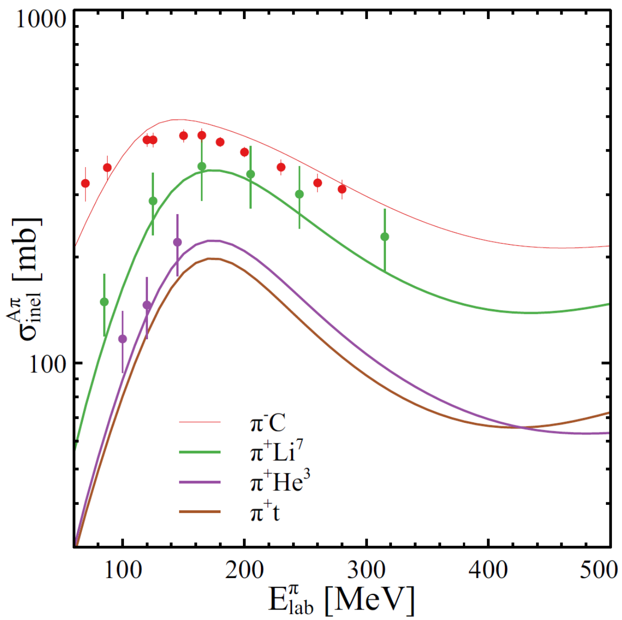
$$N_A(\tau) = N^{\text{saha}}_A + \left(N_A(\tau_0) - N^{\text{saha}}_A \right) e^{-\frac{\tau - \tau_0}{\tau_{\text{eq}}}}, \qquad \tau_{\text{eq}} = \frac{1}{\langle \sigma^{\text{in}}_{A\pi} v_{\text{rel}} \rangle \, n^{\text{pce}}_{\pi}}$$

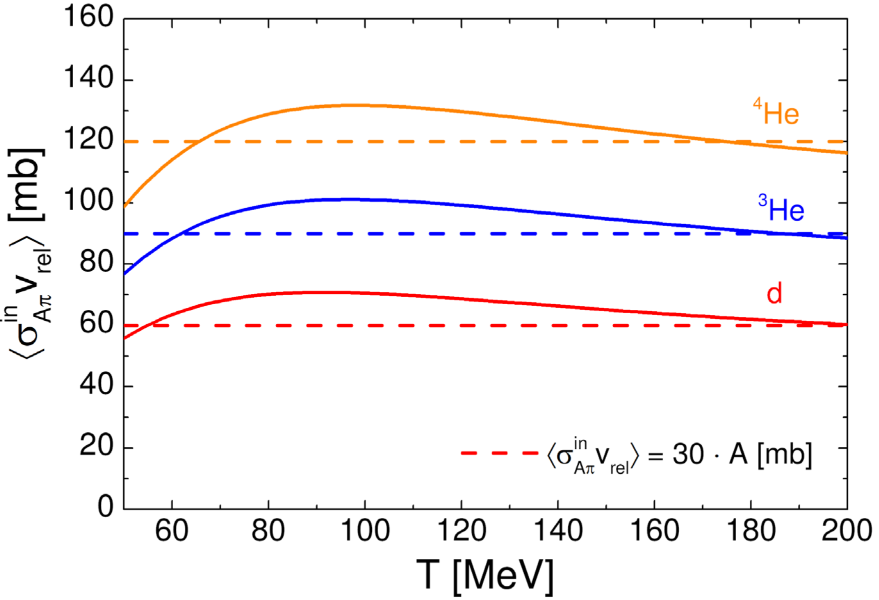
Saha limit: $\tau_{eq} \to 0$ $(\sigma^{\text{in}}_{A\pi} \to \infty)$

Model input

- **Cross sections**

Optical model for $\sigma^{\text{in}}_{A\pi}$ [J. Eisenberg, D.S. Koltun, '80]





Being implemented in SMASH [Dima's talk]

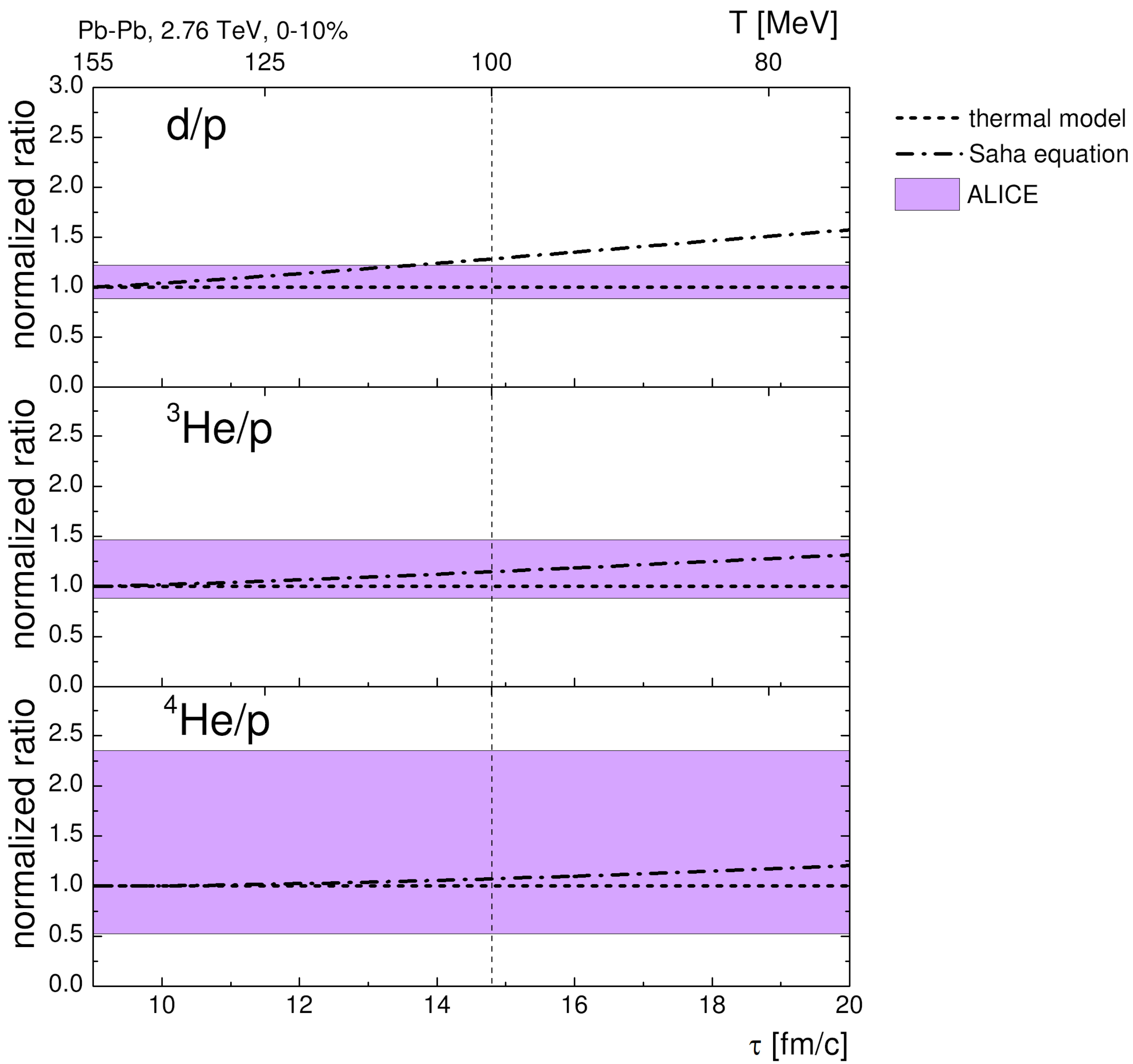
In practice $\langle \sigma^{\text{in}}_{A\pi} v_{rel} \rangle \gtrsim 30 \cdot A$ [mb]

- **Expansion** (both transverse and longitudinal)

$$\frac{V}{V_{\text{ch}}} = \frac{\tau}{\tau_{\text{ch}}} \frac{\tau_\perp^2 + \tau^2}{\tau_\perp^2 + \tau_{\text{ch}}^2}, \qquad \tau_{\text{ch}} = 9 \text{ fm}, \qquad \tau_\perp = 6.5 \text{ fm}$$

[Y. Pan, S. Pratt, PRC 89, 044911 (2014)]

Rate equations at LHC



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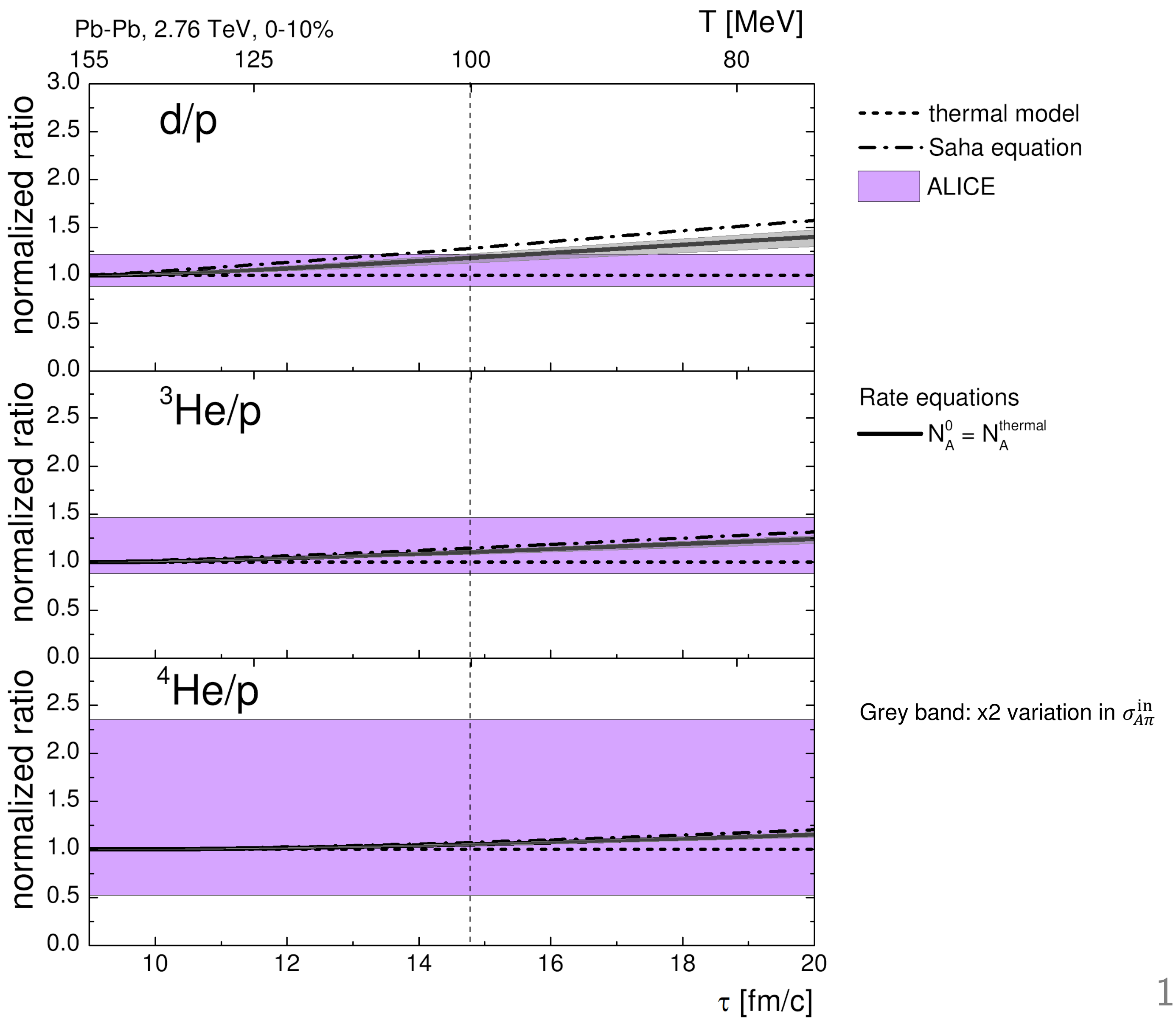
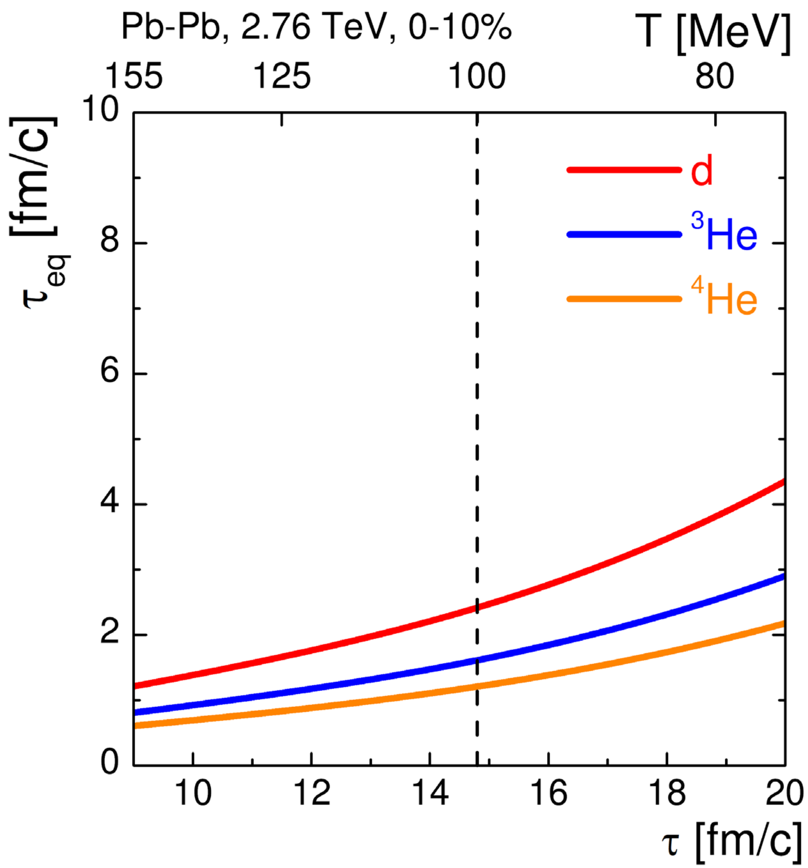
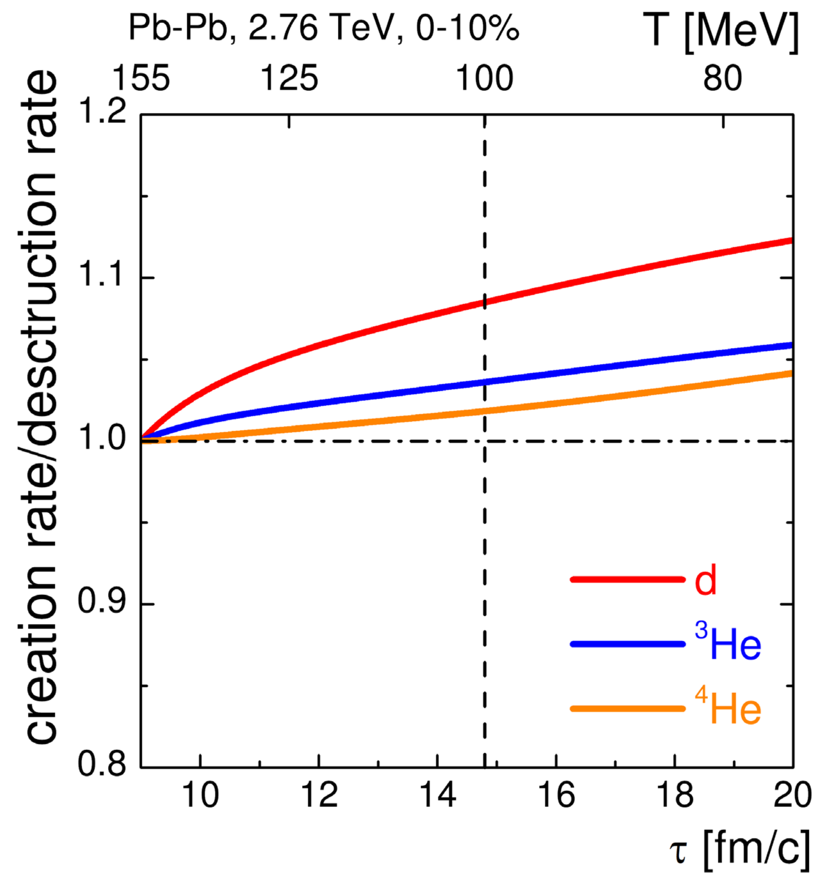


Degree of equilibration

$$\tau_{\mathrm{eq}}^{-1} = \langle \sigma_{A\pi}^{\mathrm{in}} v_{rel} \rangle \, n_{\pi}^{\mathrm{pce}}$$



gain vs loss

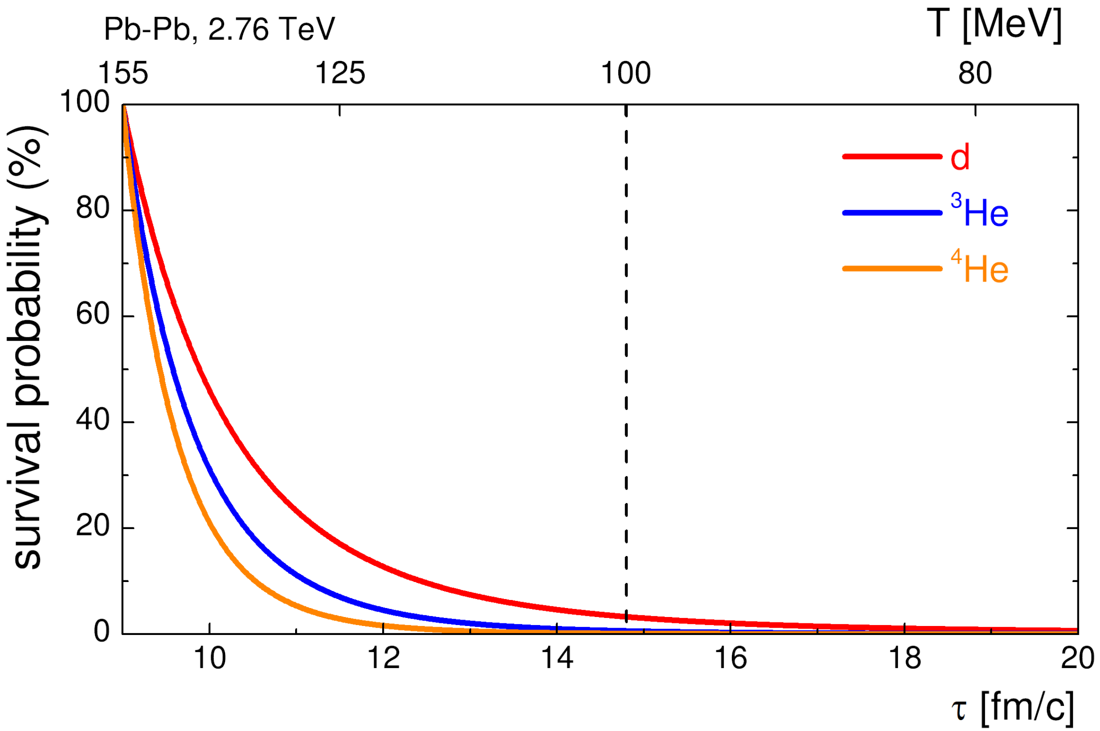


- Local equilibration times remain small (but also $\tau_A^{\mathrm{eq}} \ll B_A^{-1}$)
- (**gain** + **loss**) ≫ |**gain** – **loss**| → **Saha equation at work**

Can snowballs survive hell?

Count only the nuclei produced at "QGP hadronization" (at T_{ch})

$$\frac{dN_A^{qgp}}{d\tau} = -\langle \sigma_{A\pi} v_{rel} \rangle n_\pi^{pce} N_A^{qgp}, \qquad \text{survival probability} = N_A^{qgp}(\tau)/N_A^{qgp}(\tau_{ch})$$



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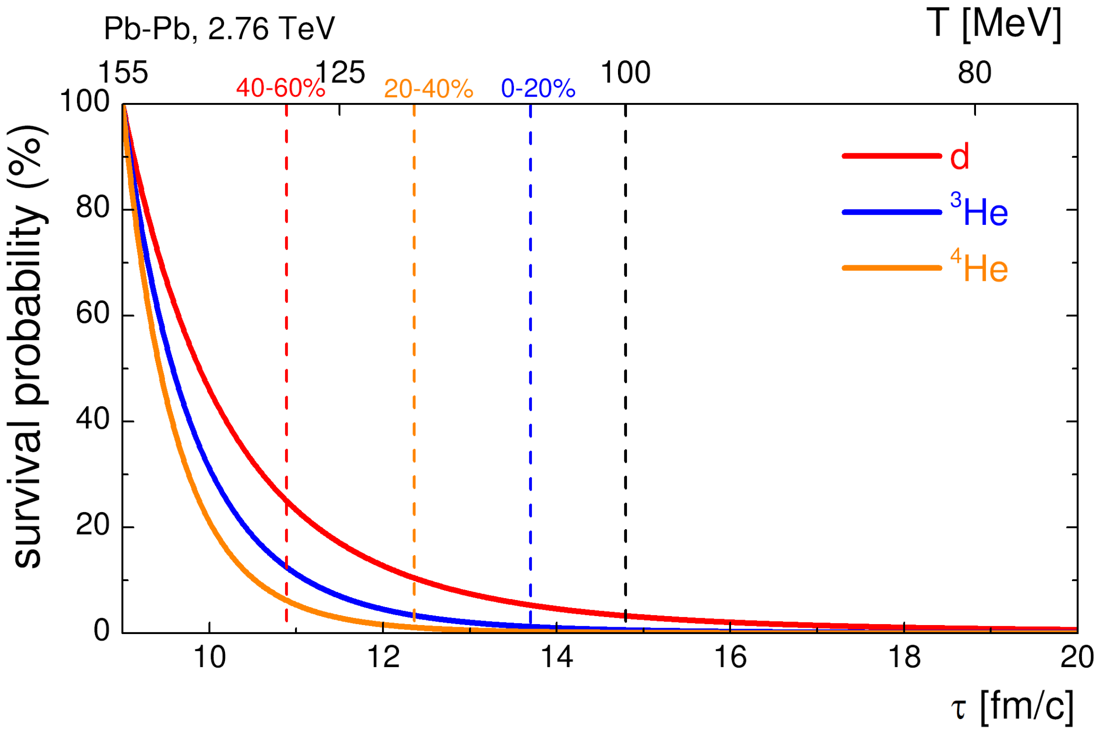
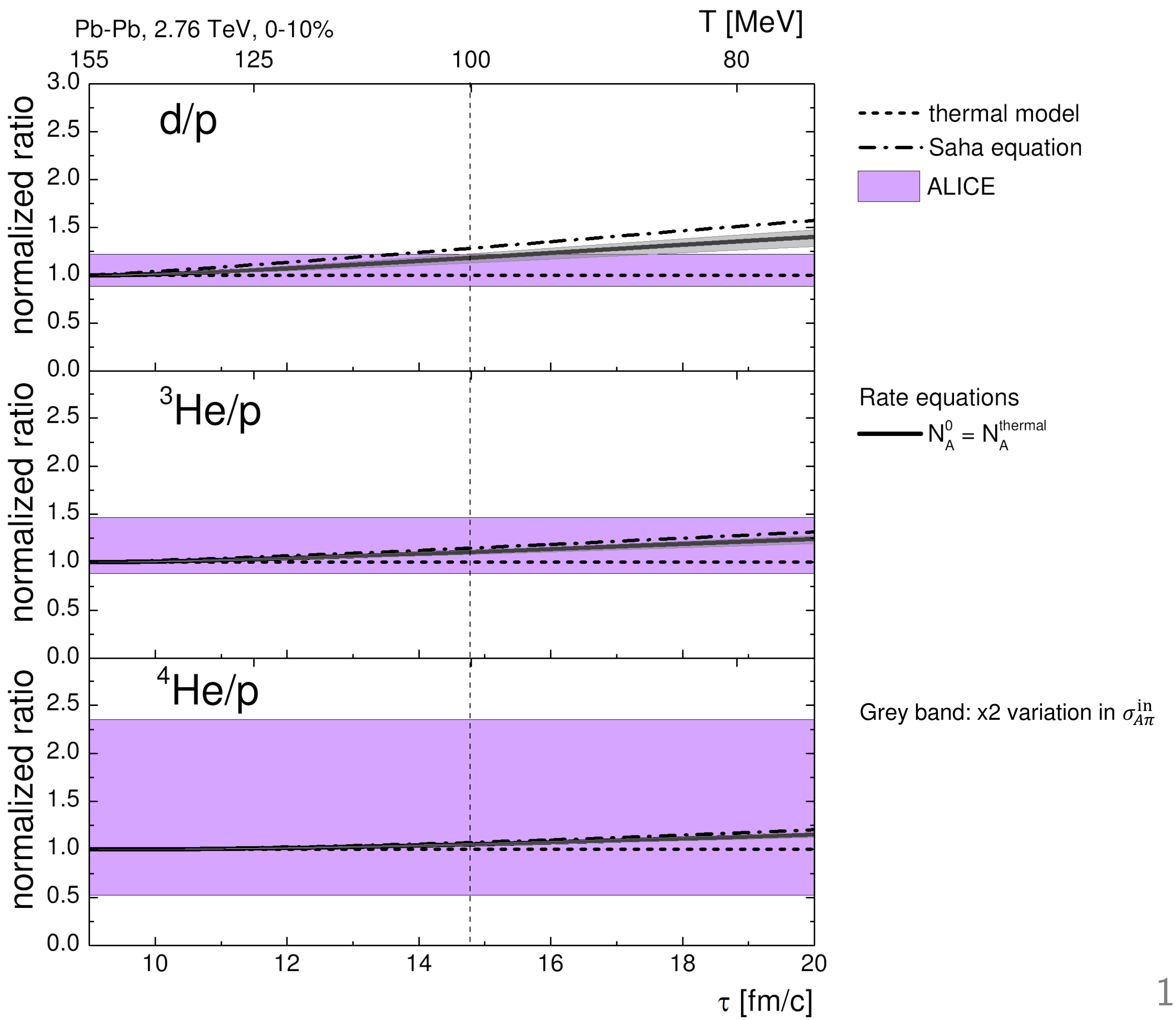


Dashed lines: T_{kin} values from A. Motornenko et al., 1908.11730

- Survival down to 100 MeV is unlikely
- Peripheral collisions might offer better chances

Rate equations at LHC



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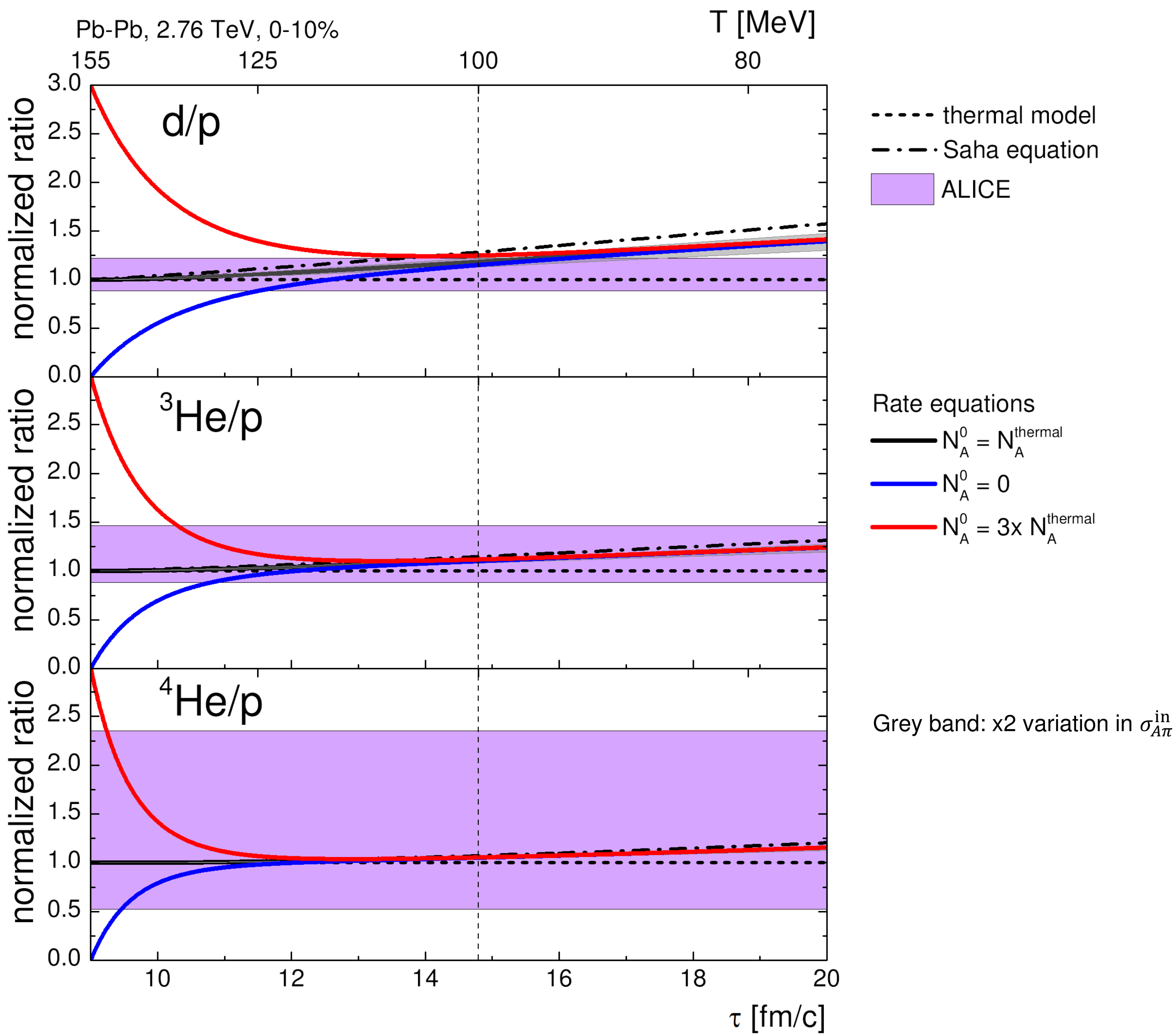

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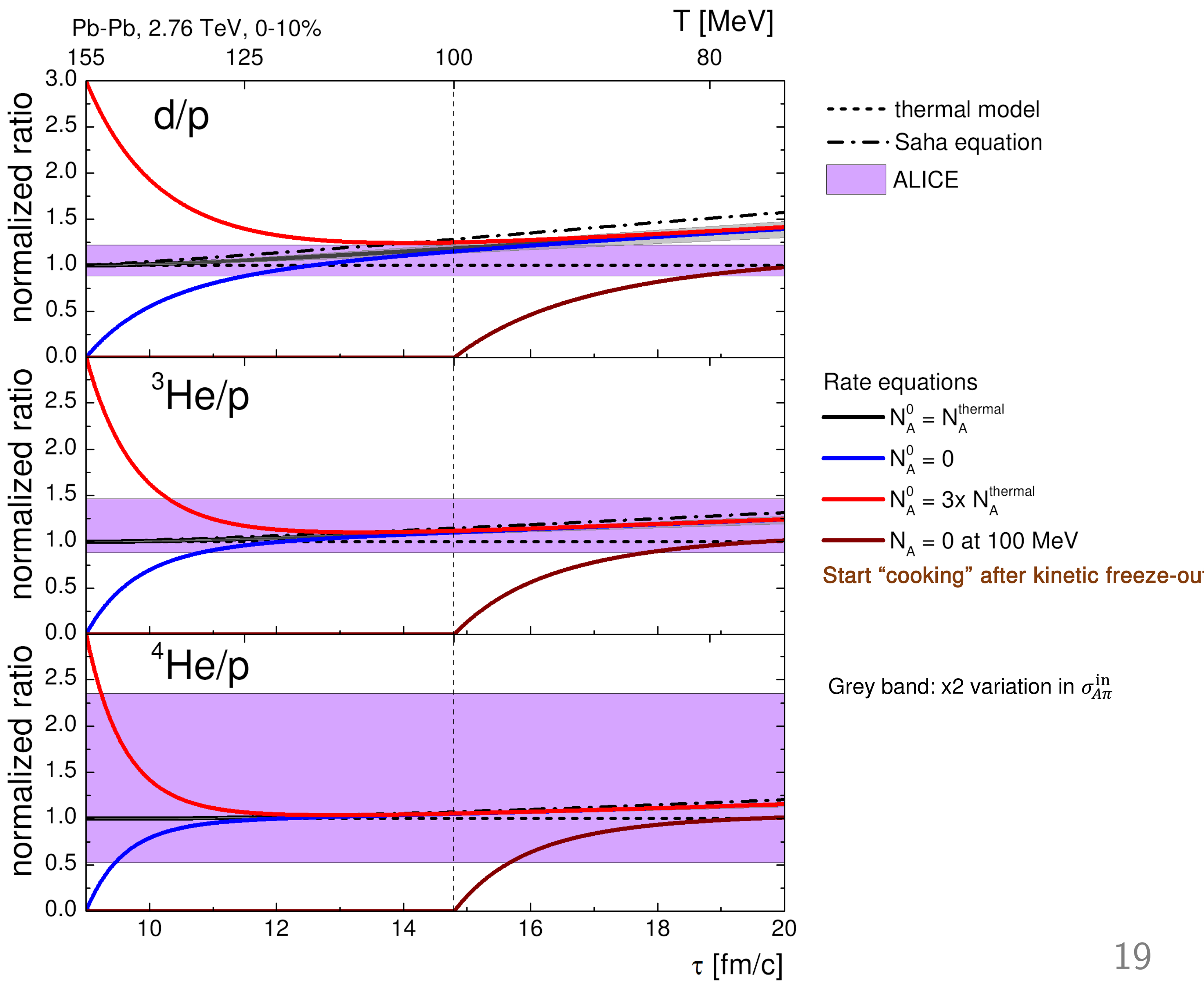

Summary and outlook

- Nucleosynthesis in HICs at LHC via the Saha equation is in analogy to initial stages of big bang nucleosynthesis in the early universe. Results agree with the thermal model, but *any* $T < T_{ch}$ permitted!

- Description of pion-catalyzed nuclear cluster production using rate equations agrees with the Saha equation, for *all* nuclei up to ^{4}He.

- "Snowballs" produced at hadronization do not survive "hell" down to $T_{\text{kin}} = 100$ MeV.

- Outlook: Rate equations for resonances and $B\bar{B}$ annihilations.

- Open questions: $\tau_A^{\text{eq}} \ll B_A^{-1}$, i.e. deuteron in the hadronic phase cannot yet know that it is deuteron. Quantum mechanical treatment of bound systems in medium needed.

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Thanks for your attention!

Backup slides

(Simplified) Saha equation vs thermal model

Saha equation:

$$\frac{N_A(T)}{N_A(T_{\text{ch}})} \simeq \left(\frac{T}{T_{\text{ch}}}\right)^{\frac{3}{2}(A-1)} \exp\left[B_A\left(\frac{1}{T}-\frac{1}{T_{\text{ch}}}\right)\right]$$

$B_A \ll T$

Thermal model:

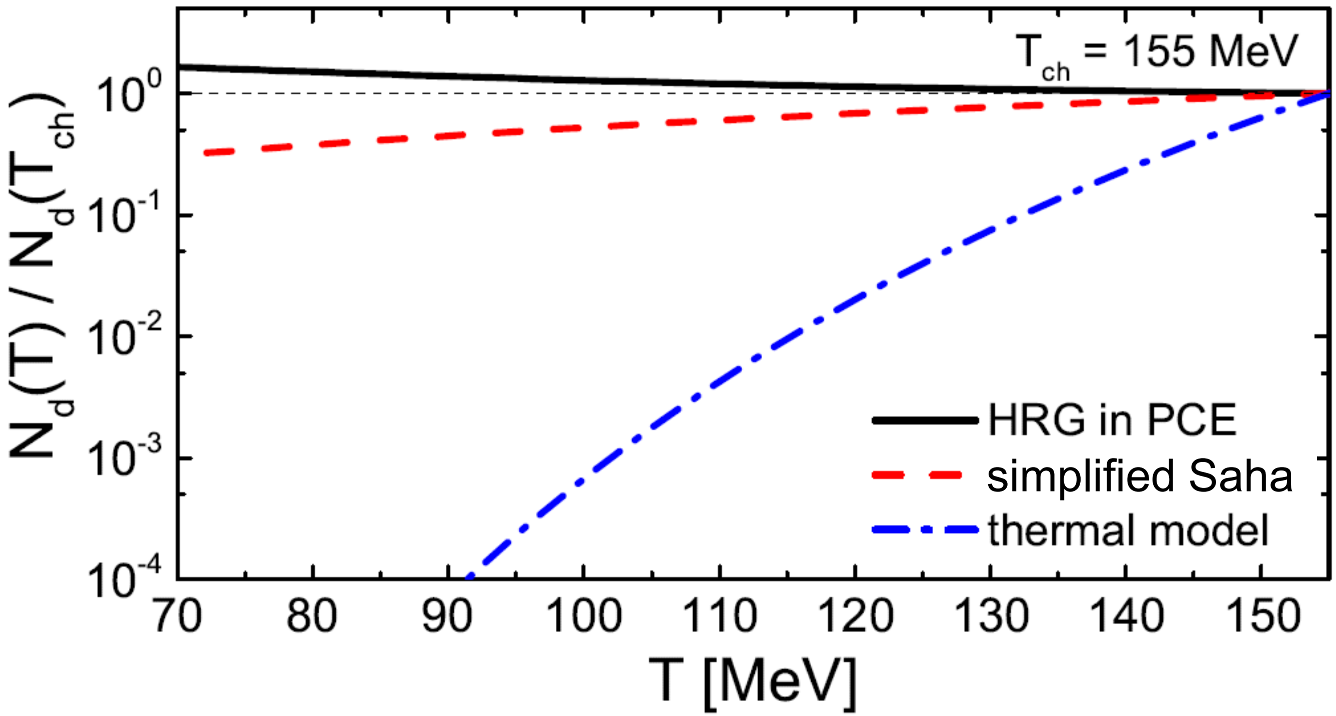
$$\left[\frac{N_A(T)}{N_A(T_{\text{ch}})}\right]_{\text{eq.}} \simeq \left(\frac{T}{T_{\text{ch}}}\right)^{-\frac{3}{2}} \exp\left[-m_A\left(\frac{1}{T}-\frac{1}{T_{\text{ch}}}\right)\right]$$

$m_A \gg T$

Strong exponential dependence on the temperature is eliminated in the Saha equation approach

Further, quantitative applications require numerical treatment of full spectrum of *massive* mesonic and baryonic resonances

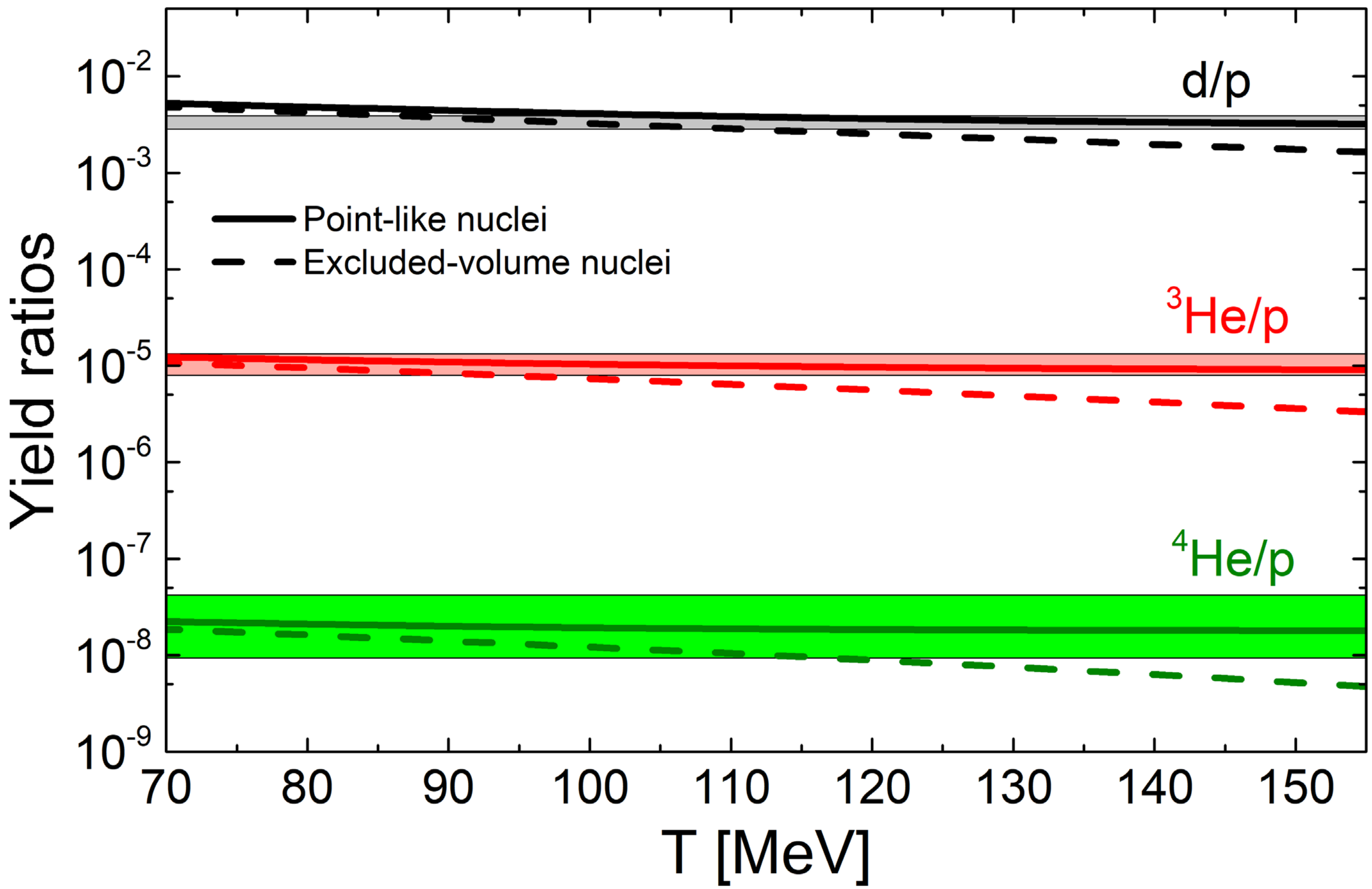
Full calculation: deuteron yield



Resonance feed-down is important in precision studies

Saha equation and excluded volume effects

Eigenvolumes: effective mechanism for nuclei suppression at large densities



Excluded-volume effects go away as the system dilutes. At $T \cong 100$ MeV agrees with the point-particle model. Does not describe data for $T = T_{ch}$

Rate equation for nuclei and resonances

Treat both nuclear reactions and resonances decays using rate equations, i.e. PCE not enforced

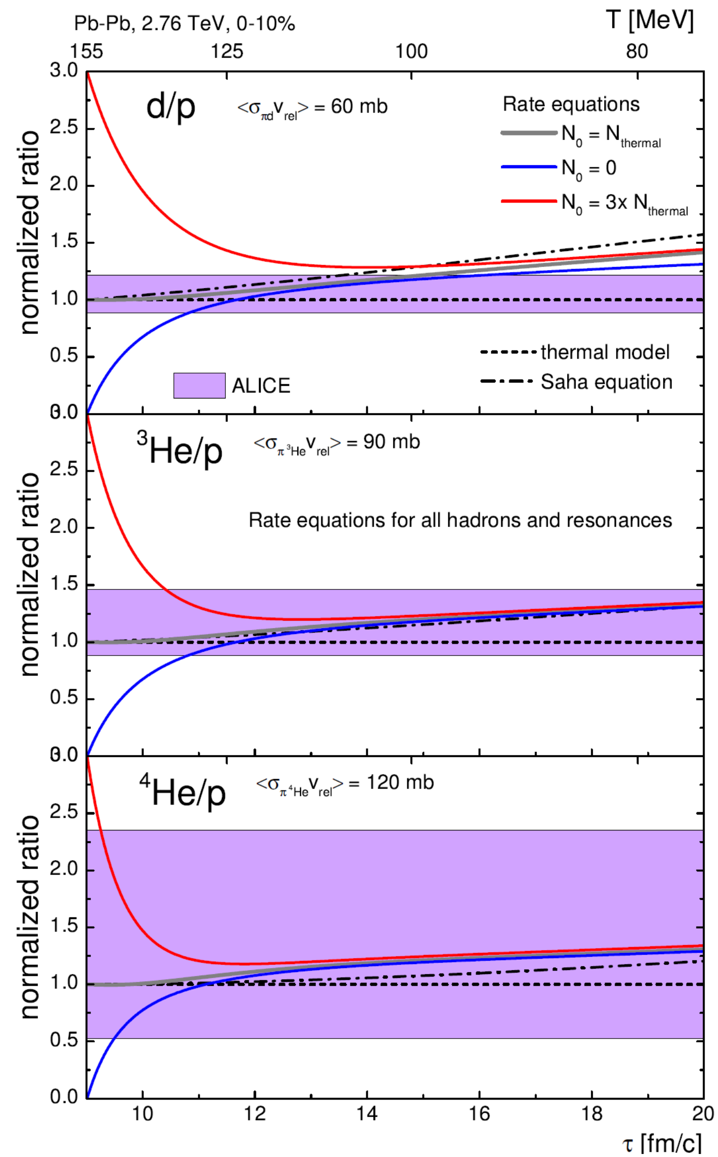
Rate equations for all particles

$$\frac{dN_A}{d\tau} = \langle \sigma_{A\pi} v_{rel} \rangle N_\pi \, n_A^{\text{eq}} (e^{A\mu_N/T} - e^{\mu_A/T})$$

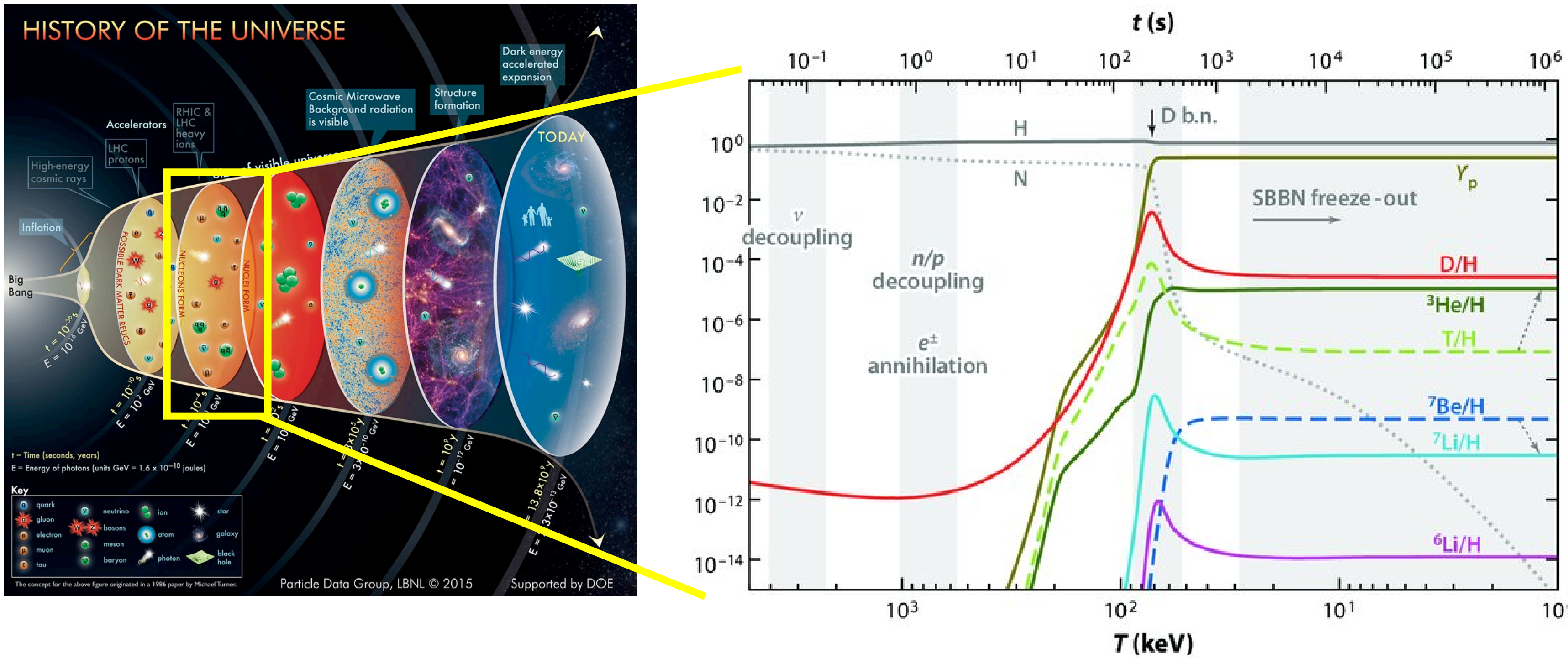
$$\frac{dN_R}{d\tau} = \langle \Gamma_{R\to\sum_i a_i} \rangle N_R^{\text{eq}} (e^{\sum_{i\in R}\mu_i/T} - e^{\mu_R/T})$$

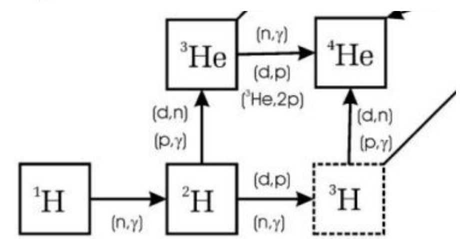
Entropy production: 0.6% at $T_{\text{kin}} = 100$ MeV

Results are very close to Saha equation



Big Bang nucleosynthesis





- Nuclei start to form after proton-neutron ratio freeze-out (T $<$ 1 MeV)
- Early stage of Big Bang nucleosynthesis described by Nuclear Statistical Equilibrium, $\mu_A = A\mu_N$ (**Saha equation**)

$$X_A = d_A \left[\zeta(3)^{A-1}\,\pi^{\frac{1-A}{2}}\,2^{\frac{3A-5}{2}}\right] A^{\frac{5}{2}} \left(\frac{T}{m_N}\right)^{\frac{3}{2}(A-1)} \eta^{A-1} X_p^Z X_n^{A-Z} \exp\left(\frac{B_A}{T}\right)$$

$\eta \sim 10^{-10}$ – baryon-to-photon ratio

[E. Kolb, M. Turner, “The Early Universe” (1990)]

Big Bang vs LHC nucleosynthesis

Similarities:

- Inelastic nucleonic reactions freeze-out before nuclei formation
- Isentropic expansion of boson-dominated matter (photons in BBN vs mesons in HIC), baryon-to-boson ratio: $\eta_{BBN} \sim 10^{-10}$, $\eta_{LHC} \sim 0.05$
- Strong nuclear formation and regeneration reactions → **Saha equation**

Differences:

- Time scales: 1-100 s in BBN vs $\sim 10^{-22}$ s in HIC
- Temperatures: $T_{BBN} < 1$ MeV vs $T_{HIC} \sim 100$ MeV
- Binding energies, proton-neutron mass difference, and neutron lifetime important in BBN, less so in HICs
- $\mu_B \approx 0$ at the LHC, $\mu_B \neq 0$ in BBN
- Resonance feeddown important at LHC, irrelevant in BBN

LHC deuteron-synthesis

PHYSICAL REVIEW C **99**, 044907 (2019)

Editors' Suggestion | Featured in Physics

Microscopic study of deuteron production in PbPb collisions at $\sqrt{s} = 2.76$ TeV via hydrodynamics and a hadronic afterburner

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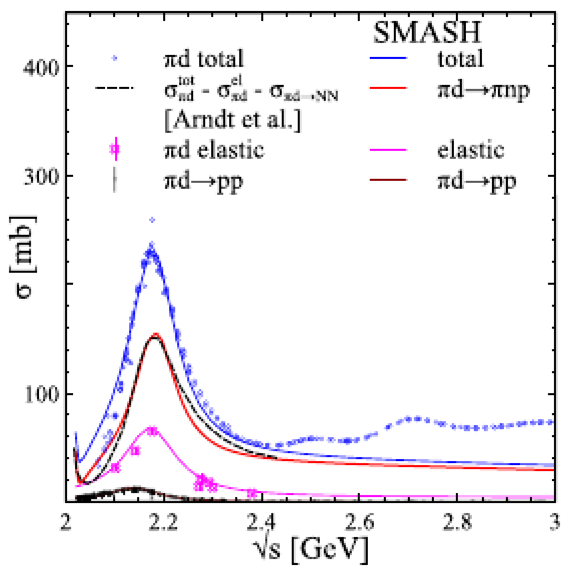


FIG. 1. Deuteron-pion interaction cross sections from SAID database [40] and partial wave analysis [41] are compared to our parametrizations (Tables II and III in the Appendix). Inelastic $d\pi \leftrightarrow$

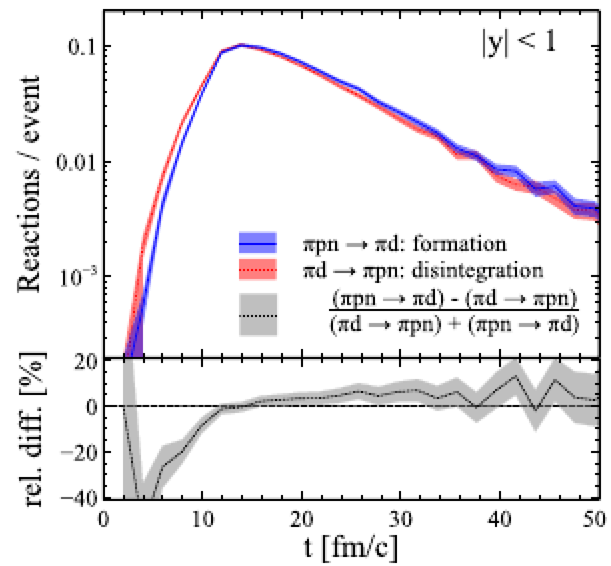


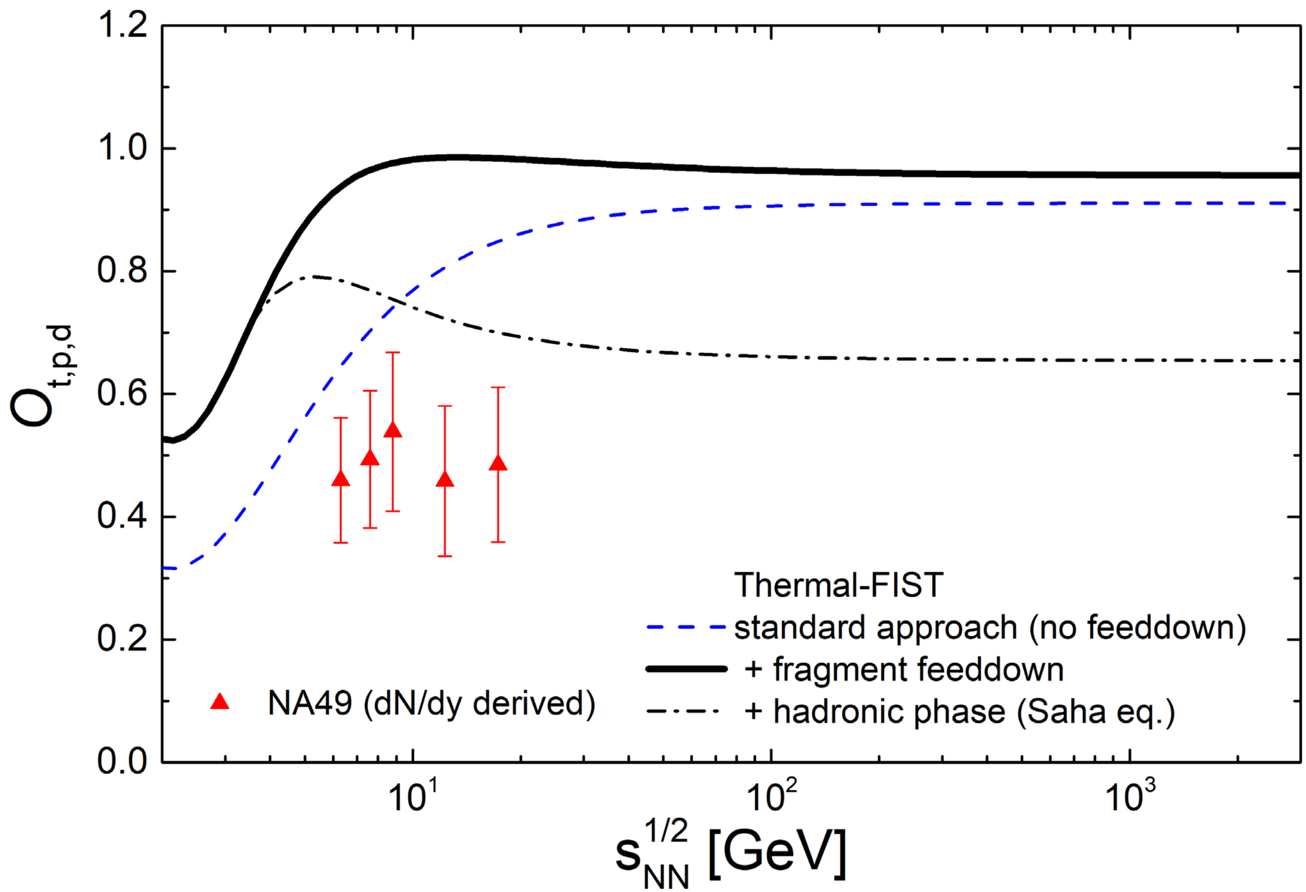
FIG. 5. Reaction rates of the most important $\pi d \leftrightarrow \pi pn$ reaction in forward and reverse direction.

- Law of mass action at work

$O_{\mathrm{t,p,d}}$

$O_{\mathrm{t,p,d}} = N_t\, N_p/(N_d)^2$ suggested as a possible probe of critical behavior

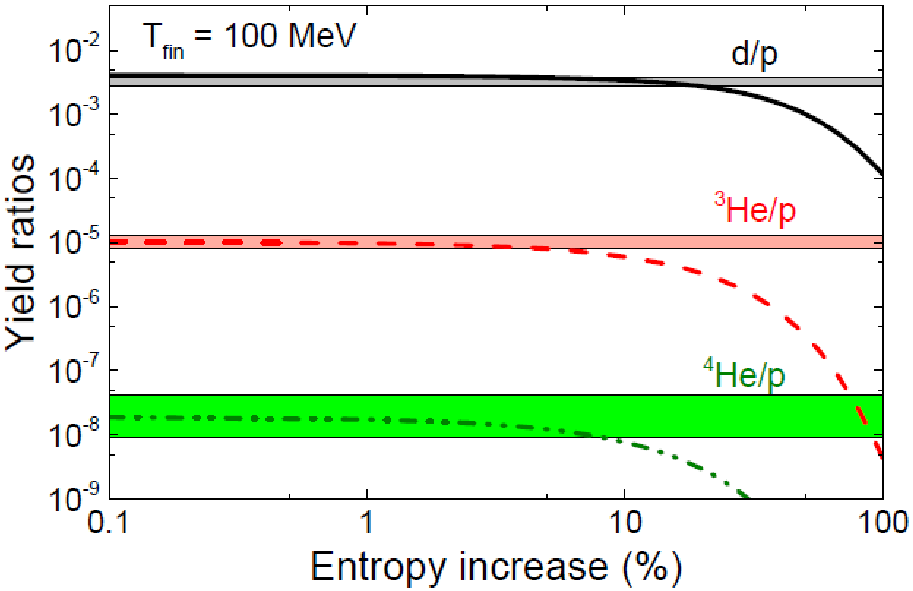
[K.J. Sun et al., PLB '17, PLB '18]

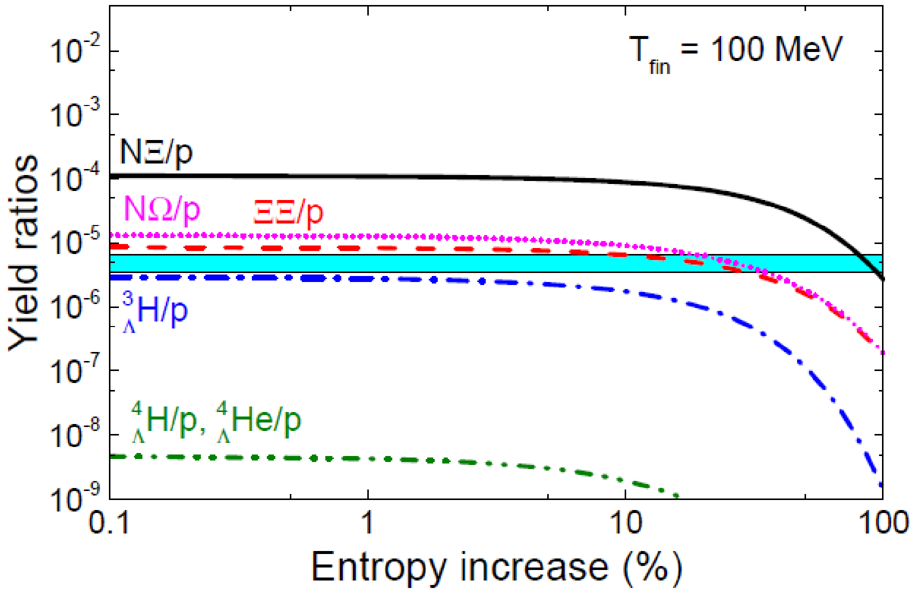


Possible to obtain a non-monotonic behavior of $O_{t,p,d}$ in ideal gas picture

Relevance of excited ^{4}He states also pointed out in baryon preclustering study [Torres-Rincon, Shuryak, 1910.08119]

Saha equation: Entropy production effect

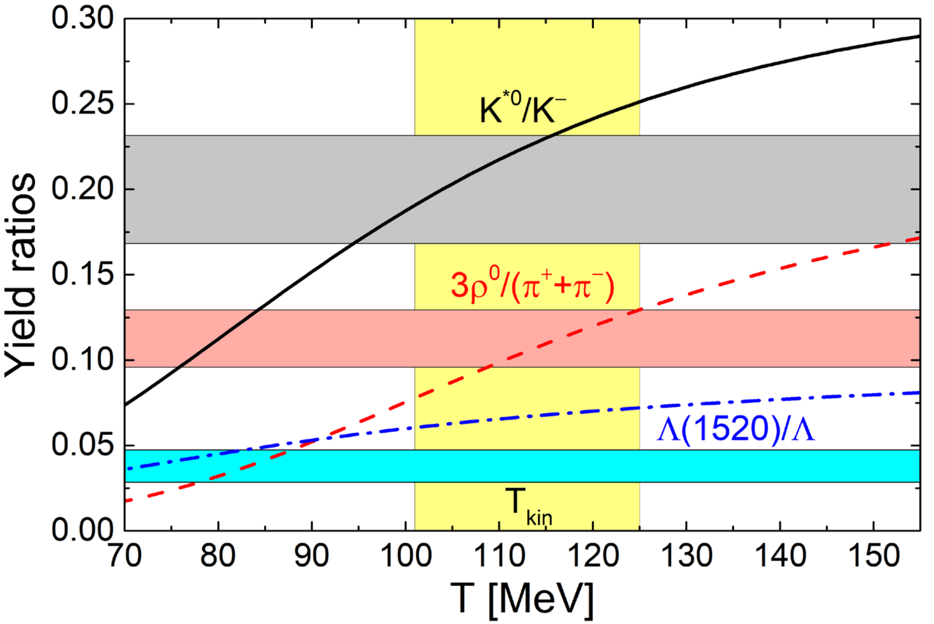




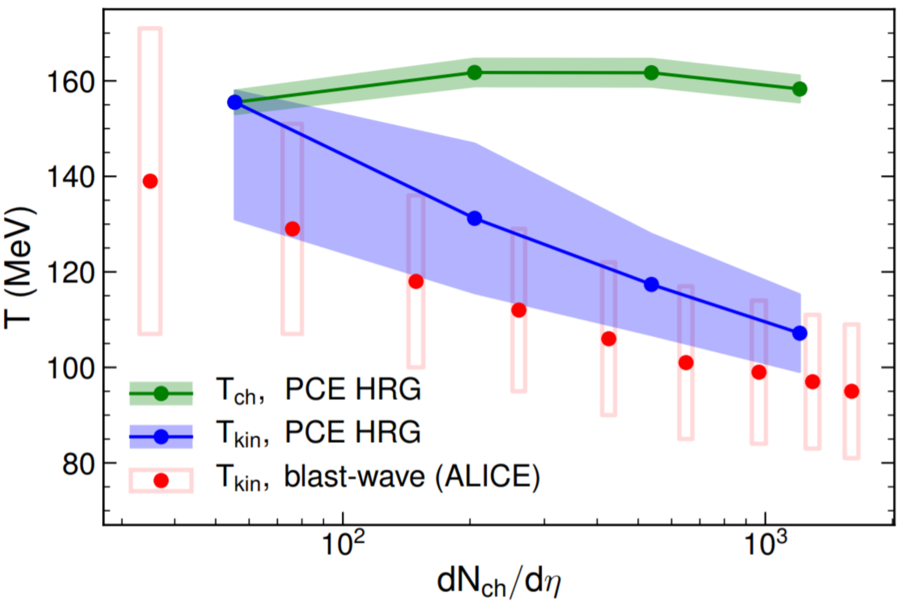
Resonance suppression in hadronic phase

Yields of resonances are *not* conserved in partial chemical equilibrium

E.g. K^* yield dilutes during the cooling through reactions $\pi\mathrm{K} \leftrightarrow \mathrm{K}^*$



[**V.V.**, Gallmeister, Schaffner-Bielich, Greiner, 1903.10024]

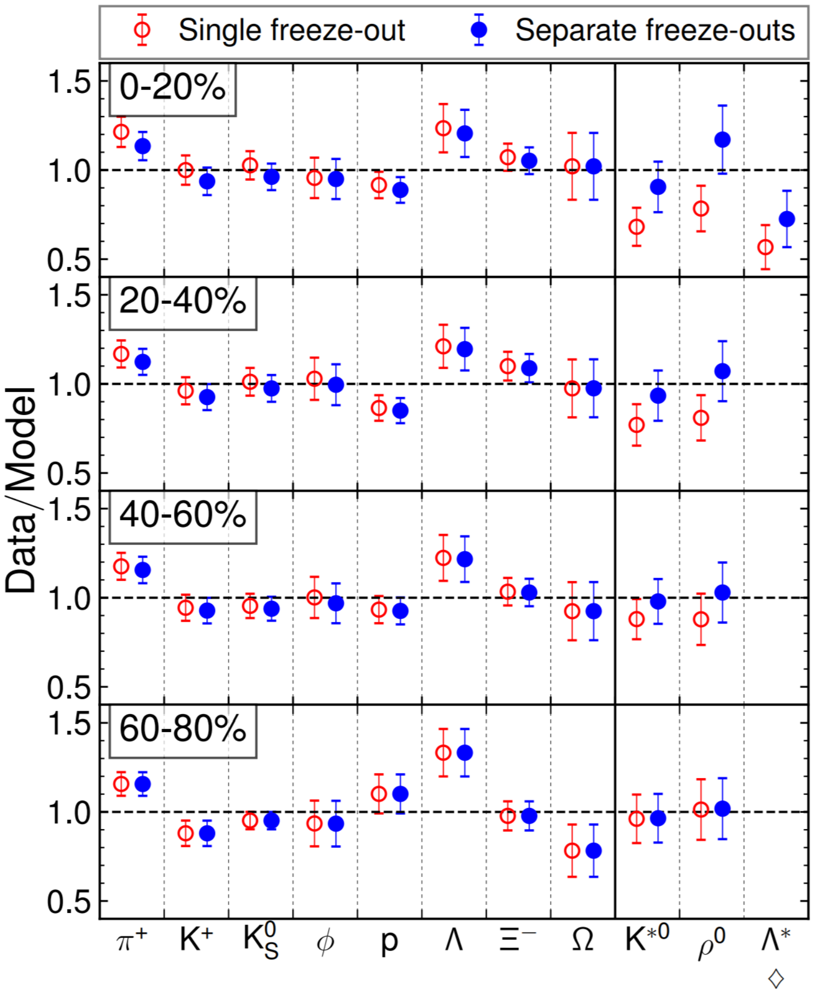


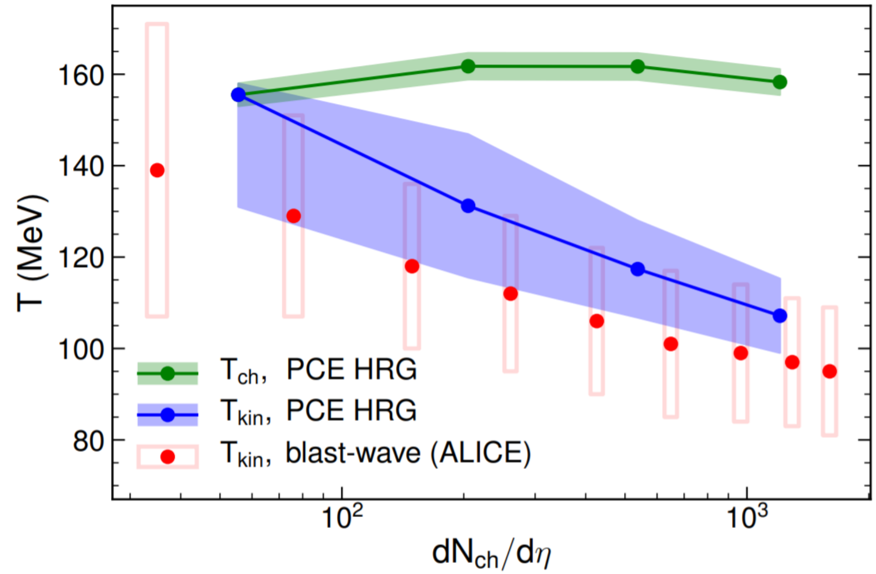
[Motornenko, **V.V.**, Greiner, Stoecker, 1908.11730]

Fitting the yields of short-lived resonances is a new way to extract the kinetic freeze-out temperature

Kinetic freeze-out temperature from resonances

Fit of K^{*0} and ρ^0 abundances extracts the kinetic freeze-out temperature





Centrality	$T_{\rm ch}$ (MeV)	$T_{\rm kin}$ (MeV)	χ^2/dof
0-20%	160.2 ± 3.1	–	23.6/8
	158.3 ± 2.8	107.1 ± 8.2	10.5/7
20-40%	162.9 ± 3.1	–	19.5/8
	161.7 ± 2.9	117.3 ± 10.8	12.8/7
40-60%	162.3 ± 3.0	–	12.5/8
	161.8 ± 2.9	131.2 ± 15.9	10.6/7
60-80%	155.5 ± 2.5	–	19.1/8
	155.5 ± 2.5	$155.5^{+2.5}_{-24.5}$	19.1/7

Solves the T_{kin}-*vs*-$\langle\beta_T\rangle$ anticorrelation problem of blast-wave fits