Recent results on light nuclei production in extended thermal model descriptions

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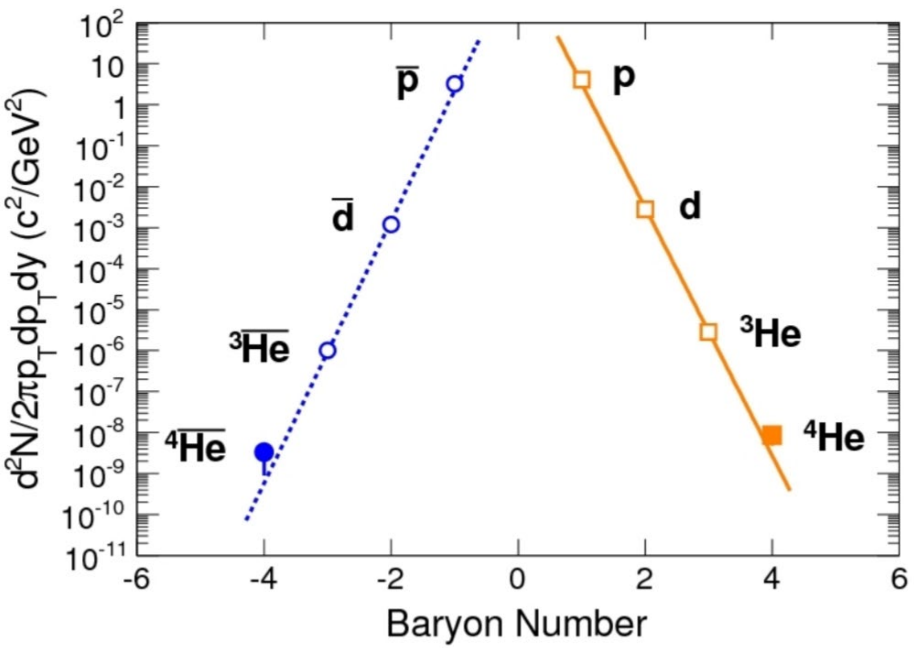
Outline

1. Short intro to thermal model and **Thermal-FIST**

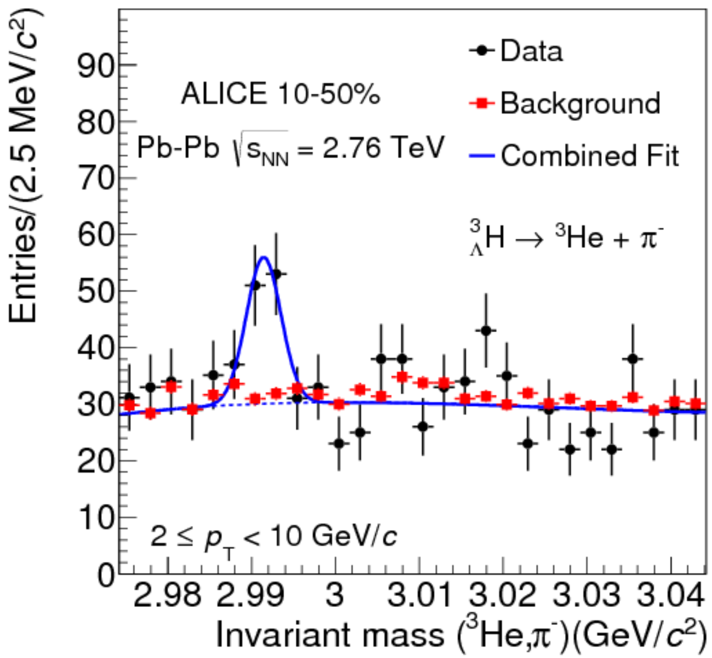
2. Light nuclei in extended thermal model descriptions
   - Canonical suppression
   - The Saha equation approach
   - Feeddown contributions from excited nuclear states

3. Summary

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"

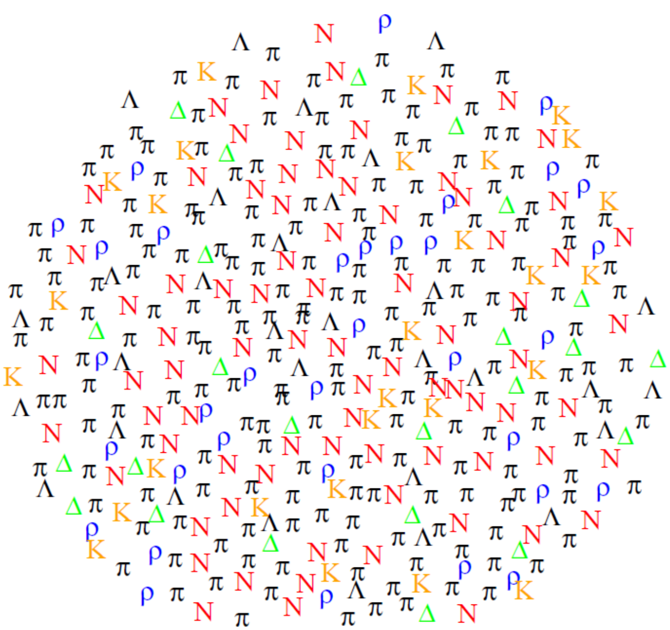
The production mechanism is not established. Common approaches include **thermal** nuclei emission together with hadrons [Andronic et al., PLB '11;...] or final-state **coalescence** of nucleons close in phase-space [Butler, Pearson, PRL '61; Scheibl, Heinz, PRC '99;...]

Hadron resonance gas (HRG) at freeze-out

HRG: Equation of state of hadronic matter as a multi-component (non-)interacting gas of known hadrons, resonances, and *light nuclei*

$$\ln Z \approx \sum_{i\in M,B} \ln Z_i^{id} = \sum_{i\in M,B} \frac{d_i V}{2\pi^2} \int_0^\infty \pm p^2 dp \ln\left[1 \pm \exp\left(\frac{\mu_i - E_i}{T}\right)\right]$$

Grand-canonical ensemble: $\mu_i = b_i \mu_B + q_i \mu_Q + s_i \mu_S$ ***chemical equilibrium***



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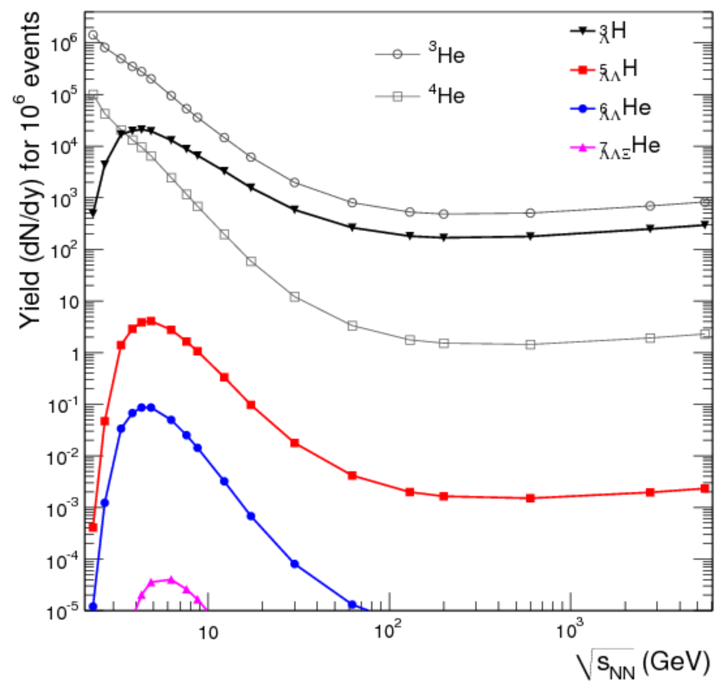


[A. Andronic et al., PLB '12]

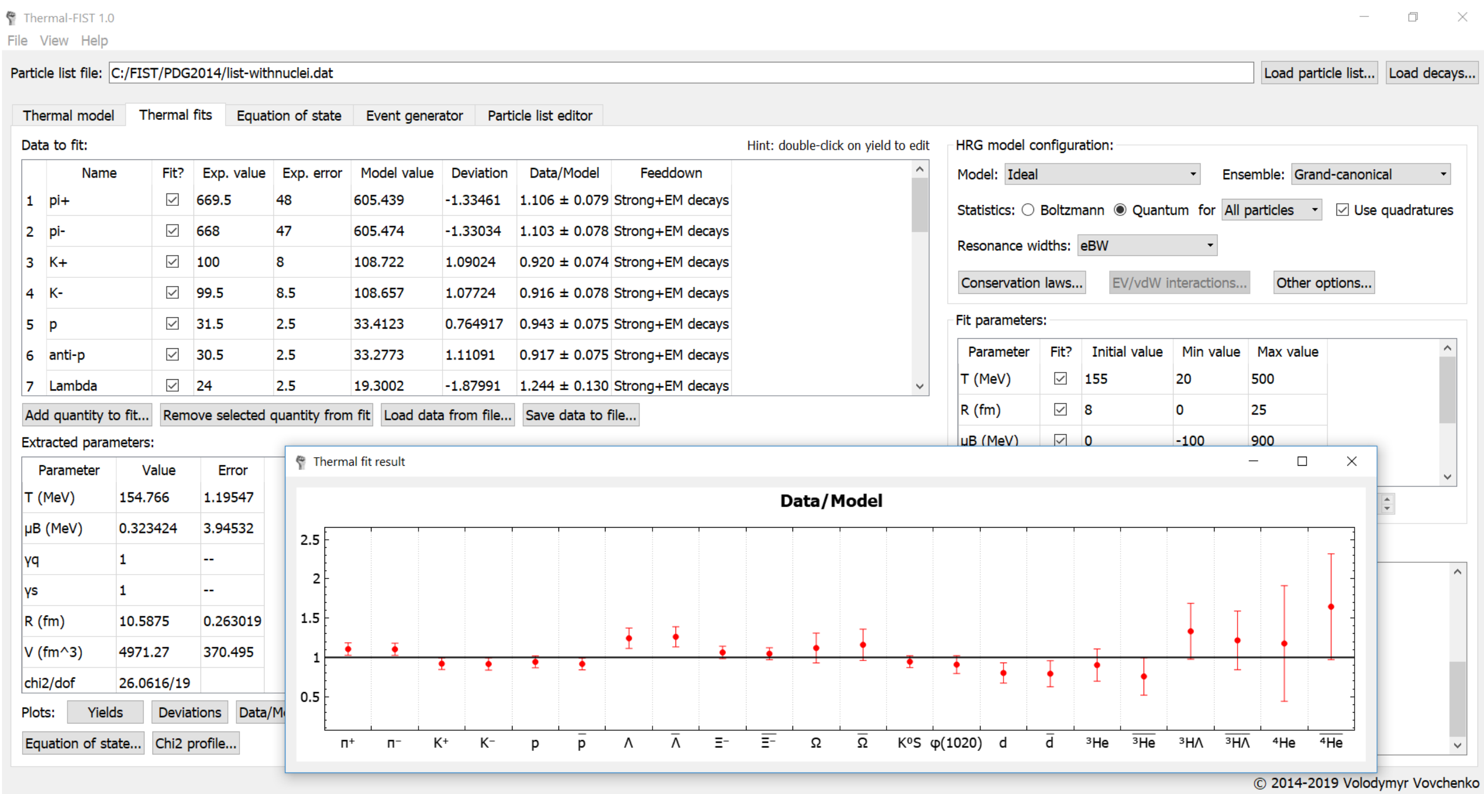
Thermal-FIST

Thermal-FIST* (a.k.a. **FIST** or **FAUST**)

C++/Qt/Jupyter

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

reference: **V.V.**, H. Stoecker, *Computer Physics Communications* ***244***, *295 (2019)*



A framework for general-purpose statistical-thermal model applications

*****_**T**hermal, **F**ast and **I**nteractive **S**tatistical **T**oolkit_

Using Thermal-FIST

The package is ***cross-platform*** (Linux, Mac, Windows, Android)
Installation using **git** and **cmake**

```
# Clone the repository from GitHub
git clone https://github.com/vlvovch/Thermal-FIST.git
cd Thermal-FIST

# Create a build directory, configure the project with cmake
# and build with make
mkdir build
cd build
cmake ../
make

# Run the GUI frontend
./bin/QtThermalFIST

# Run the test calculations from the paper
./bin/examples/cpc1HRGTDep
./bin/examples/cpc2chi2
./bin/examples/cpc3chi2NEQ
./bin/examples/cpc4mcHRG
```

GUI requires free Qt5 framework, the rest of the package has no external dependencies

Quick start guide *Documentation* *Physics manual*

Statistical-thermal model aspects in FIST

- Extensions of the HRG model
  - finite resonance widths
  - repulsive (excluded volume) and van der Waals (*criticality*) interactions
  - particle number fluctuations and correlations
  - chemical non-equilibrium (γ_q , γ_s) a la Rafelski
  - unstable nuclei
- Equation of state
- Canonical statistical model (CSM)
  - (local) (selective) exact conservation of conserved charges
  - canonical suppression of light nuclei
- Monte Carlo generator (Blast-wave, canonical ensemble,...)
- Hadronic phase and dynamical freeze-out
  - partial chemical equilibrium
  - suppression of resonance yields
  - evolution of light nuclei abundances via the Saha equation

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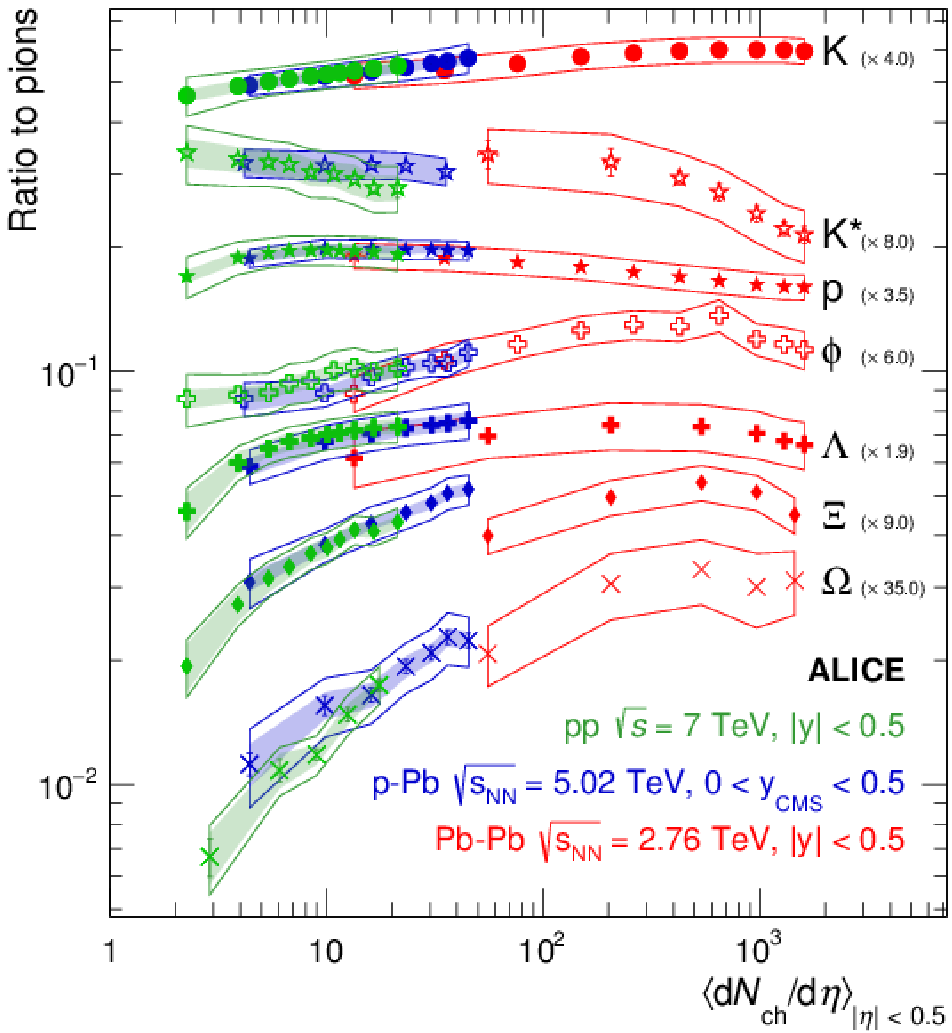
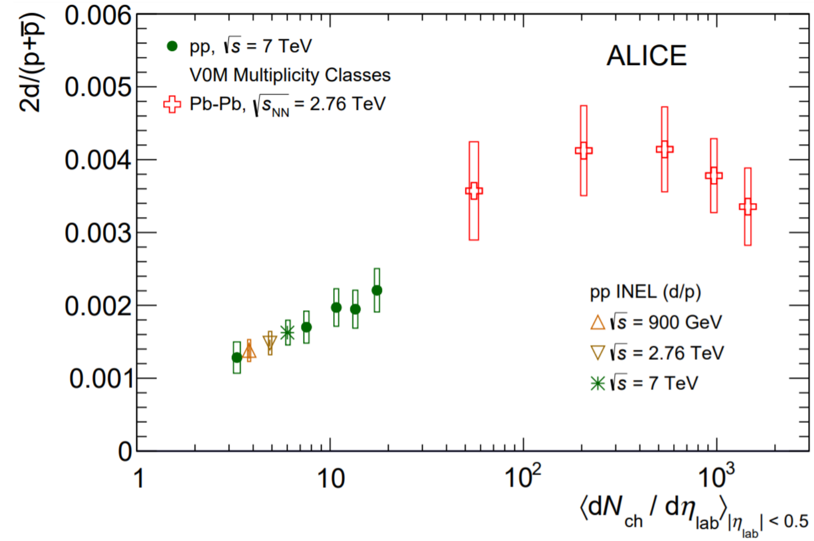
Canonical suppression of light nuclei at the LHC

V. Vovchenko, B. Doenigus, H. Stoecker, Phys. Lett. B 785, 171 (2018)
source code: https://github.com/vlvovch/CSM

Multiplicity dependence of hadrochemistry



[ALICE collaboration, 1807.11321]



[ALICE collaboration, 1902.09290]

- Grand-canonical thermal picture predicts no multiplicity dependence
- Apply **canonical** statistical model?

Canonical statistical model (CSM)

Exact conservation of B, Q, S in a correlation volume V_C

[Rafelski, Danos, et al., PLB '80; Hagedorn, Redlich, ZPC '85]

$$\mathcal{Z}(B,Q,S) = \int_{-\pi}^{\pi} \frac{d\phi_B}{2\pi} \int_{-\pi}^{\pi} \frac{d\phi_Q}{2\pi} \int_{-\pi}^{\pi} \frac{d\phi_S}{2\pi} \, e^{-i\,(B\phi_B + Q\phi_Q + S\phi_S)} \, \exp\left[\sum_j z_j^1 \, e^{i\,(B_j\phi_B + Q_j\phi_Q + S_j\phi_S)}\right]$$

$$z_j^1 = V_c \int dm \, \rho_j(m) \, d_j \frac{m^2 T}{2\pi^2} K_2(m/T) \qquad \langle N_j^{\rm prim} \rangle^{\rm ce} = \frac{Z(B-B_j, Q-Q_j, S-S_j)}{Z(B,Q,S)} \langle N_j^{\rm prim} \rangle^{\rm gce}$$

[Becattini et al., ZPC '95, ZPC '97]

Implemented in Thermal-FIST for a full HRG

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Net-proton fluctuations affected by baryon number conservation

[Bzdak, Koch, Skokov, 1203.4529; Braun-Munzinger, Rustamov, Stachel, 1612.00702]

$$\frac{\kappa_2(\mathrm{p}-\bar{\mathrm{p}})}{\langle \mathrm{p} \rangle + \langle \bar{\mathrm{p}} \rangle} \simeq 1 - \frac{\langle \mathrm{p} \rangle}{k \, dN_B/dy}$$

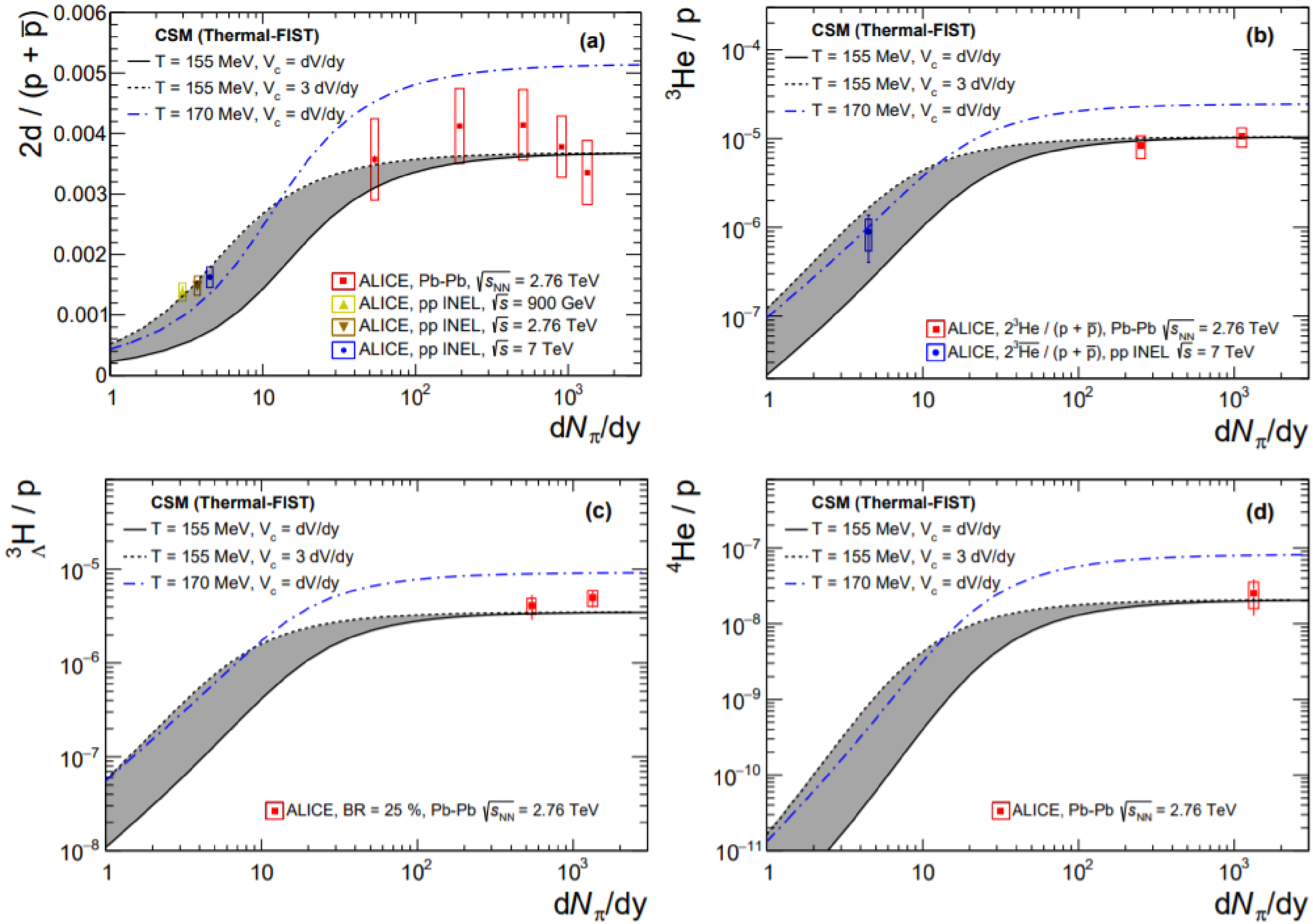
Using ALICE data for net-p fluctuations [1910.14396] one obtains $k \sim 3$-4 for most of the centrality bins in Pb-Pb collisions

[**V.V.**, Dönigus, Stoecker, 1906.03145, PRC '19]

“Vanilla” CSM

$T_{ch} = 155$ MeV, $V_C = 3dV/dy$, multiplicity dependence driven by V_C only

[**V.V.**, Dönigus, Stoecker, 1808.05245, PLB ‘18]



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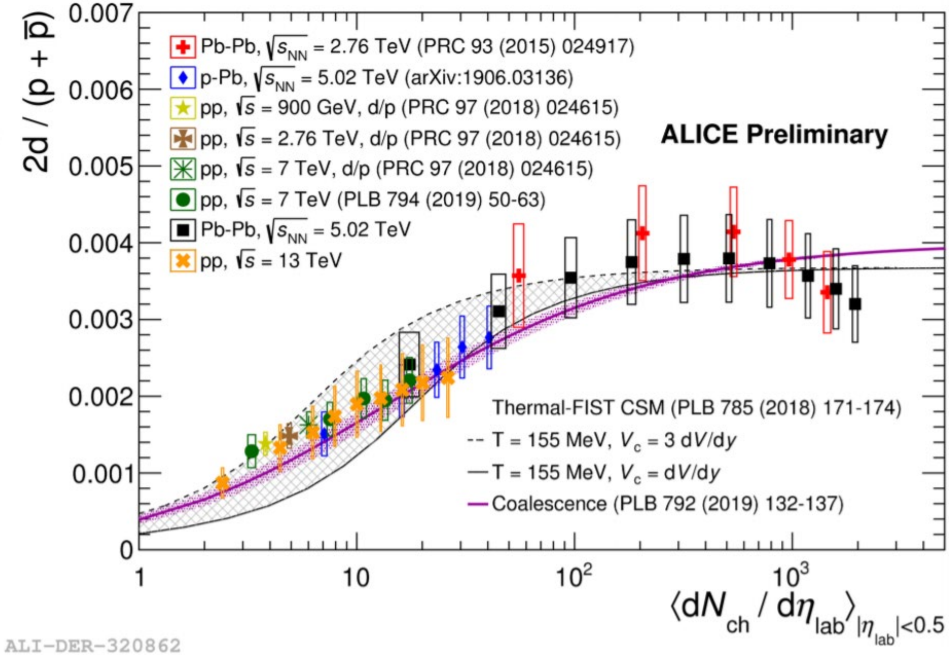
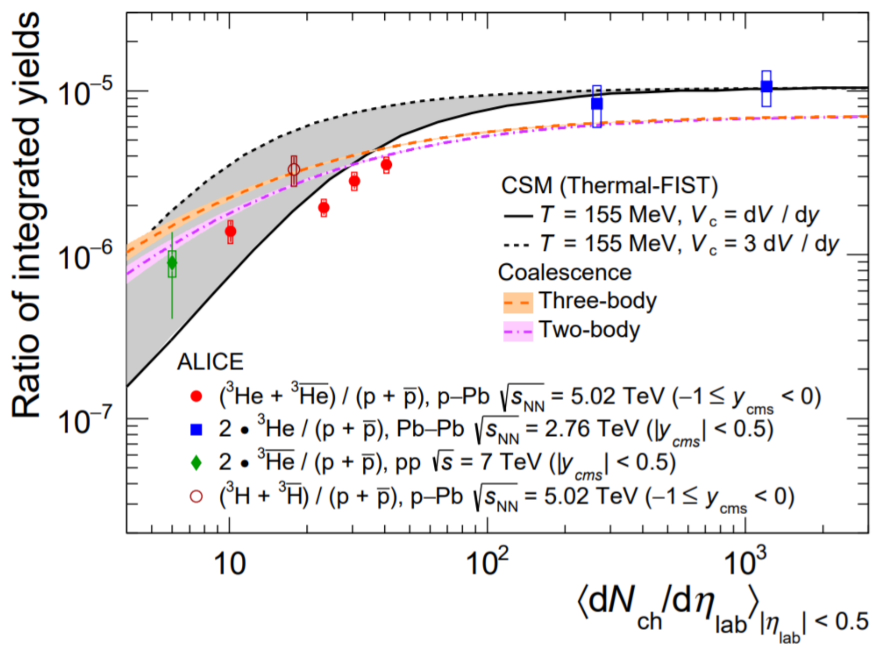


[L. Barioglio, QM19]



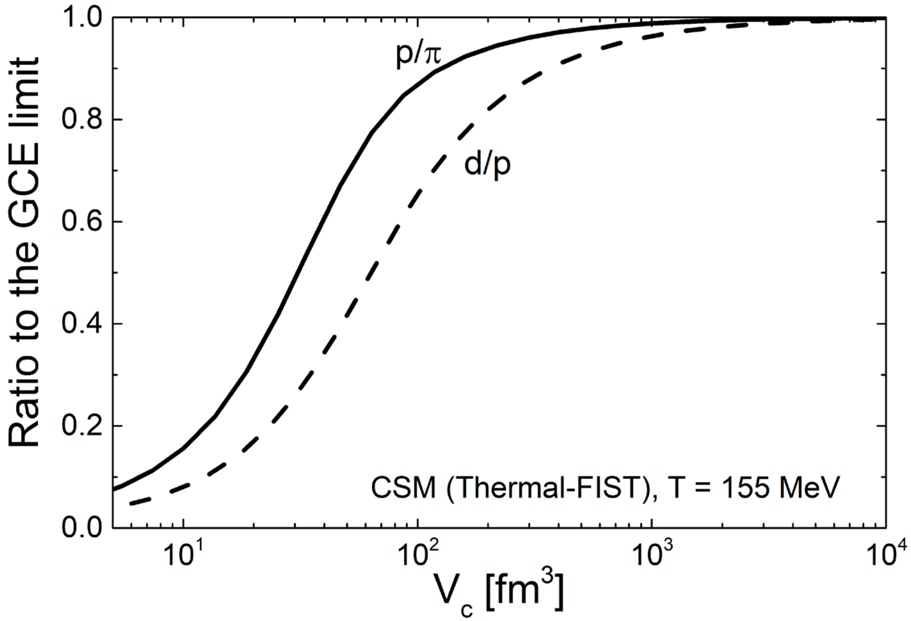
[ALICE collaboration, 1910.14401]

Basic CSM appears to capture trends seen in light nuclei production data

"Vanilla" CSM: nuclei vs p/π ratio

Canonical suppression affects not only nuclei, but also the p/π ratio

The effect for p/π is generally milder than d/p, but not insignificant



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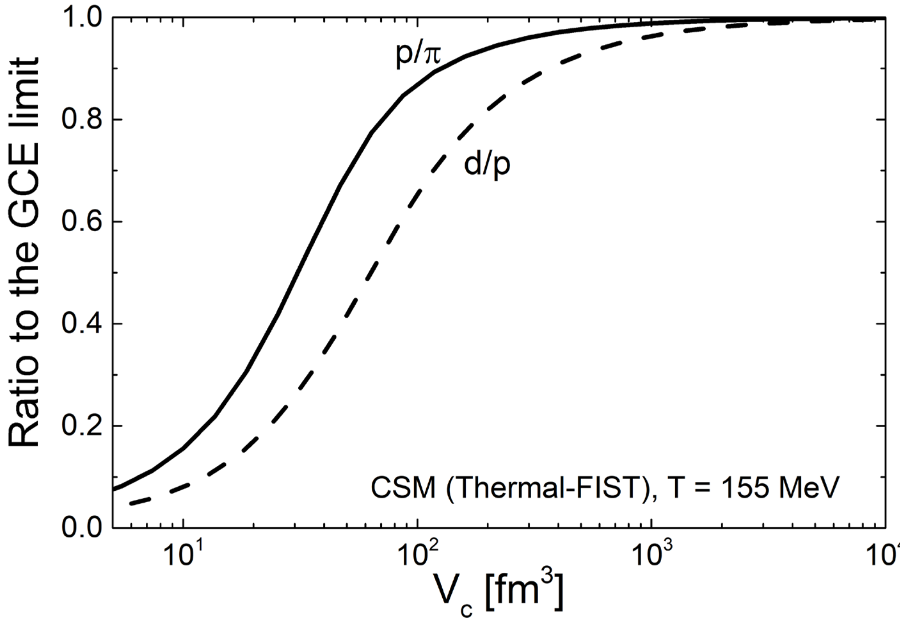
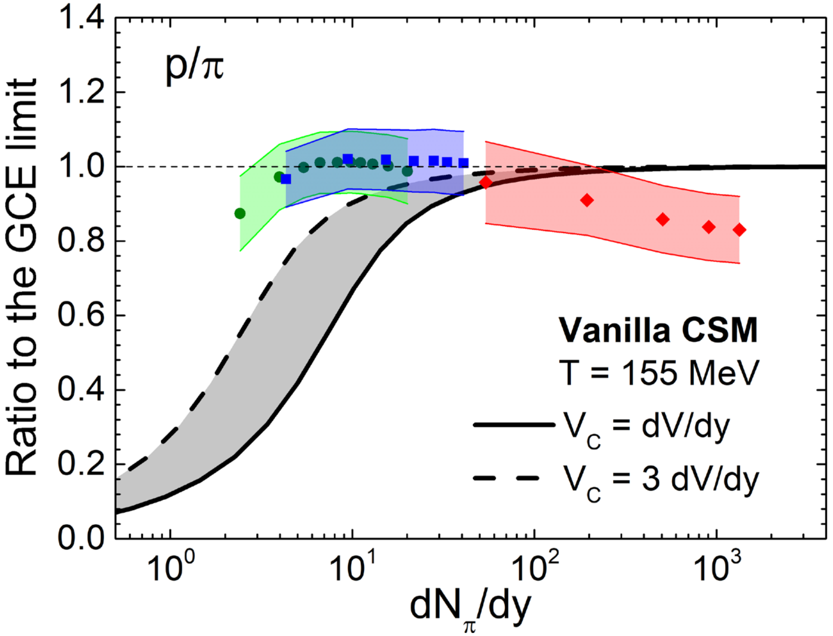




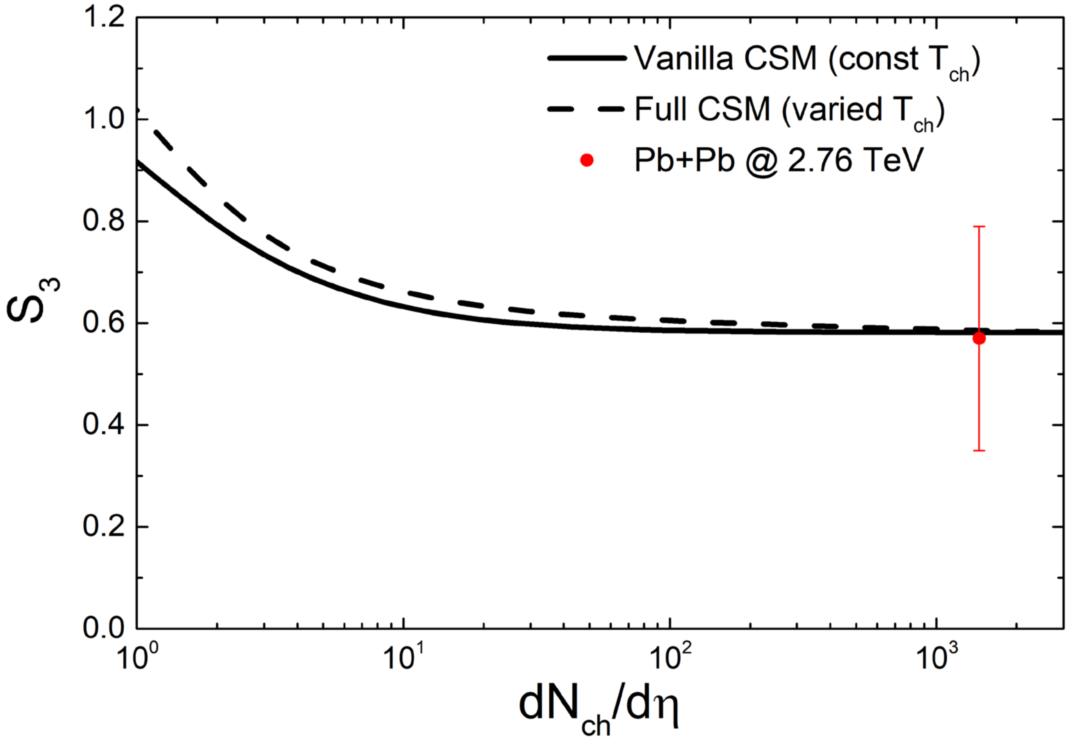
p/π suppression predicted by vanilla CSM not supported by the data

Simultaneous description of light nuclei and p/π ratio remains challenging

CSM: S_3

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

[E864 collab., PRC '04; Zhang et al., PLB '10]



Different versions of CSM give similar predictions, mild increase of S_3 due to baryon and strangeness conservation

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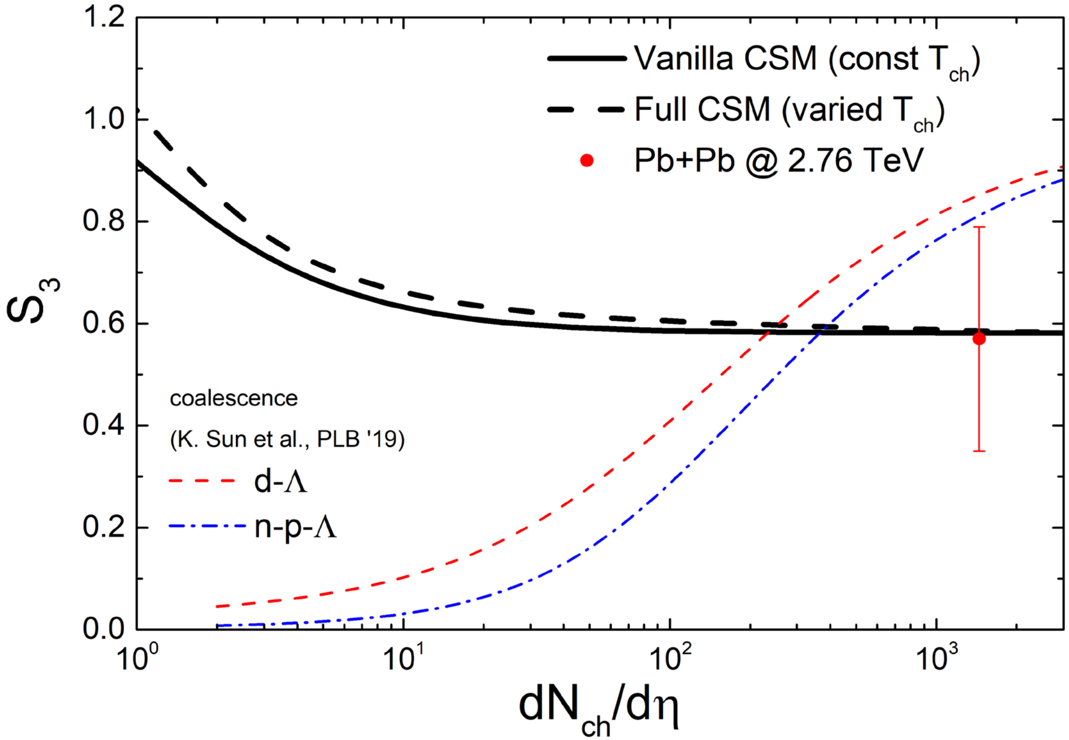

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Coalescence [Sun, Dönigus, Ko, PLB '19] predicts opposite trend

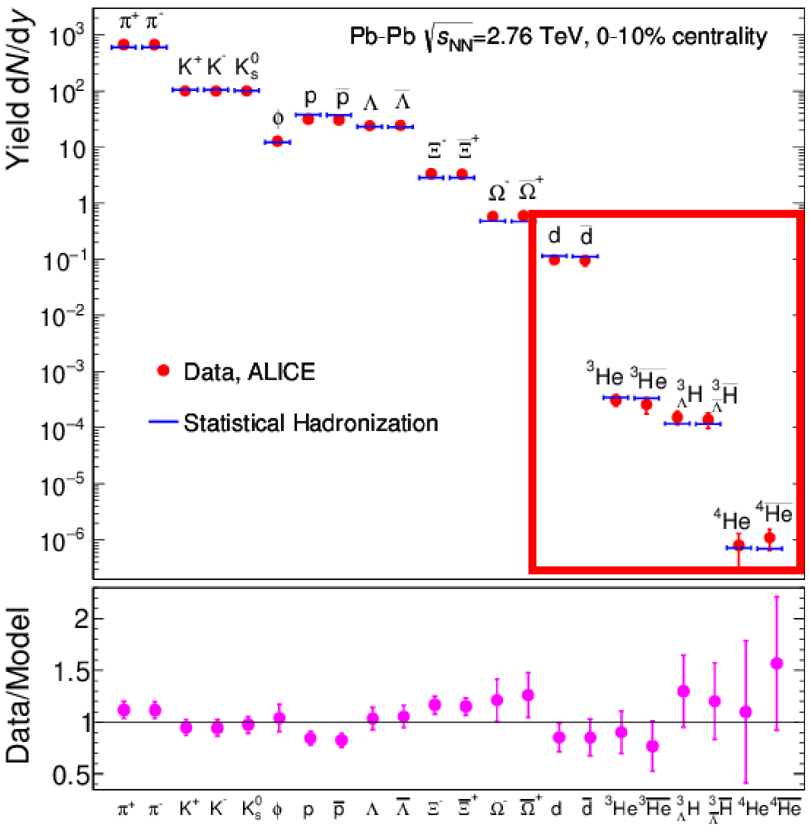
Hadronic phase and the Saha equation approach to light nuclei production

V.V., *K. Gallmeister, J. Schaffner-Bielich, C. Greiner,* *Phys. Lett. B* ***800,*** *135131 (2020)*

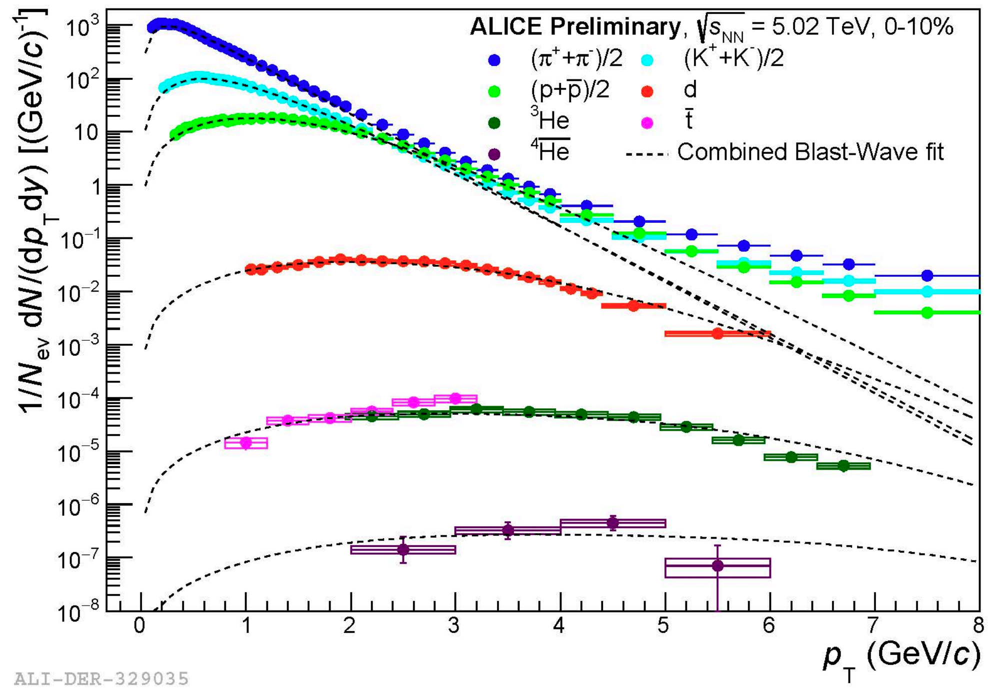
Two experimental observations at the LHC

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

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



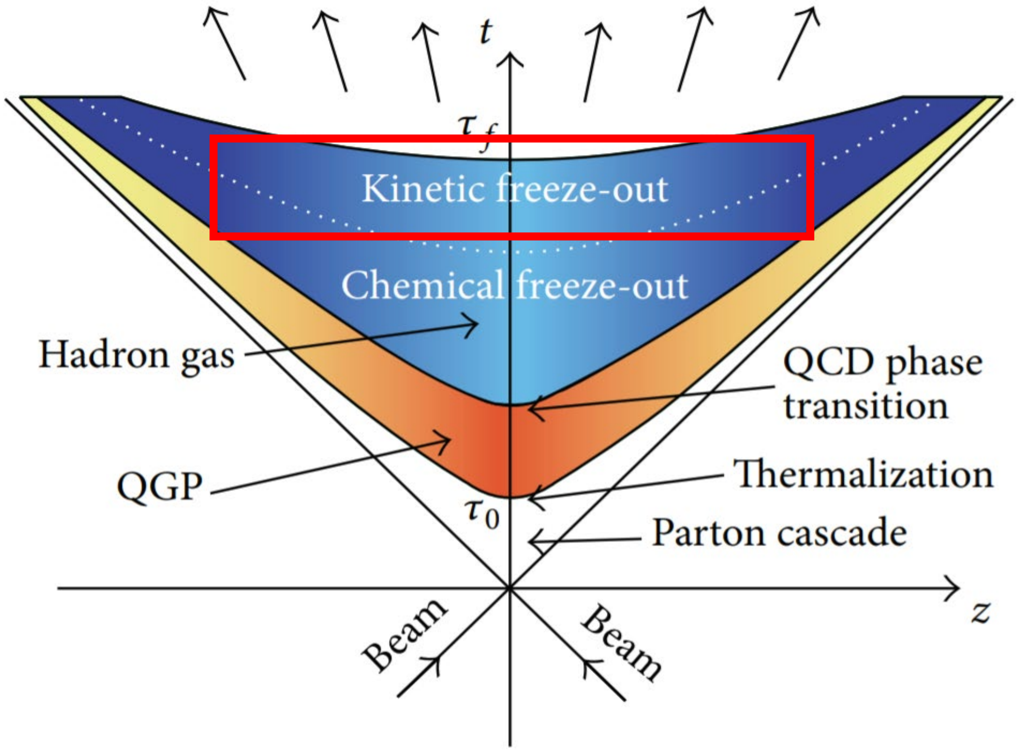
[A. Andronic et al., Nature **561**, 321 (2018)]



[E. Bartsch (ALICE Collaboration), QM2019]

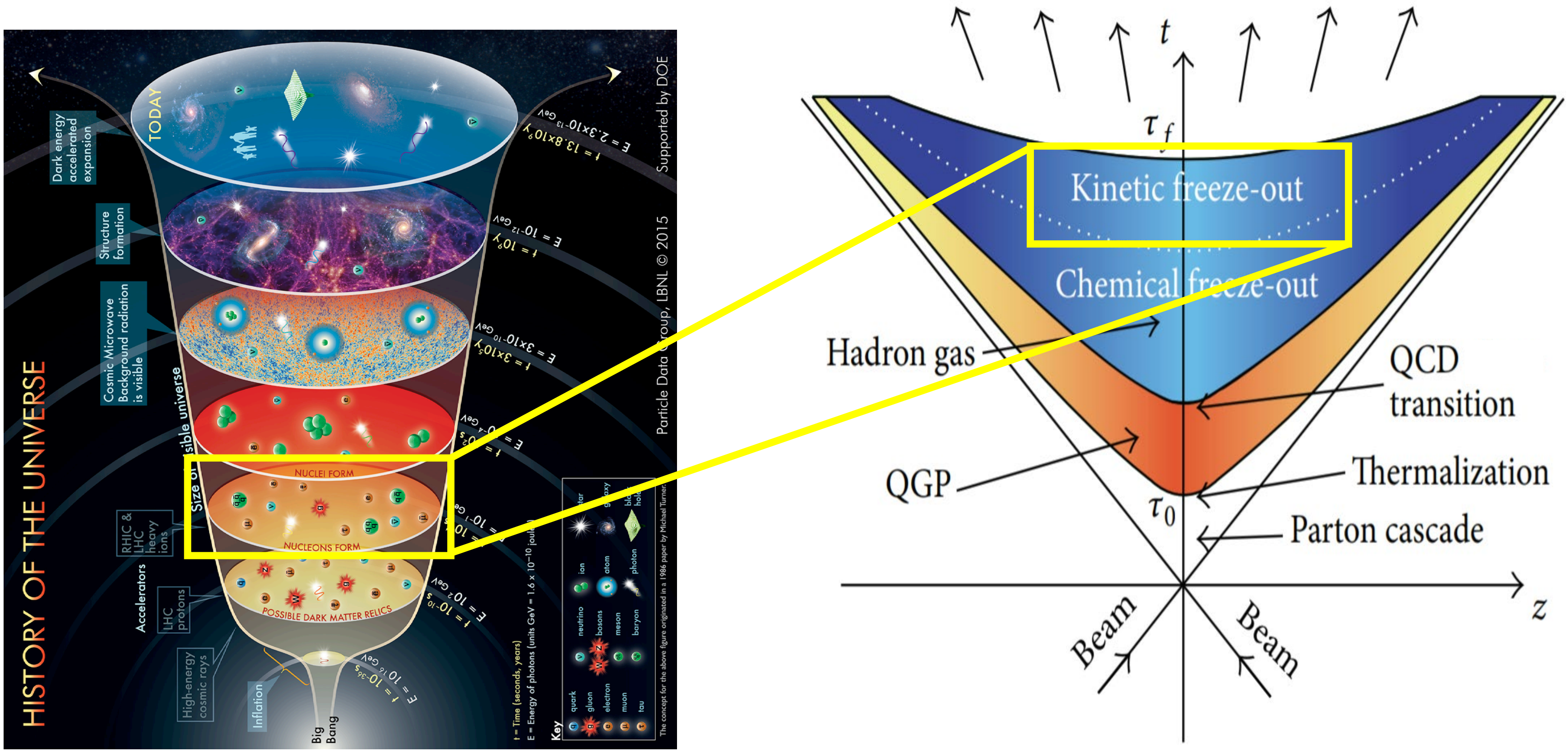
What happens between $T_{\rm ch}$ and $T_{\rm kin}$?

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

- Equivalently, chemical potentials: $\mu_0 = \mu_1 + \mu_e$

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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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small ***big*** ***big***

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small ***big*** ***big***

gain ≈ loss → $\mu_d \approx \mu_p + \mu_n$

Saha equation
= detailed balance
= law of mass action

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

Effective chemical potentials:

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

Conservation laws:

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

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

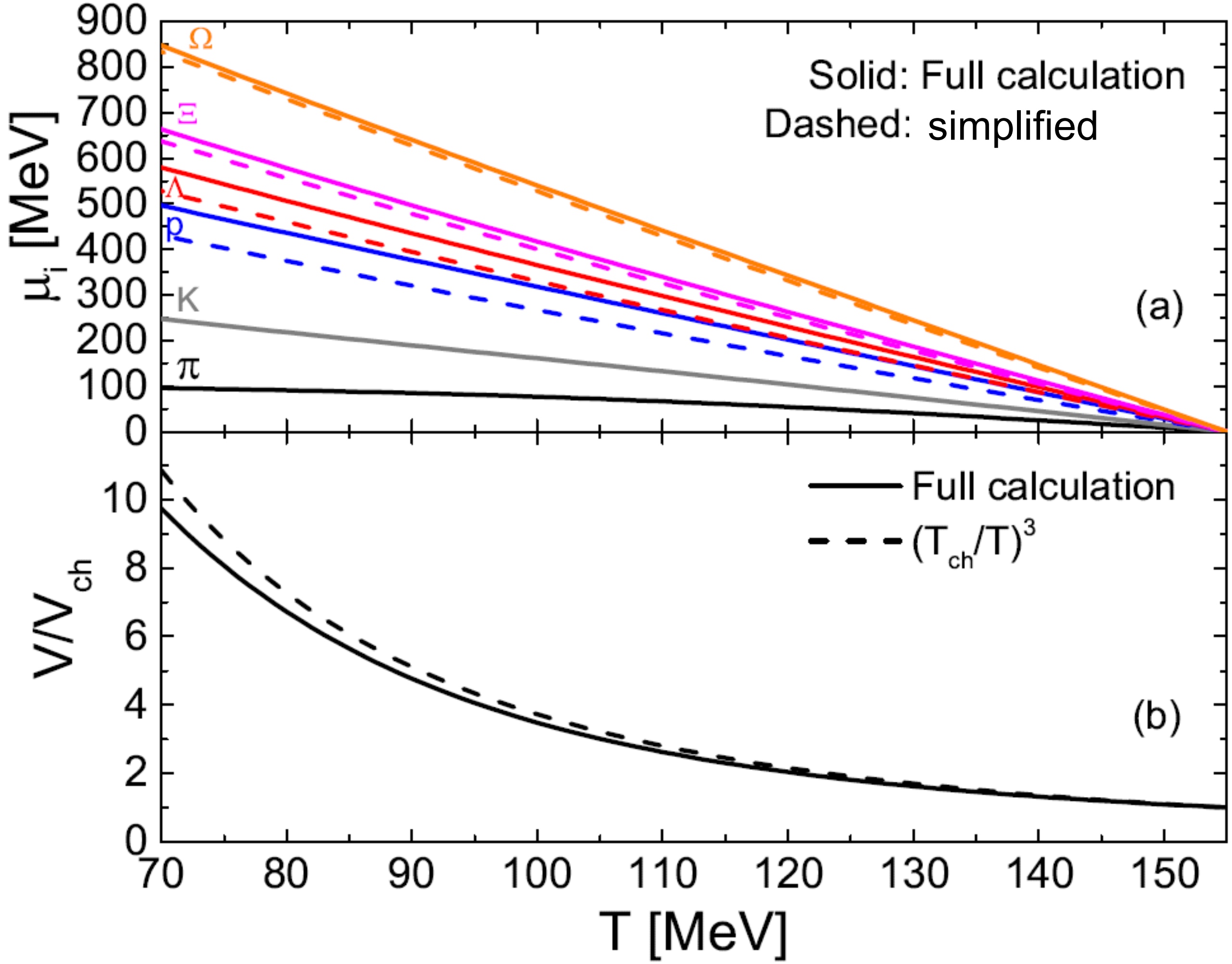
numerical solution → $\{\mu_i(T)\}, V(T)$

Numerical implementation of PCE in **Thermal-FIST**

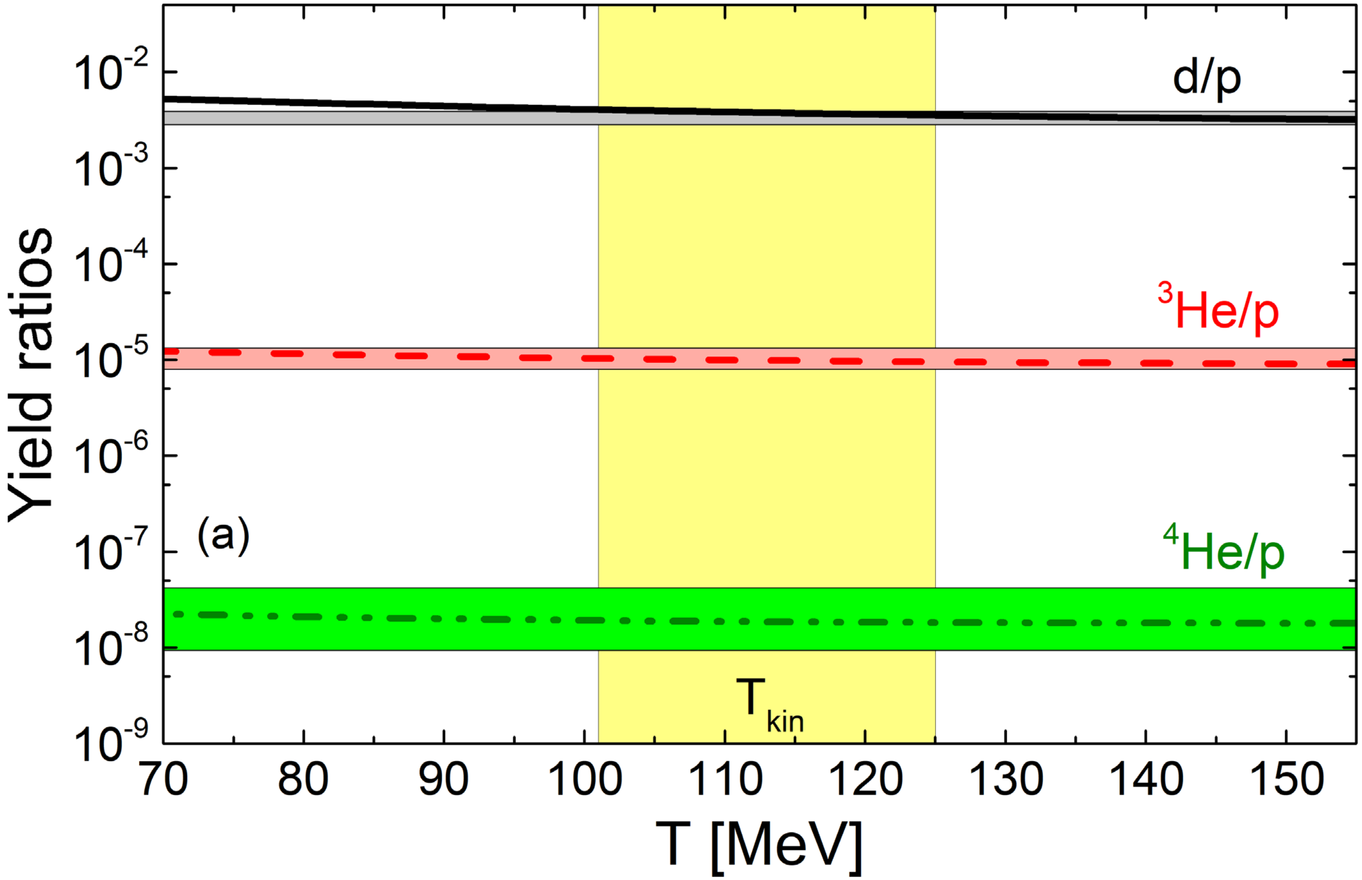
Full calculation: parameters

"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

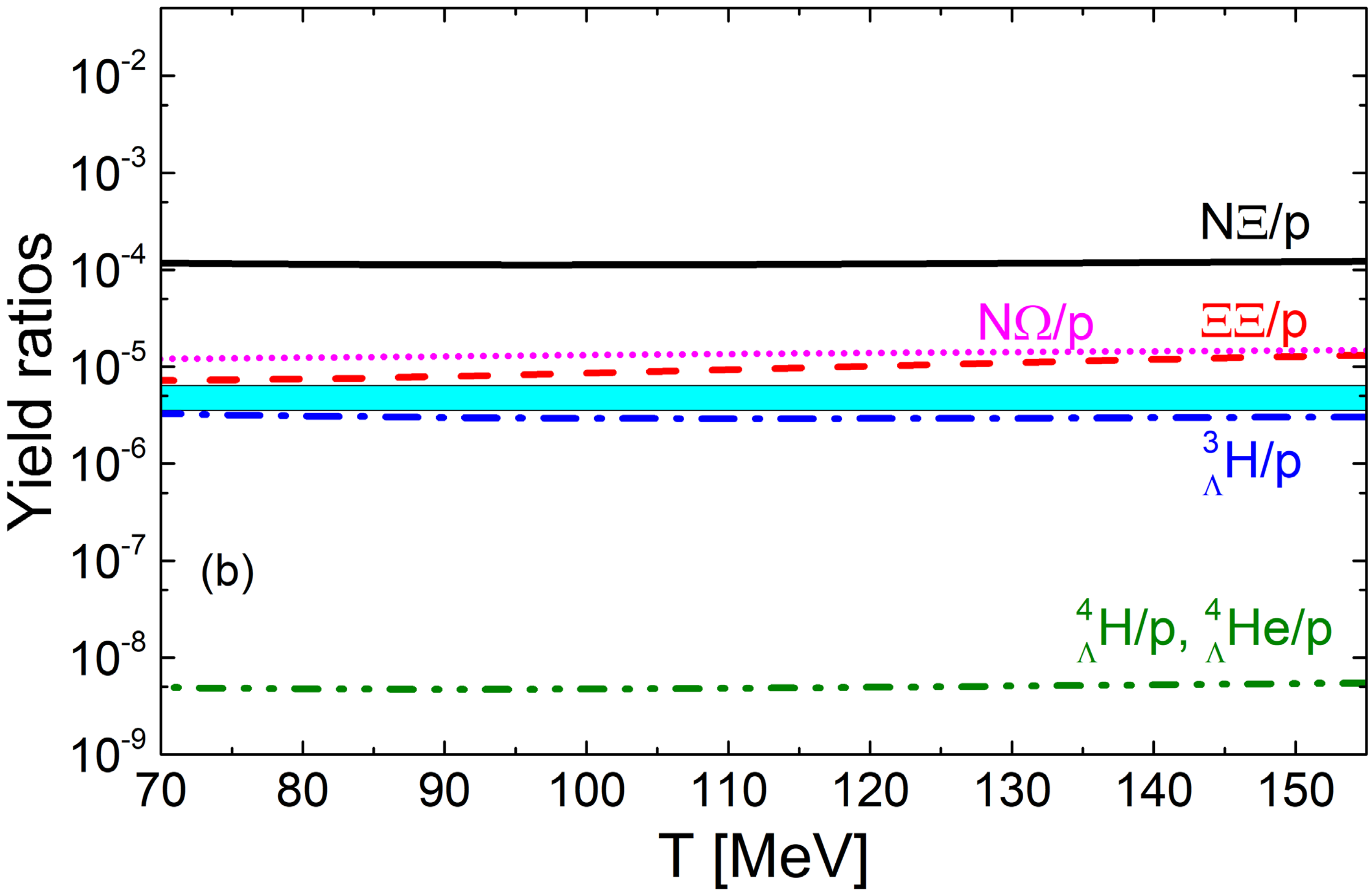


Deviations from thermal model predictions are moderate despite significant cooling and dilution. Is this the reason for why thermal model works so well?

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)]

Saha equation: hypernuclei

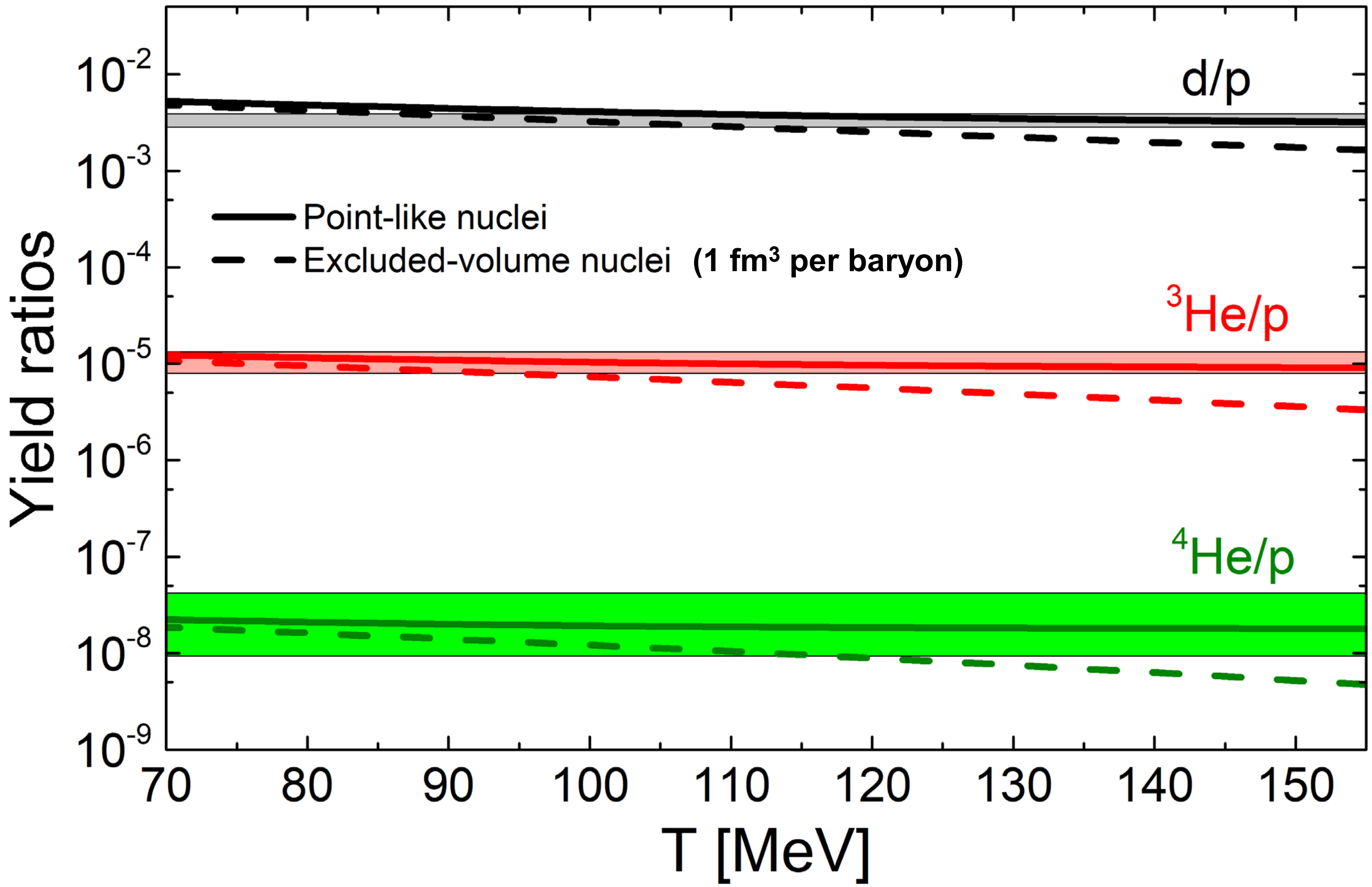


Hypernuclei stay close to the thermal model prediction. An exception is a hypothetical ΞΞ state ← *planned measurement in Runs 3 & 4 at the LHC*

[LHC Yellow Report, 1812.06772]

Saha equation and excluded volume effects

Eigenvolumes: effective mechanism for nuclei suppression at large densities



Excluded-volume effects go away as the system dilutes.

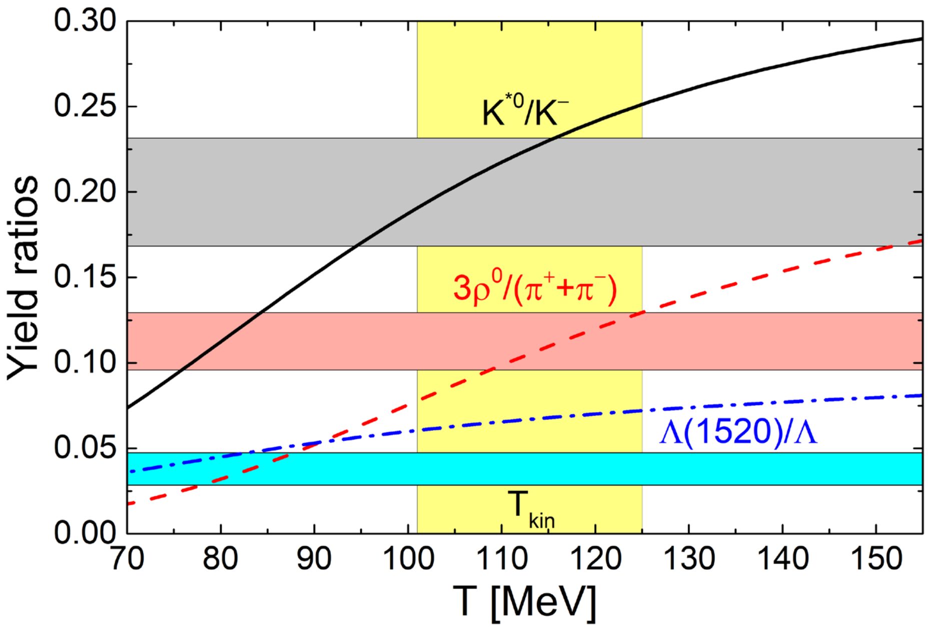
At $T \cong 100$ MeV agrees with the point-particle model and describes data.

At $T = T_{ch}$ does not describe data

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 $\pi K \leftrightarrow K^*$



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

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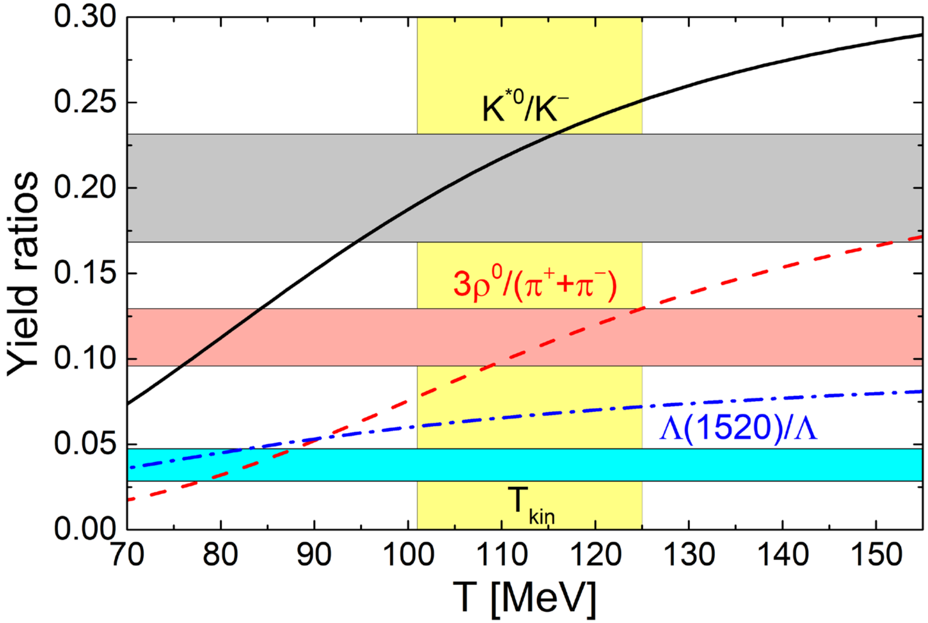

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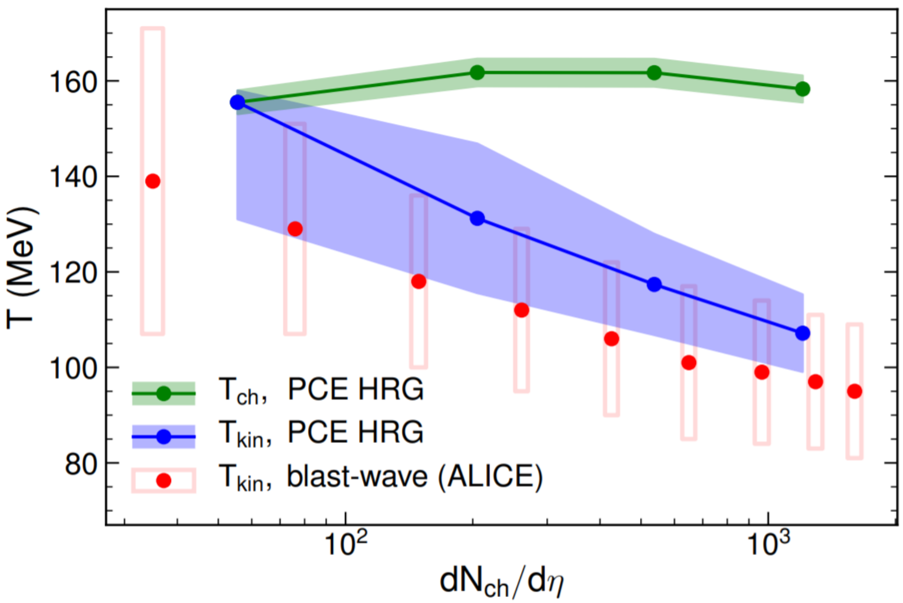


[Motornenko, **V.V.**, Greiner, Stoecker, 1908.11730]

Suppressed resonance yields are consistent with existence of hadronic phase

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

Saha equation vs rate equations

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

Saha equation vs rate equations

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

gain **loss**

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

small ***big*** ***big***

Saha equation

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

= law of mass action

Saha equation vs rate equations

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

gain **loss**

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

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

~~**Saha equation**~~

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

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

Saha equation vs 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

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

Static fireball: $n_\pi^{\rm pce}, N_A^{\rm saha}, \langle \sigma^{\rm in}_{A\pi} v_{rel} \rangle = const$

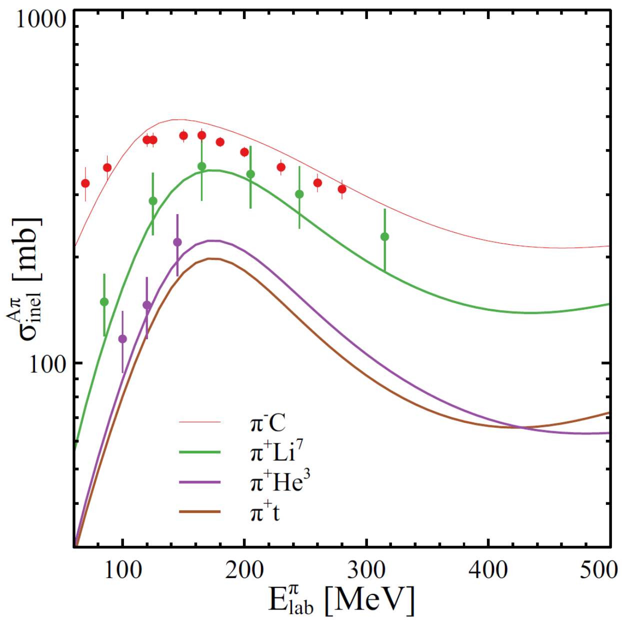
$$N_A(\tau) = N_A^{\rm saha} + \left(N_A(\tau_0) - N_A^{\rm saha} \right) e^{-\frac{\tau - \tau_0}{\tau_{\rm eq}}}, \qquad \tau_{\rm eq} = \frac{1}{\langle \sigma^{\rm in}_{A\pi} v_{\rm rel} \rangle \, n_\pi^{\rm pce}}$$

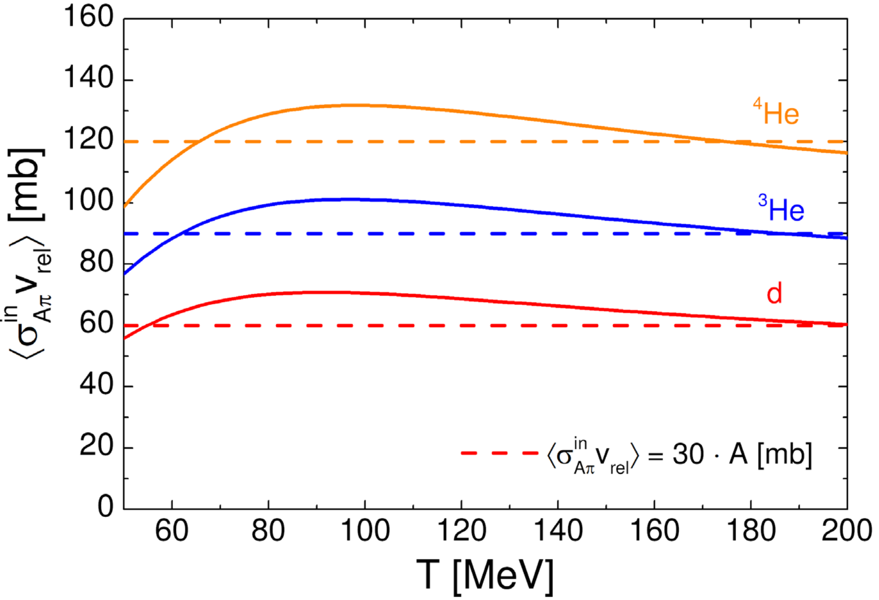
Saha limit: $\tau_{eq} \to 0$ $(\sigma^{\rm in}_{A\pi} \to \infty)$

Model input

- **Cross sections**

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





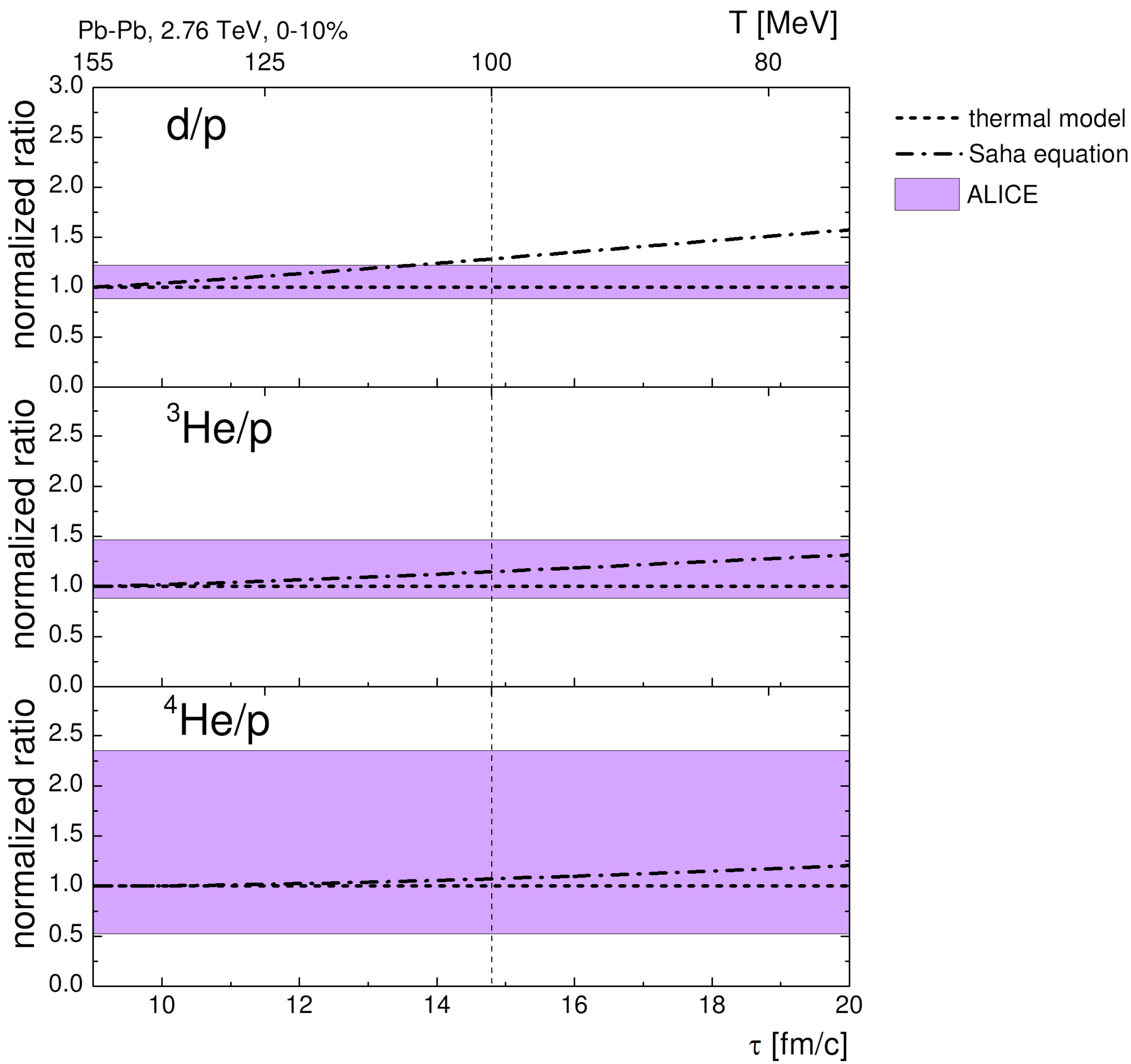
Being implemented in SMASH [D. Oliinychenko]

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

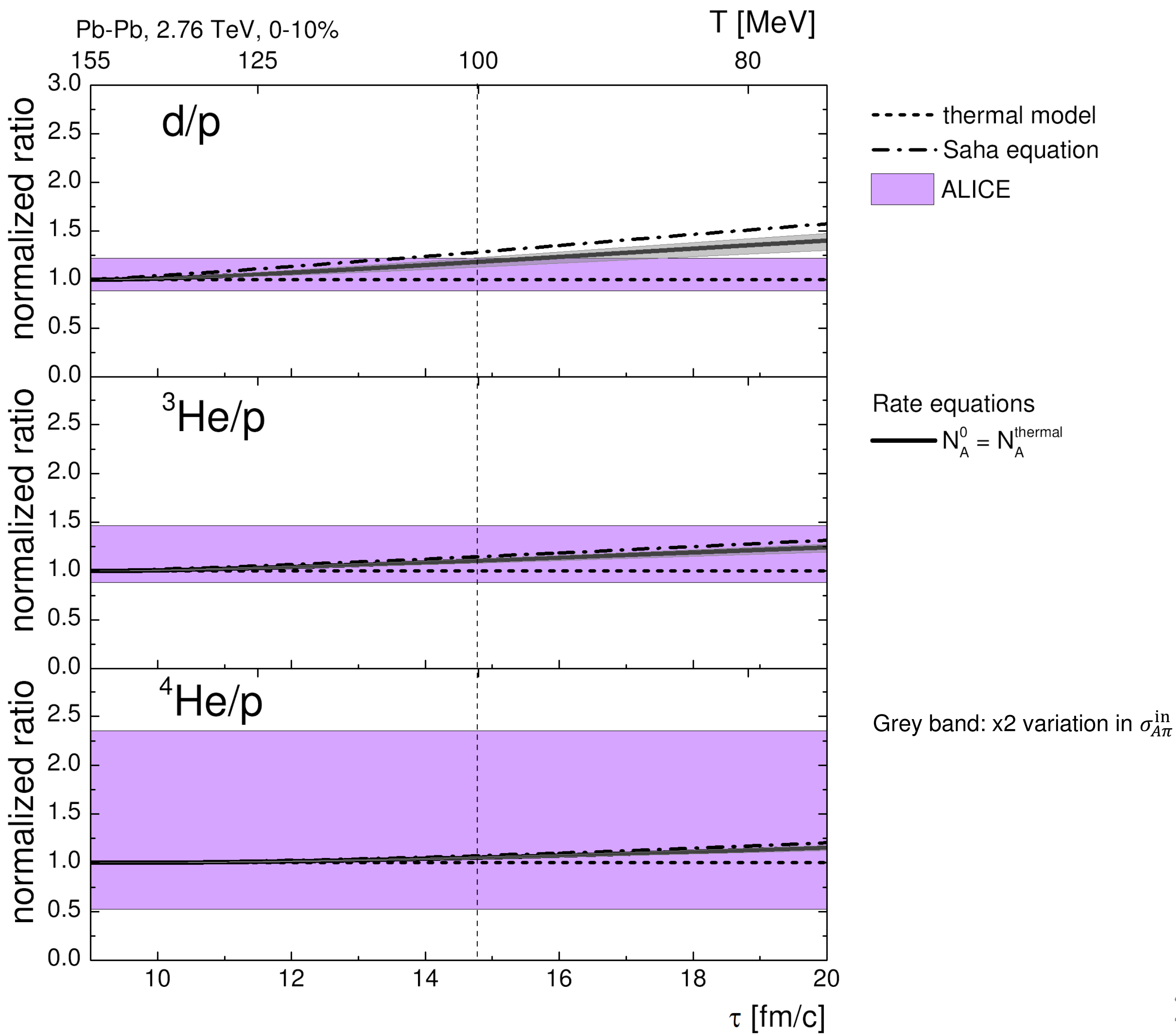
$$\frac{V}{V_{\text{ch}}} = \frac{\tau}{\tau_{\text{ch}}} \frac{\tau_\perp^2 + \tau^2}{\tau_\perp^2 + \tau_{\text{ch}}^2}, \qquad \tau_{\text{ch}} = 9 \text{ fm}, \qquad \tau_\perp = 6.5 \text{ fm}$$

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

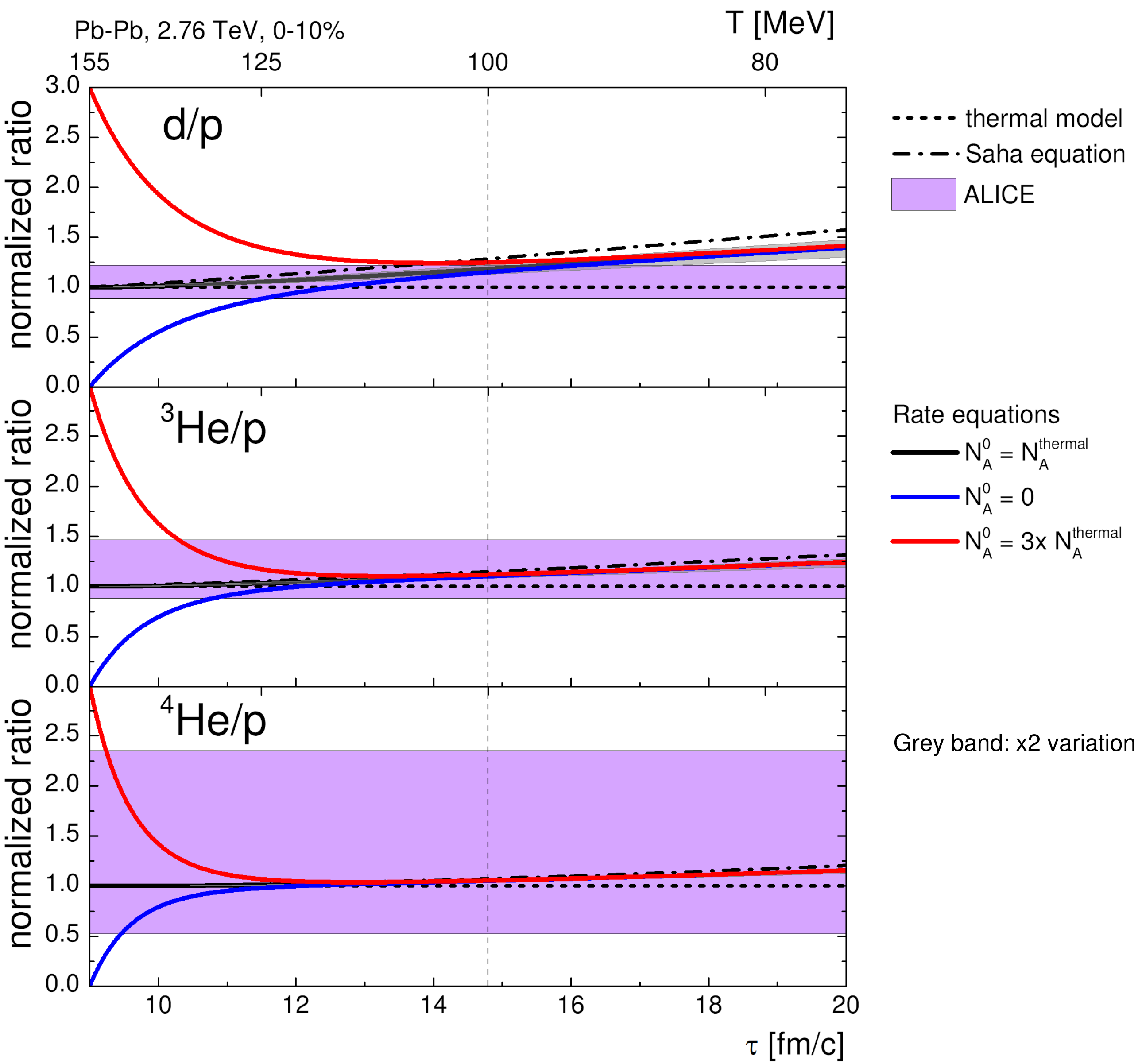
Rate equations at LHC



Rate equations at LHC



Rate equations at LHC



Grey band: x2 variation in $\sigma_{A\pi}^{in}$

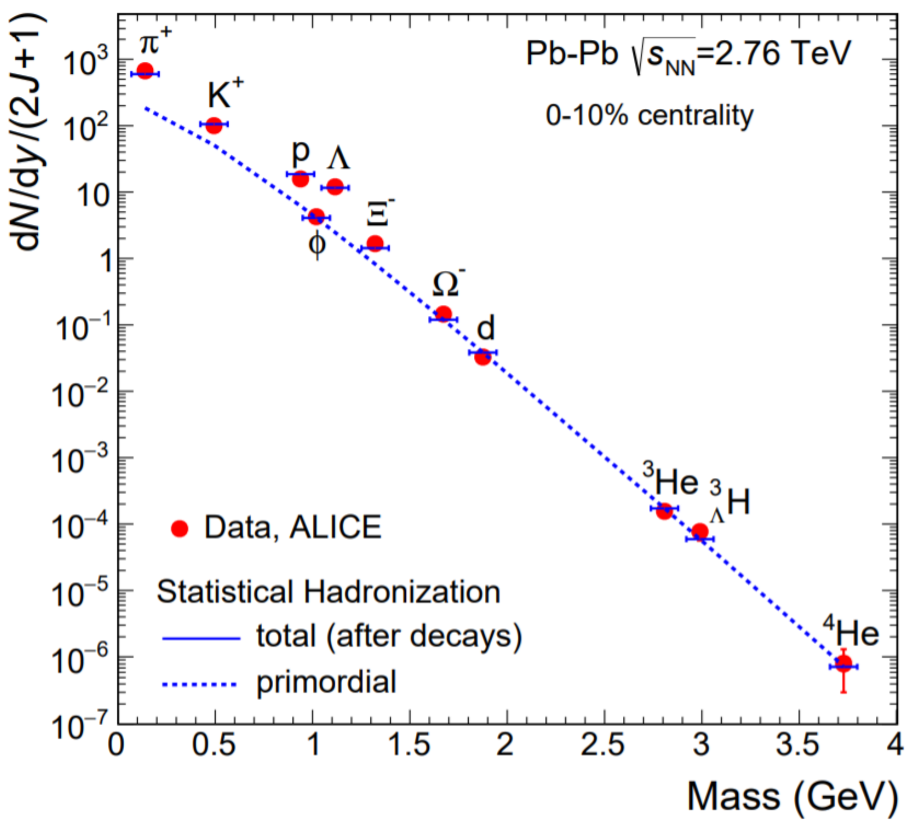
Feeddown contributions from decays of unstable nuclei

V.V., *B. Dönigus, B. Kardan, M. Lorenz, H. Stoecker,* *arXiv:2004.04411*

Feeddown in thermal model

Is well-known to be important for hadron yields

$$N_i^{\text{tot}} = N_i^{\text{prim}} + \sum_j BR(j \to i) N_j^{\text{prim}}$$



[Andronic et al., Nature (2018)]

Production of p

$T = 155$ MeV

Primordial density = 0.0028648 fm^{-3}

Primordial yield = 11.4594

Total yield = 31.4347

Primordial + strong decays = 31.4347

Primordial + strong + EM decays = 31.4347

Primordial + strong + EM + weak decays = 48.5857

Source	Multiplicity	Fraction (%)
Primordial	11.4594	36.4545
Decays from primordial Delta(1232)++	4.86466	15.4755
Decays from primordial Delta(1232)+	3.24327	10.3175
Decays from primordial Delta(1232)0	1.62139	5.15797
Decays from primordial N(1520)0	0.5628	1.79038
Decays from primordial Delta(1600)++	0.540859	1.72058
Decays from primordial N(1520)+	0.436374	1.38819
Decays from primordial N(1440)0	0.412215	1.31134
Decays from primordial Delta(1600)+	0.3931	1.25053
Decays from primordial N(1440)+	0.367071	1.16773
Decays from primordial N(1675)+	0.362324	1.15263
Decays from primordial N(1680)0	0.352206	1.12044

[**V.V.**, Stoecker, CPC (2019)]

Feeddown to yields of light nuclei seldom considered in HICs

Feeddown from excited nuclei

^{4}He

E_x (MeV)	J^π	Decay
g.s.	0^+	
20.21	0^+	p
21.01	0^-	p, n
21.84	2^-	p, n
23.33	2^-	p, n
23.64	1^-	p, n, (γ)
24.25	1^-	p, n, d
25.28	0^-	p, n
25.95	1^-	p, n, γ
27.42	2^+	p, n, d
28.31	1^+	p, n, d
28.37	1^-	(p, n), d
28.39	2^-	(p, n), d
28.64	0^-	d
28.67	2^+	d, γ
29.89	2^+	(p, n), d

^{4}H

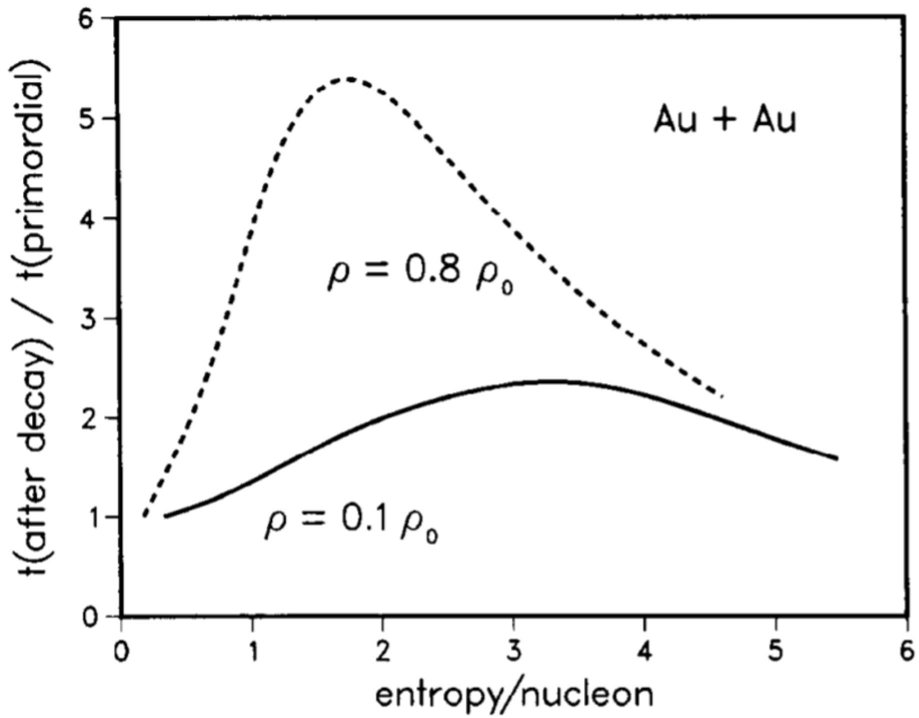
E_x (MeV)	J^π	Decay
g.s. [a]	2^-	n, ^{3}H
0.31	1^-	n, ^{3}H
2.08	0^-	n, ^{3}H
2.83	1^-	n, ^{3}H

^{4}Li

E_x (MeV)	J^π	Decay
g.s. [a]	2^-	p, ^{3}He
0.32	1^-	p, ^{3}He
2.08	0^-	p, ^{3}He
2.85	1^-	p, ^{3}He

[Tilley, Weller, Hale, NPA '92]

See also https://www.nndc.bnl.gov/



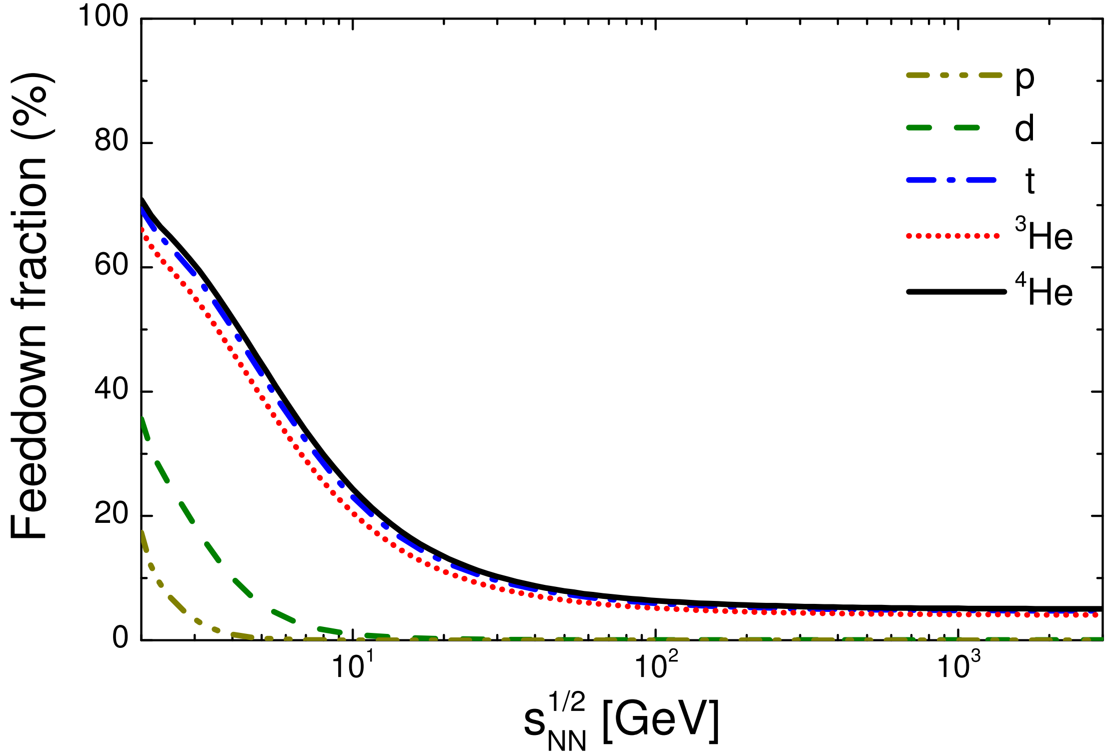
[Hahn, Stöcker, NPA '88]

In what follows feeddown from known $A = 4$ and significant $A = 5$ unstable nuclei included. Nuclei are modeled as point particles.

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

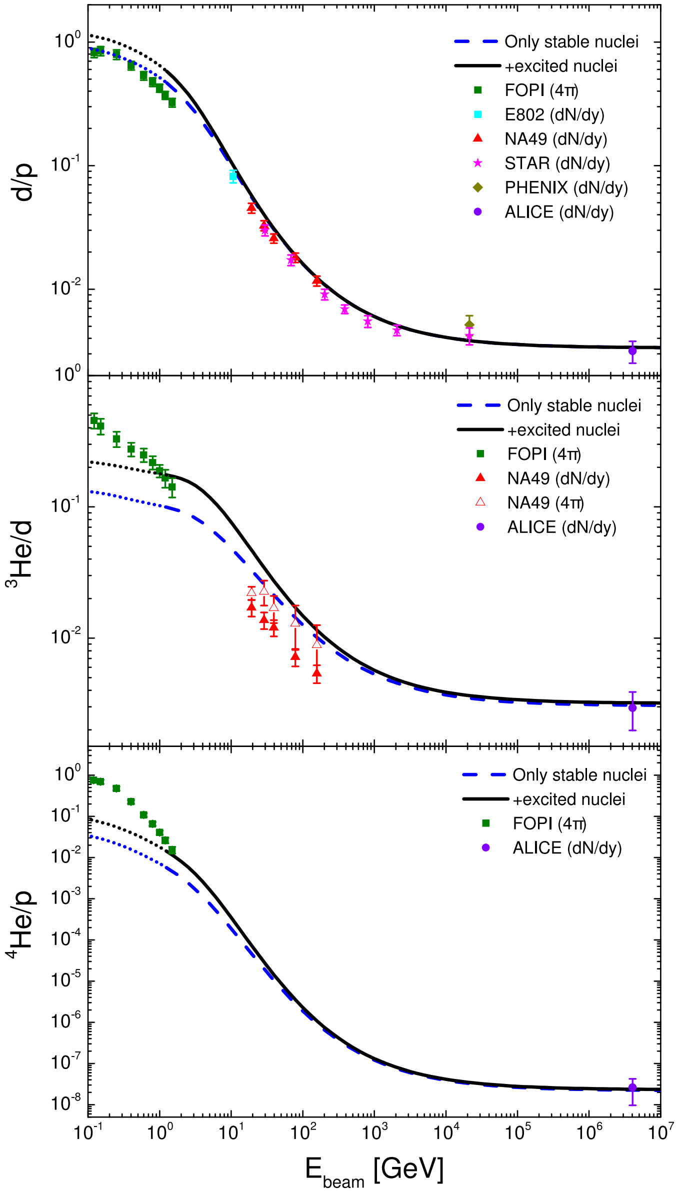
Feeddown from excited nuclei

Feeddown fraction along the phenomenological freeze-out curve



- **LHC:** 5% effect. Can be measured through p-^{3}He, p-^{4}He correlation?
- **RHIC/SPS:** 10-40% effect
- **GSI-HADES/FAIR:** Feeddown accounts for more than half of t, ^{3}He, ^{4}He

Feeddown from excited nuclei vs data



- **NA49** data on ^{3}He/d overestimated by both versions of thermal model. Large differences in dN/dy and 4π data (rapidity dependence?)

- Low energy **FOPI** data on ^{3}He/d and ^{4}He/d support nuclear feeddown but d/p data do not.

  NB: chemical freeze-out curve is an extrapolation in FOPI range

- Preliminary thermal fits to HADES data favor the scenario with feeddown.
  [M. Lorenz (HADES) @ EMMI workshop (Wroclaw, 2019)]

More data to come!

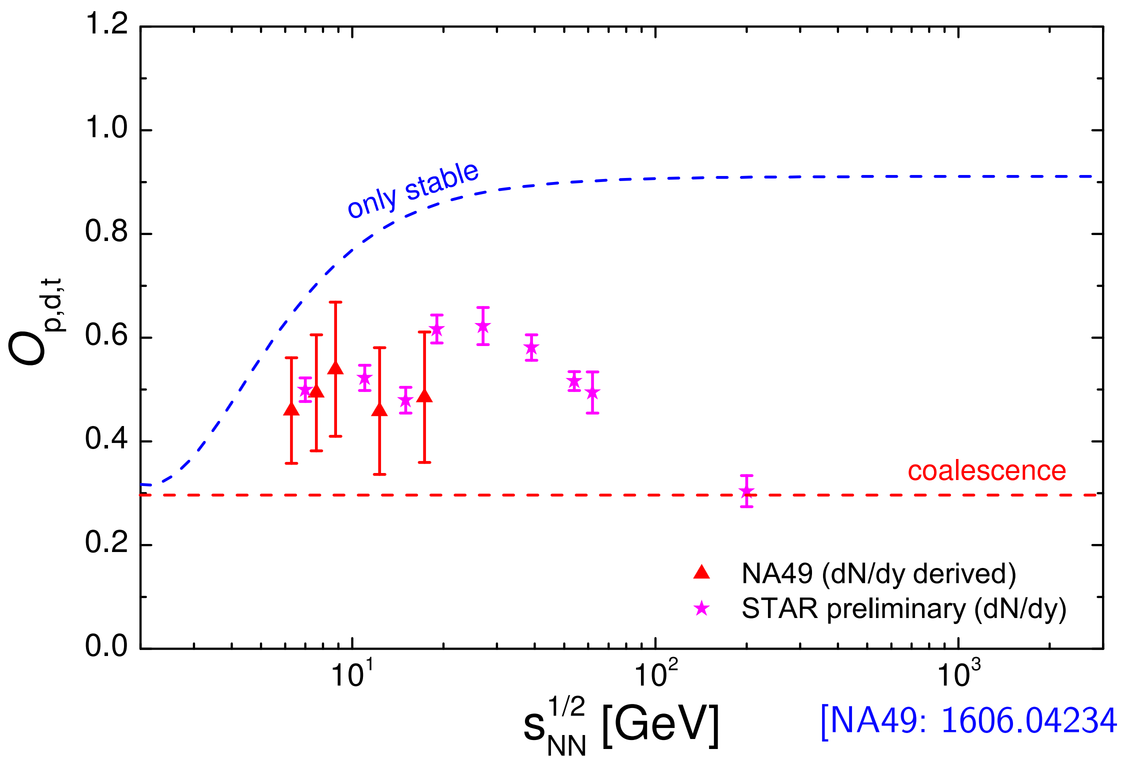
Feeddown from excited nuclei: $O_{t,p,d}$

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

[K.J. Sun et al., PLB '17, PLB '18; H. Liu et al., PLB '20]

coalescence: $O_{p,d,t} = 1/(2\sqrt{3}) \approx 0.29$ thermal/Saha: $O_{p,d,t} = 1/(2\sqrt{3}) \times (1 + Res \to p)$

+excited nuclei: $O_{p,d,t} = 1/(2\sqrt{3}) \times (1 + Res \to p)(1 + Res \to t)/(1 + Res \to d)^2$



[NA49: 1606.04234; STAR: 2002.10677]

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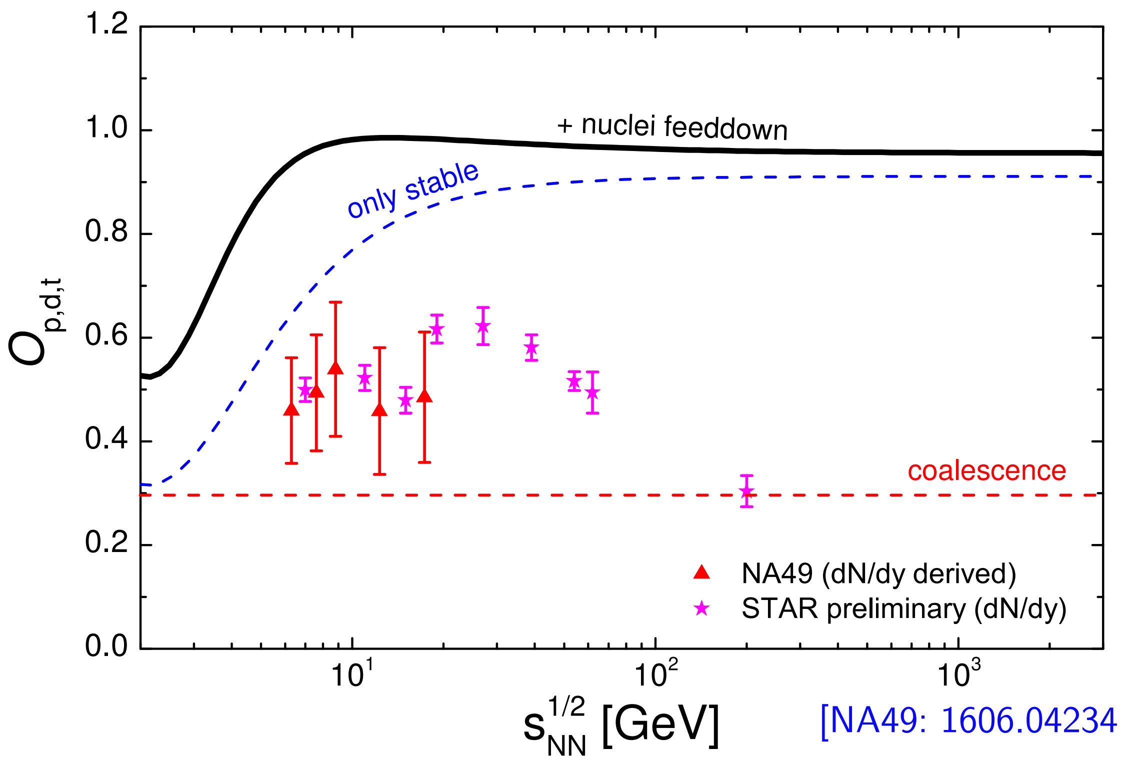

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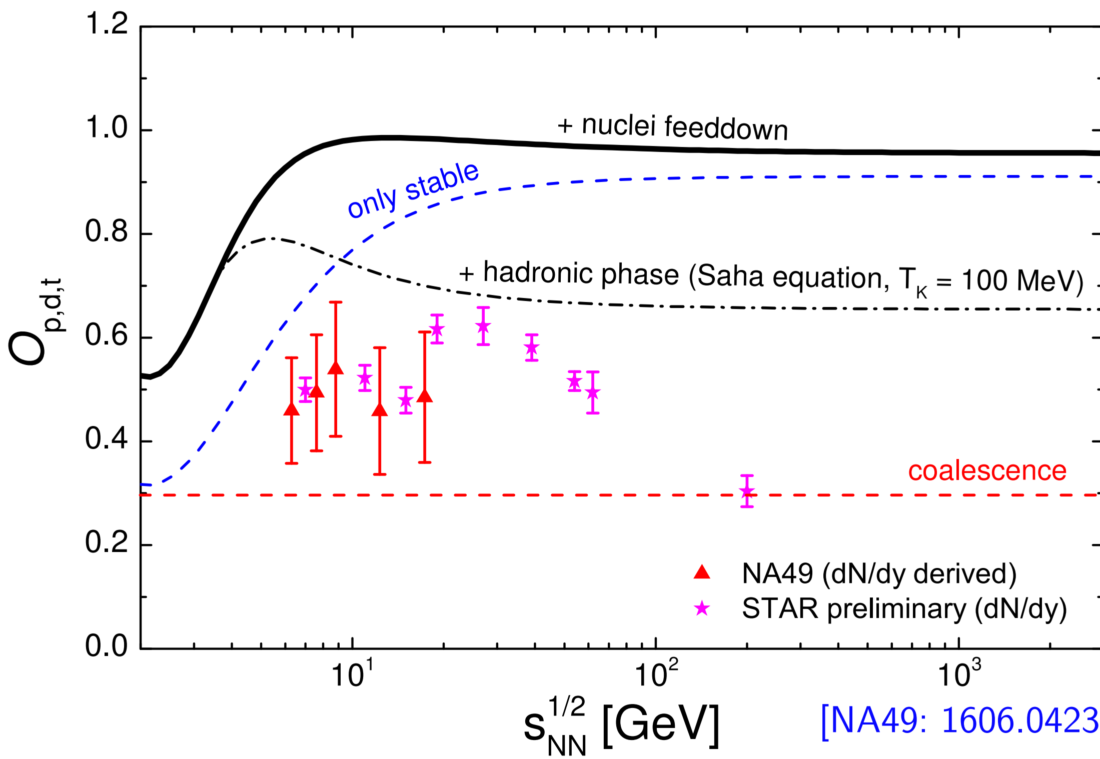

[NA49: 1606.04234; STAR: 2002.10677]

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

Summary and outlook

- Multiplicity dependence of light nuclei abundances at the LHC is consistent with basic canonical suppression considerations (CSM), but no simultaneous description of the p/π ratio is achieved.

- The Saha equation extends the thermal approach down to the kinetic freeze-out, offers possible explanation why the thermal model for point-like nuclei works so well. Kinetic theory (rate equations) agree with the Saha equation, for *all* nuclei up to ^{4}He.

- Feeddown from unstable nuclei is sizable for yields of t, ^{3}He, ^{4}He at small and intermediate energies.

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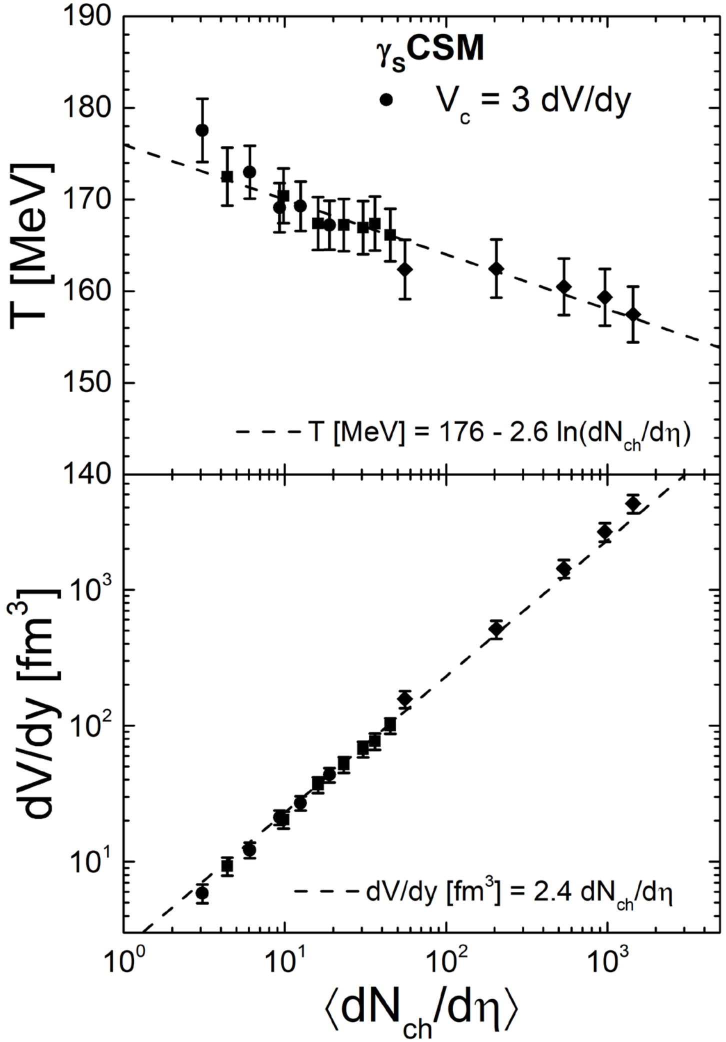
Thanks for your attention!

Backup slides

Full CSM

Full CSM: allow for multiplicity-dependent T_{ch} [**V.V.**, Dönigus, Stoecker, 1906.03145, PRC '19]



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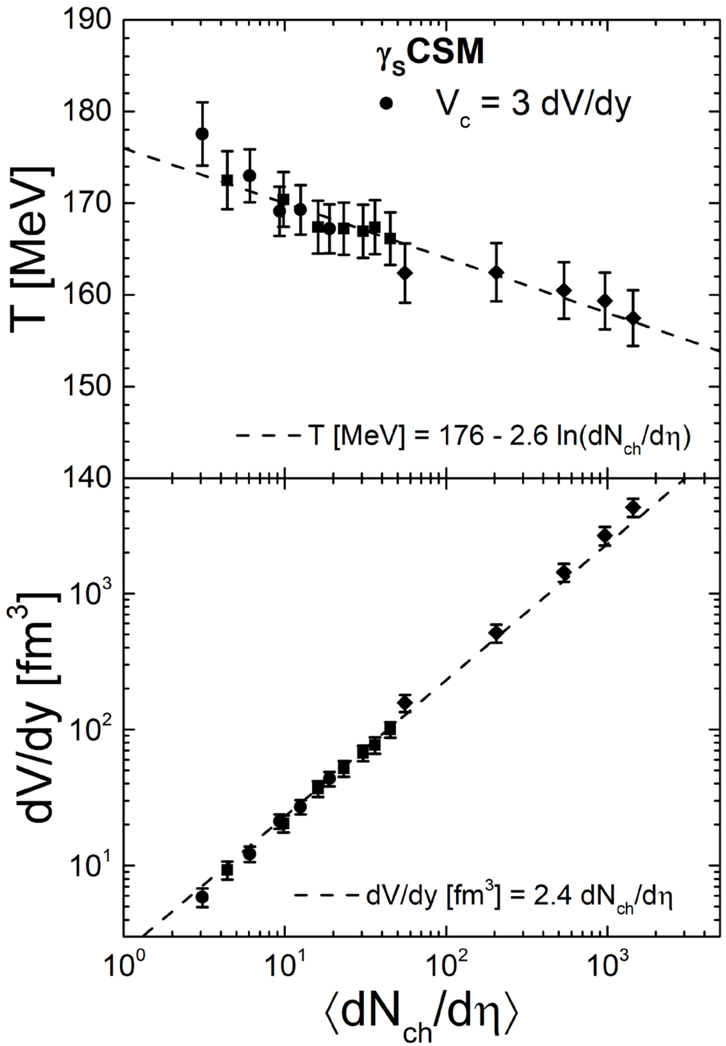

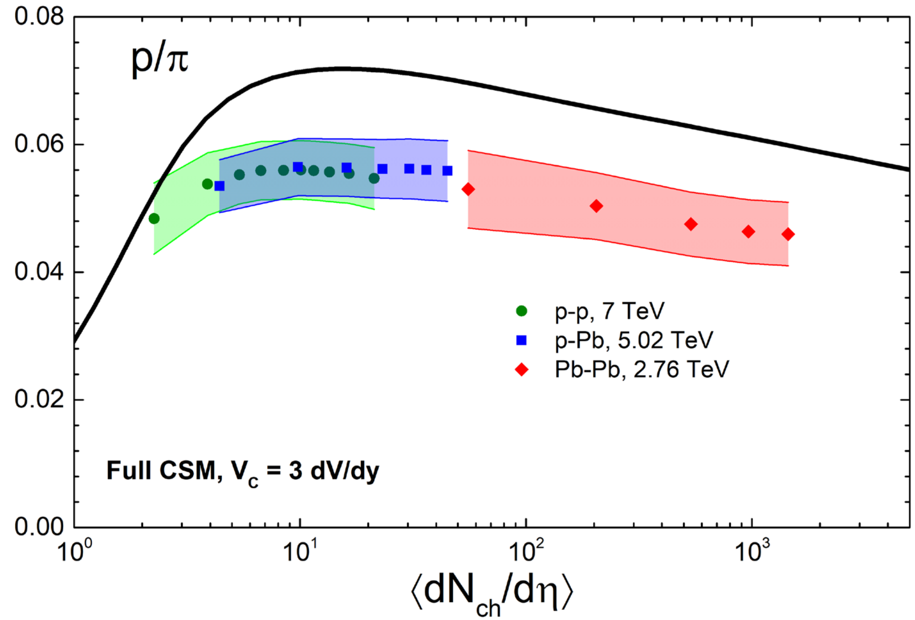

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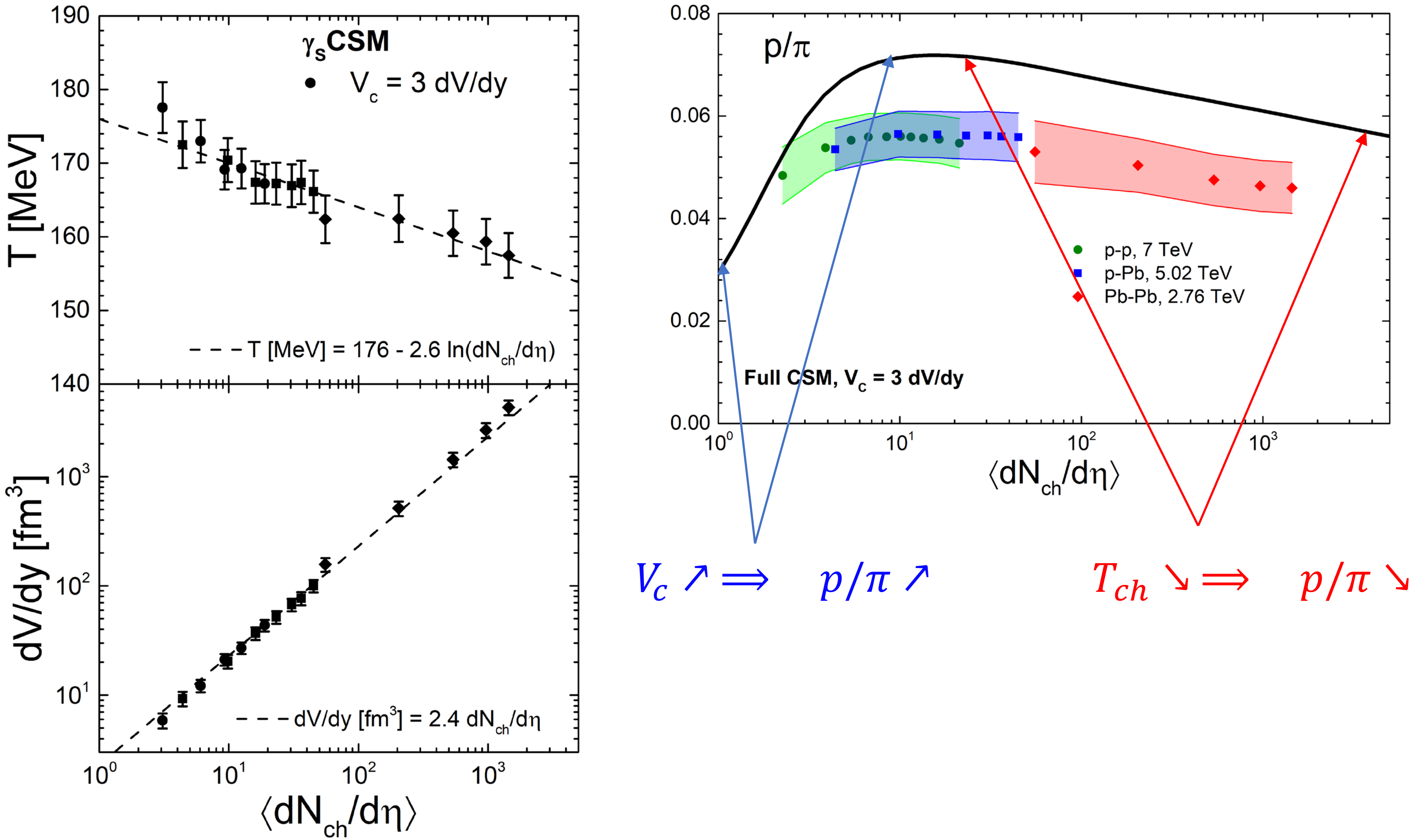
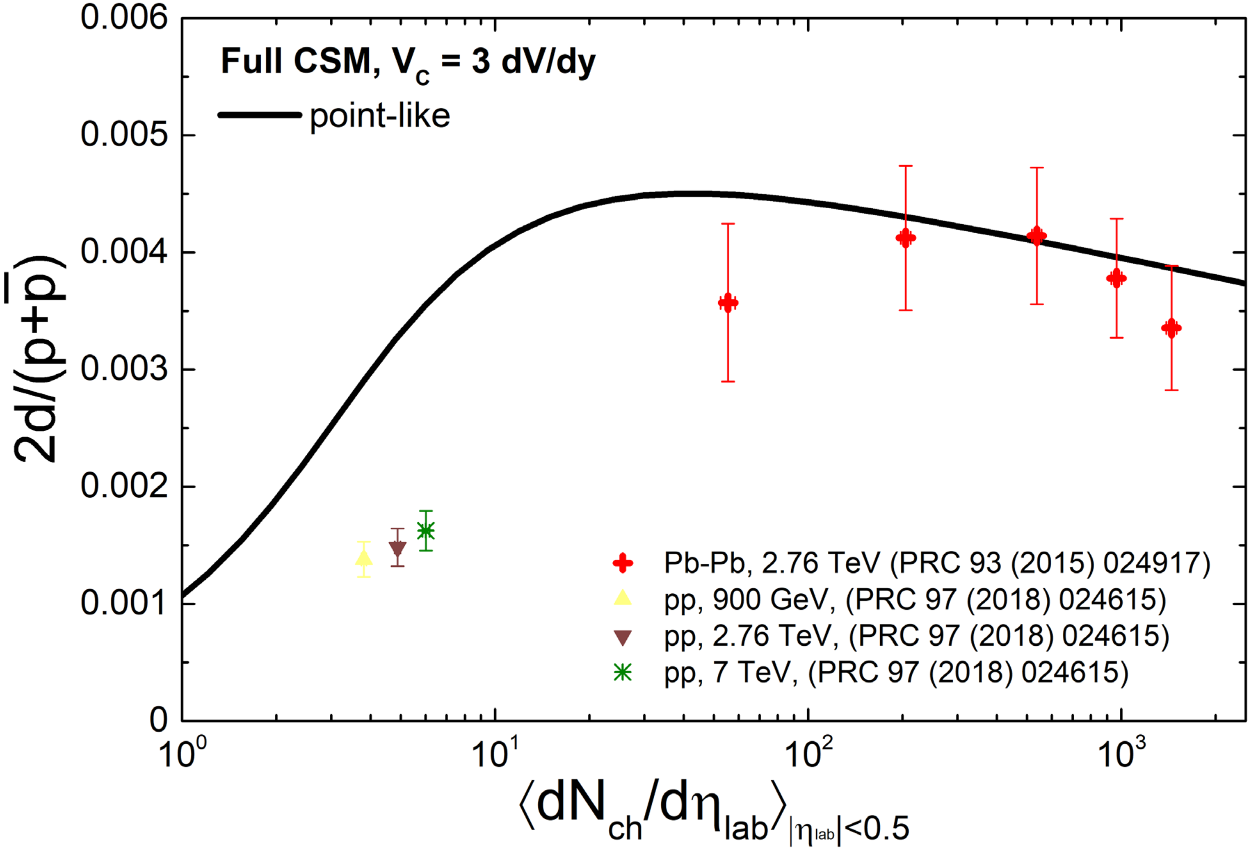


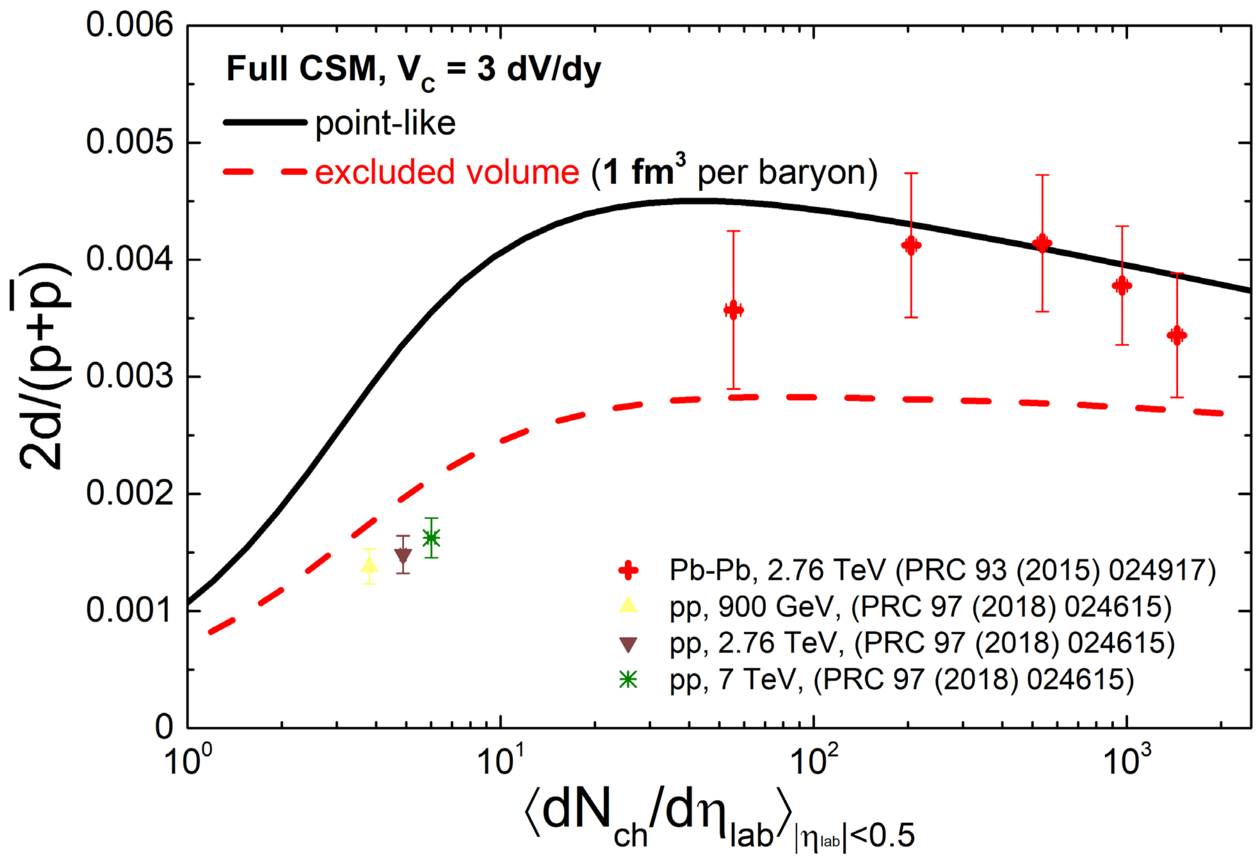
$V_c \nearrow \Longrightarrow \quad p/\pi \nearrow$ $\qquad$ $T_{ch} \searrow \Longrightarrow \quad p/\pi \searrow$

Full CSM: d/p



$T_{ch} \searrow \implies \quad p/\pi \searrow$

Full CSM: d/p



$T_{ch} \searrow \implies p/\pi \searrow$

Excluded volume (schematic): $N_i \to N_i \exp\left(-\frac{v_i\, p}{T}\right) \implies d/p \searrow$

Simultaneous description of light nuclei and p/π ratio remains challenging

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 nucleosynthesis: BBN-like setup

- Chemical equilibrium lost at $T_{ch} = 155$ MeV, abundances of nucleons are frozen and acquire effective fugacity factors: $n_i = n_i^{eq} e^{\mu_N/T}$
- Isentropic expansion driven by effectively massless mesonic d.o.f.

$$\frac{V}{V_{\rm ch}} = \left(\frac{T_{\rm ch}}{T}\right)^3, \qquad \mu_N \simeq \frac{3}{2}\, T \ln\left(\frac{T}{T_{\rm ch}}\right) + m_N \left(1 - \frac{T}{T_{\rm ch}}\right)$$

- Detailed balance for nuclear reactions, $X + A \leftrightarrow X + \sum_i A_i$, X is e.g. a pion

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

Saha equation

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

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

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:

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

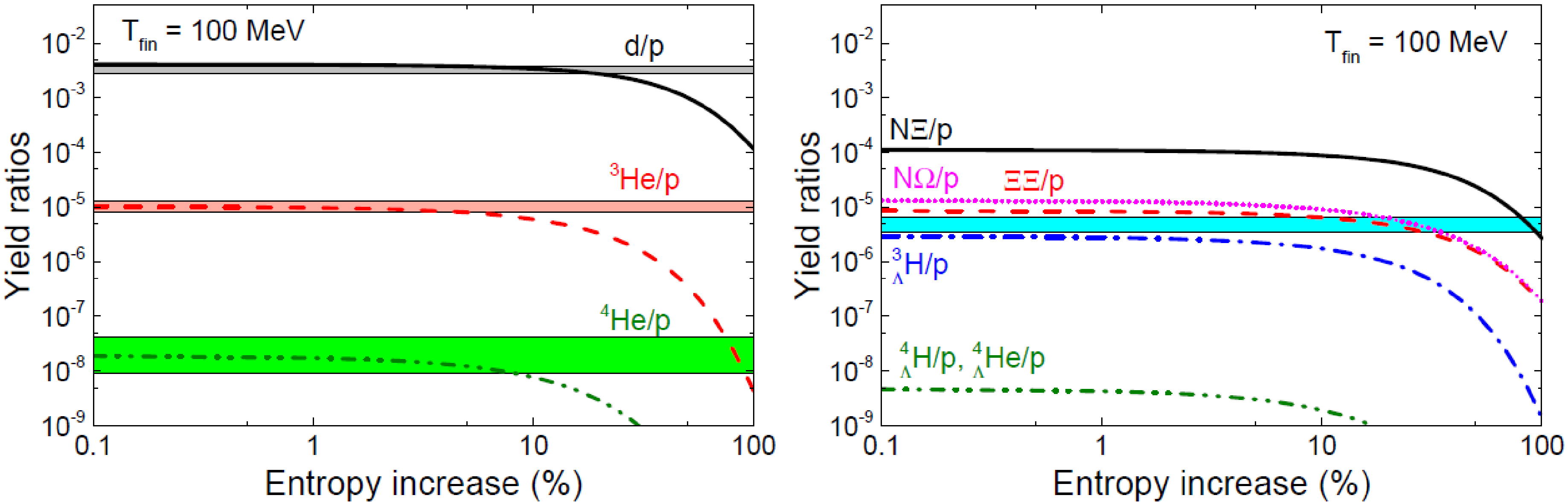
Thermal model:

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

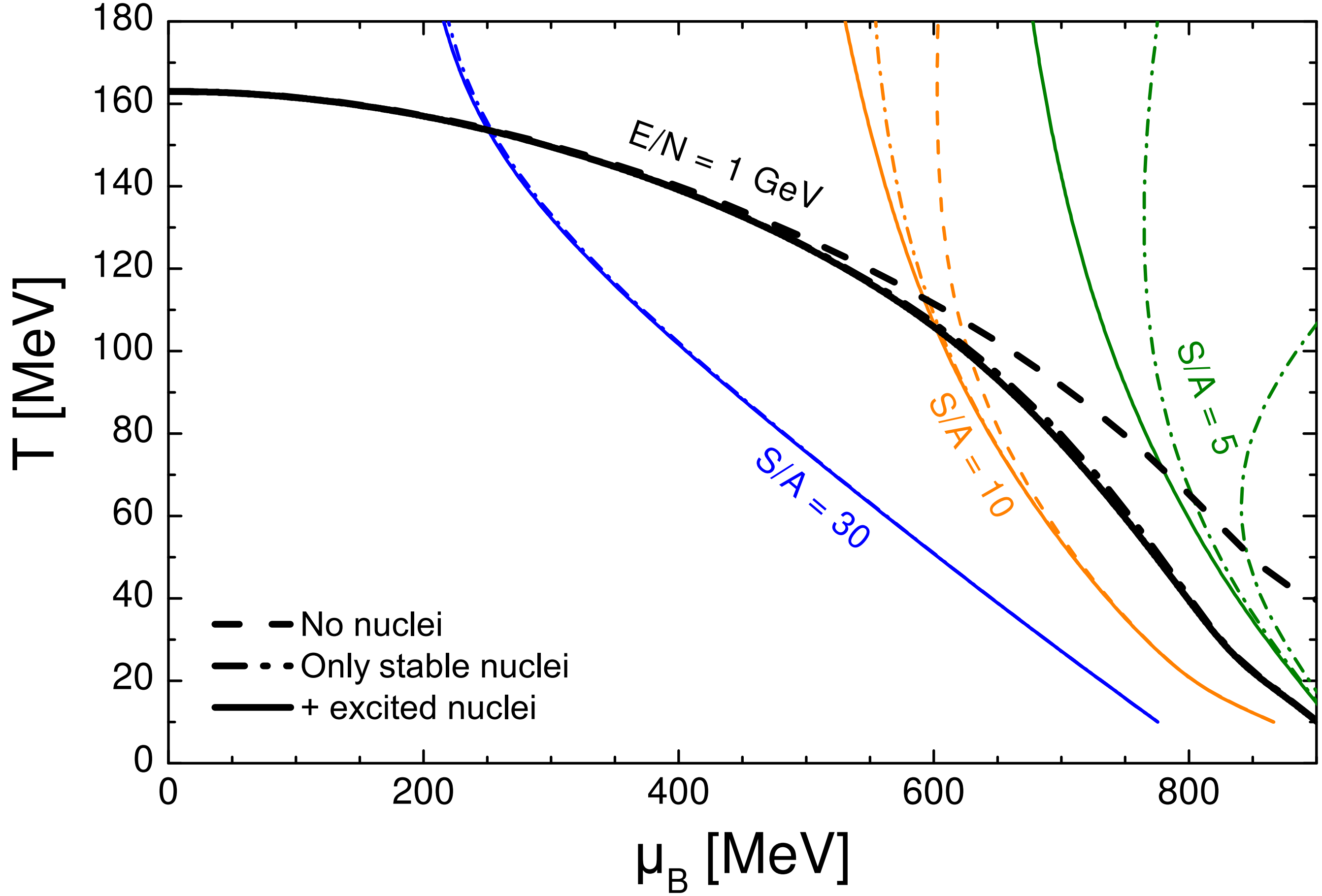
Strong exponential dependence on the temperature is eliminated in the Saha equation approach

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

Saha equation: Entropy production effect



Feeddown from nuclei: Isentropes



Feeddown from nuclei: Rapidity dependence

Fireballs at midrapidity: $\mu_B(y_s) \approx \mu_B(0) + b\, y_s^2$

[Becattini et al., 0709.2599]