Hadronic resonance production in a partial chemical equilibrium model

Volodymyr Vovchenko (INT Seattle / Berkeley Lab)

ALICE week, CERN

Jun 7, 2022

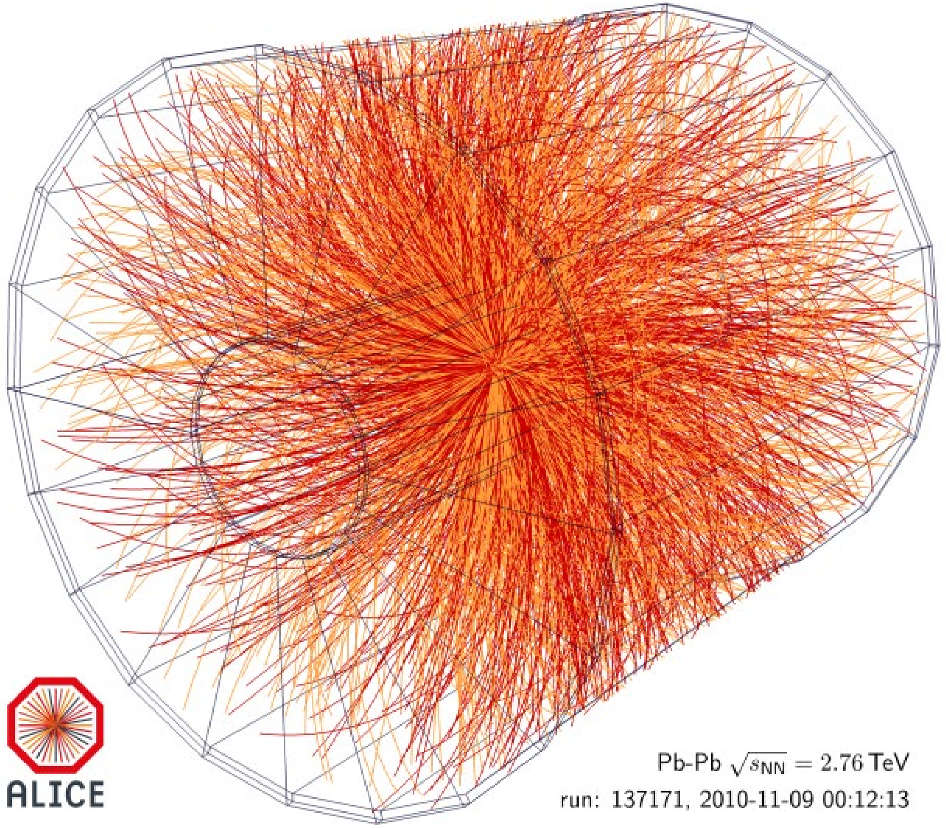
Based on:

A. Motornenko, VV, C. Greiner, H. Stocker, *Phys. Rev. C 102, 024909 (2020)*

BERKELEY LAB

INSTITUTE for NUCLEAR THEORY

Probing QCD properties with heavy-ion collisions



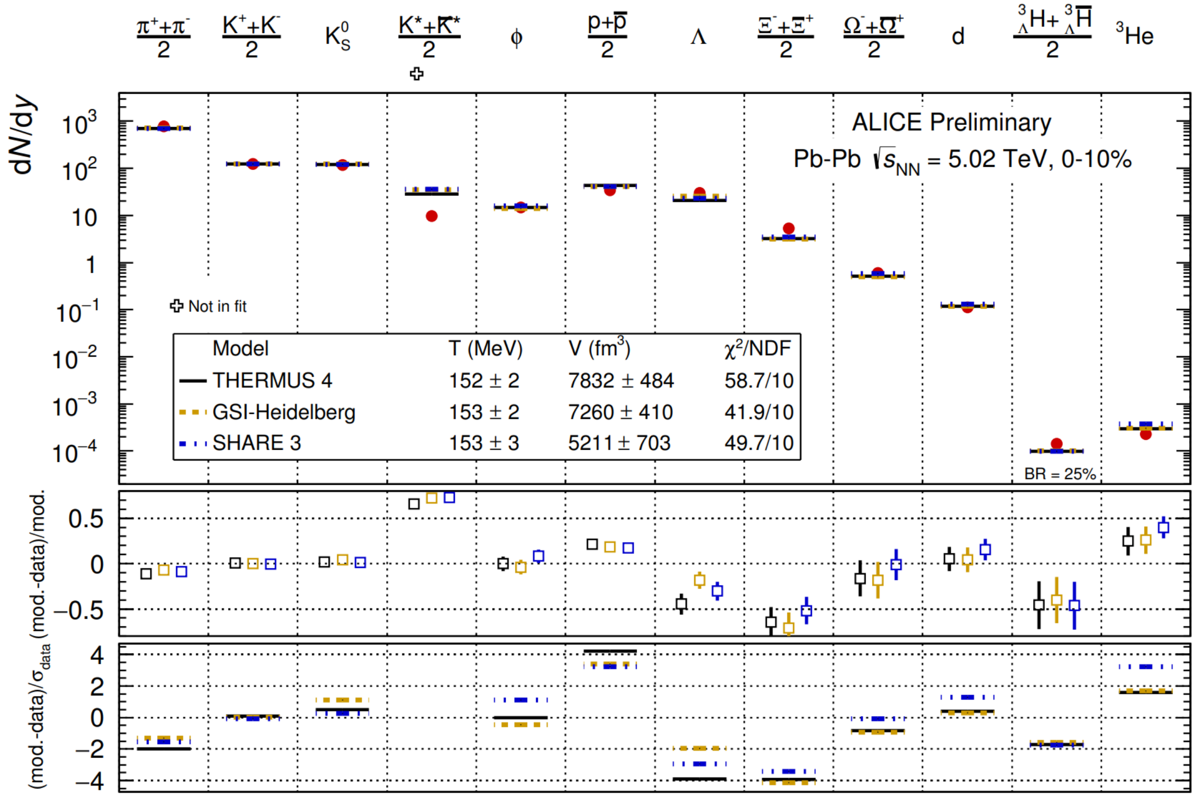
Event display of a Pb-Pb collision in ALICE at the LHC

Thousands of particles created in relativistic heavy-ion collisions

Apply concepts of statistical mechanics

Two experimental observations at the LHC

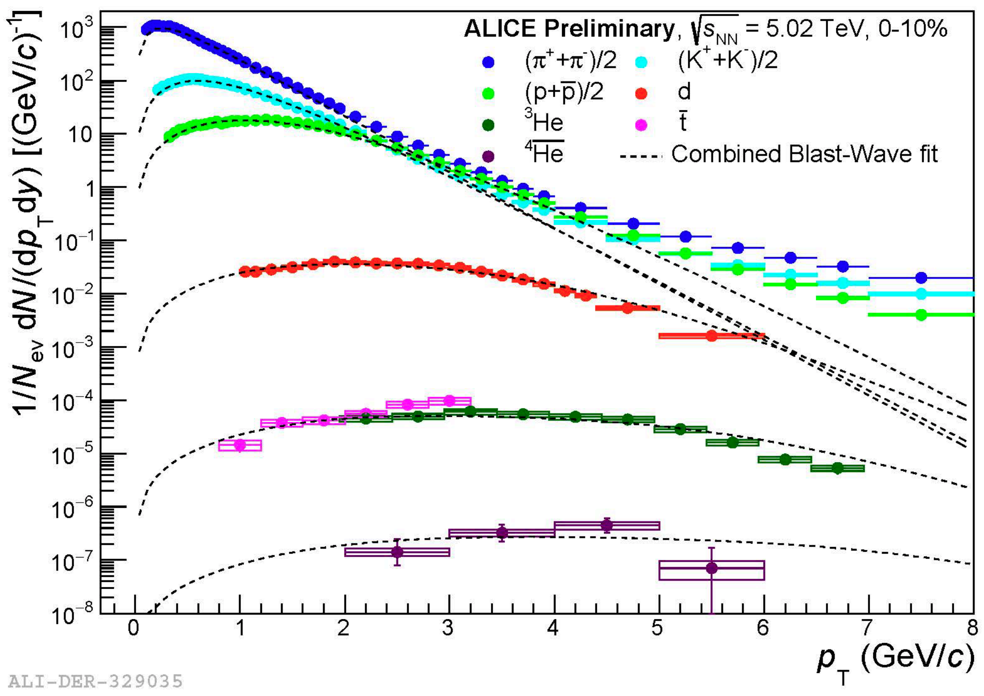
1. Measured hadron yields are described by thermal model at $T_{ch} \approx 155$ MeV



Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 4	152 ± 2	7832 ± 484	58.7/10
GSI-Heidelberg	153 ± 2	7260 ± 410	41.9/10
SHARE 3	153 ± 3	5211 ± 703	49.7/10

ALI-PREL-148739 ALICE Collaboration, arXiv:1910.07678

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

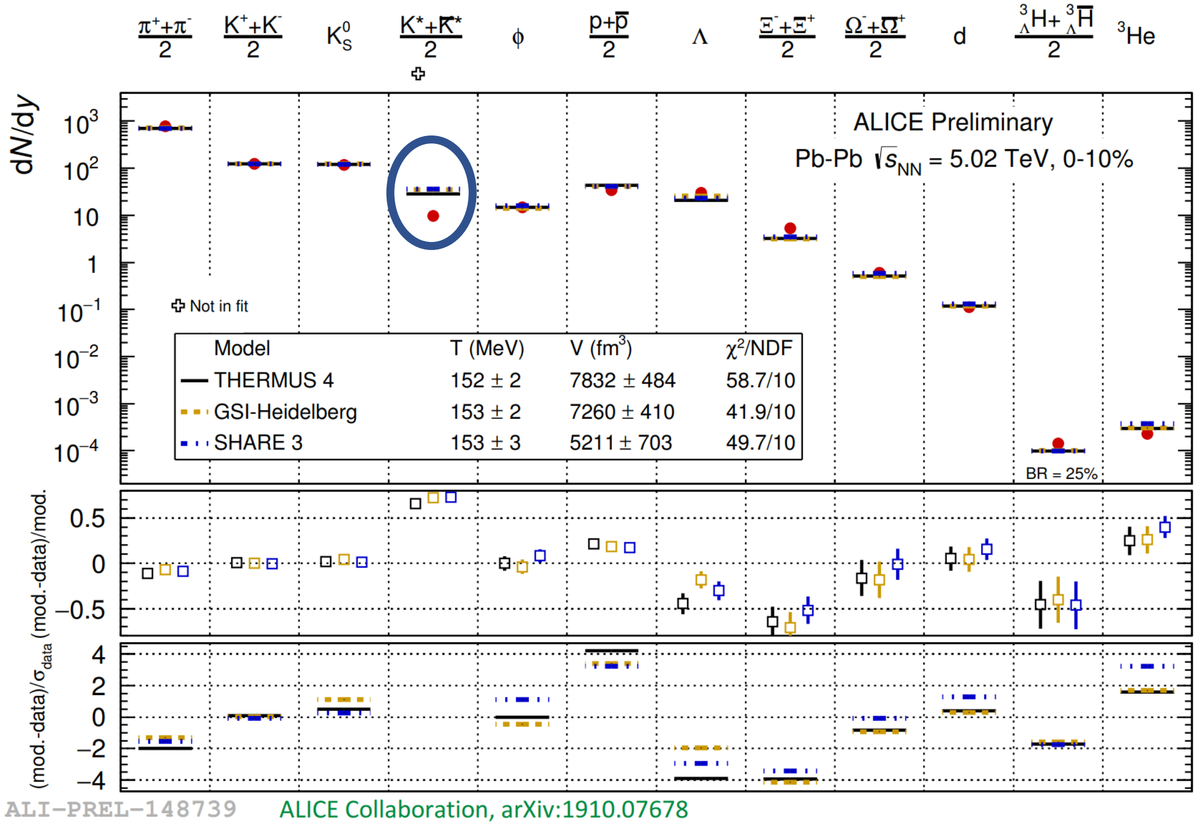


[E. Bartsch (ALICE Collaboration), QM2019]

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

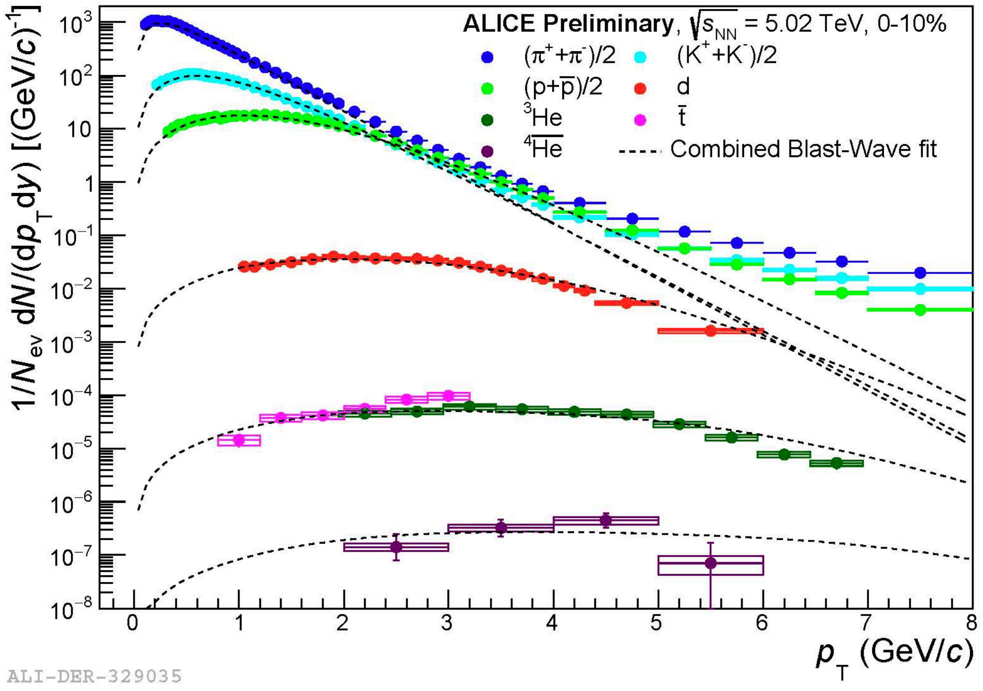
Two experimental observations at the LHC

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



ALICE Collaboration, arXiv:1910.07678

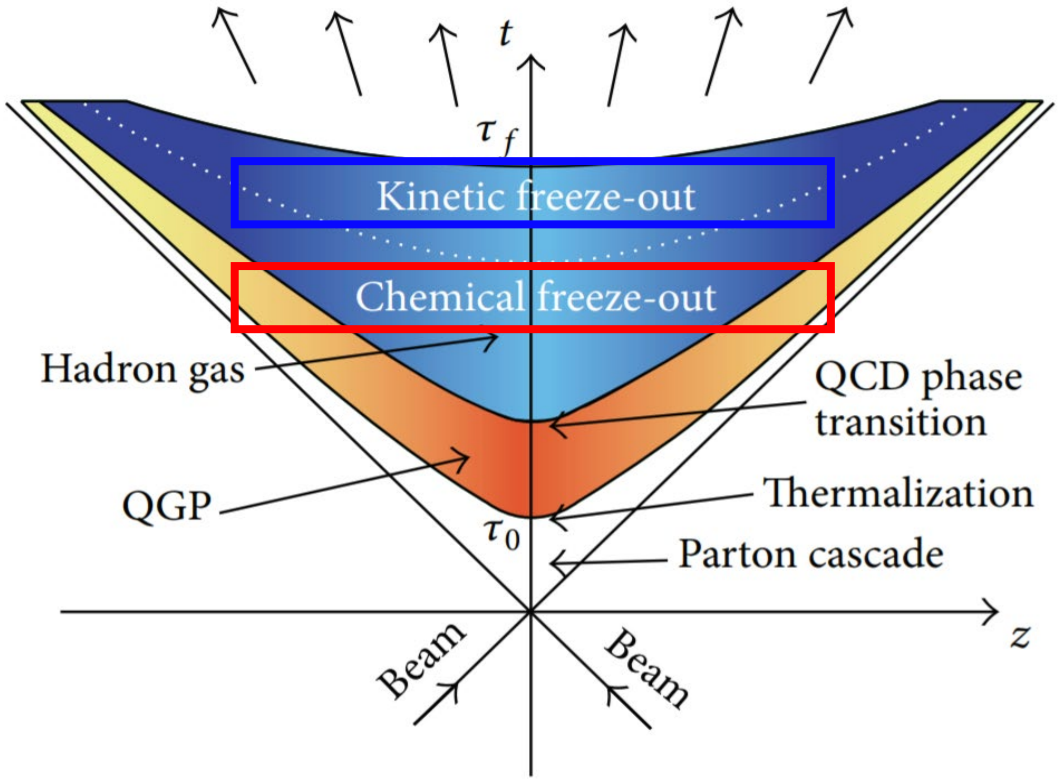
2. Momentum spectra described by the blast-wave model at $T_{kin} \approx 100 - 120$ MeV



[E. Bartsch (ALICE Collaboration), QM2019]

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

Hadronic phase in heavy-ion collisions



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

Reactions in the hadronic phase*

see e.g. T. Neidig et al., PLB 827, 136891 (2022)

- Elastic $\pi\pi \leftrightarrow \pi\pi$ and pseudo-elastic resonance reactions $\pi\pi \leftrightarrow \rho$, $\pi\mathrm{K} \leftrightarrow \mathrm{K}^*, \pi N \leftrightarrow \Delta$, etc.

- Chemical composition of stable hadrons is fixed, e.g. $\pi + 2\rho + 3\omega + \cdots = const, \quad \mathrm{K} + \mathrm{K}^* + \cdots = const$

- Kinetic but not chemical equilibrium enforced → fugacity factors $N_i = N_i^{\mathrm{eq}} e^{\mu_i/T} = V\, n_i^{\mathrm{th}}(T)\, e^{\mu_i/T}$

- Kinetic theory based description → **rate equations** for resonance abundances

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

gain (regeneration) **loss (decay)**

e.g. $\frac{dN_\rho}{d\tau} = \langle \Gamma_\rho \rangle N_\rho^{\mathrm{eq}} \left(e^{2\mu_\pi/T} - e^{\mu_\rho/T} \right)$

- and entropy production

$$\frac{dS}{d\tau} = -\sum_i \frac{dN_i}{d\tau} \frac{\mu_i}{T}$$

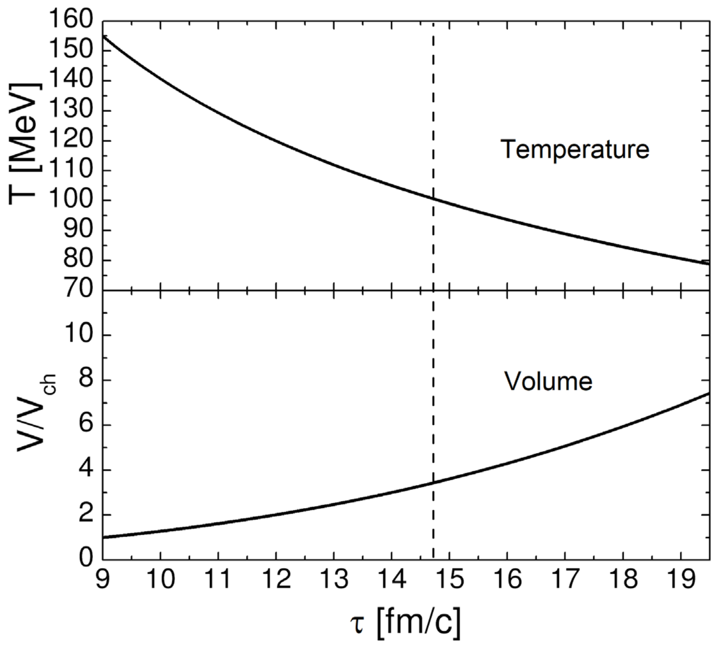
In practice less than 1% entropy generated in the hadronic phase, i.e. expansion essentially **isentropic**

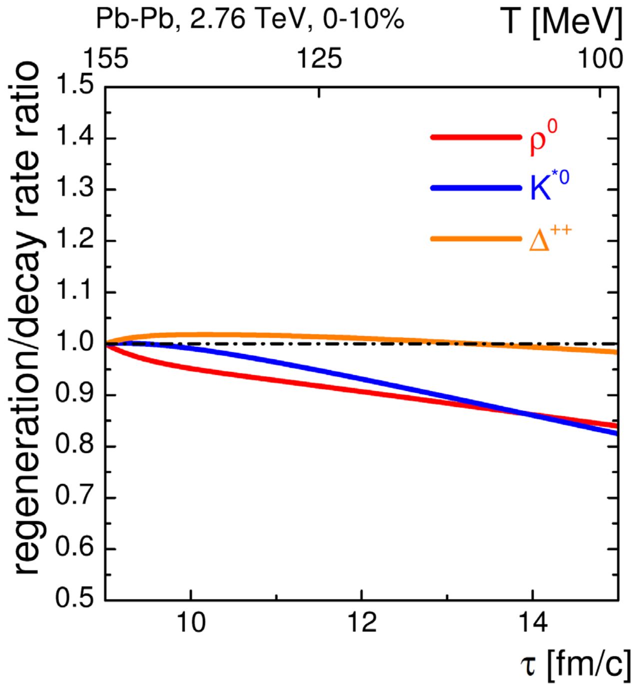
*For more complete description use Monte Carlo hadronic afterburners like UrQMD/SMASH [Steinheimer et al., *PRC*95(2017)064902; Oliinychenko, Shen, 2105.07539]

Estimate of the reaction rates at the LHC

- **Input:** transverse and longitudinal expansion [Y. Pan, S. Pratt, PRC 89, 044911 (2014)]

$$\frac{V}{V_{\mathrm{ch}}} = \frac{\tau}{\tau_{\mathrm{ch}}} \frac{\tau_\perp^2 + \tau^2}{\tau_\perp^2 + \tau_{\mathrm{ch}}^2}, \qquad \tau_{\mathrm{ch}} = 9 \text{ fm}, \qquad \tau_\perp = 6.5 \text{ fm} \qquad T_{\mathrm{ch}} = 155 \text{ MeV}$$





(regeneration + decay) $\gg$ |regeneration – decay| $\rightarrow$ **partial chemical equilibrium at work:**

$$\mu_\rho \approx 2\mu_\pi, \quad \mu_{K^*} \approx \mu_\pi + \mu_K, \quad \mu_\Delta \approx \mu_N + \mu_\pi, \ldots$$

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

Effective chemical potentials:

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

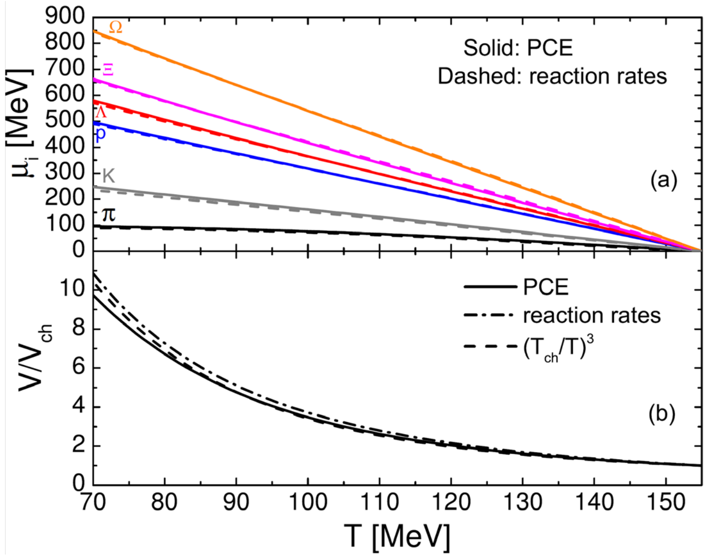
Conservation laws:

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

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

numerical solution

$\{\mu_i(T)\}, V(T)$



Numerical implementation within **Thermal-FIST** package (since v1.3)

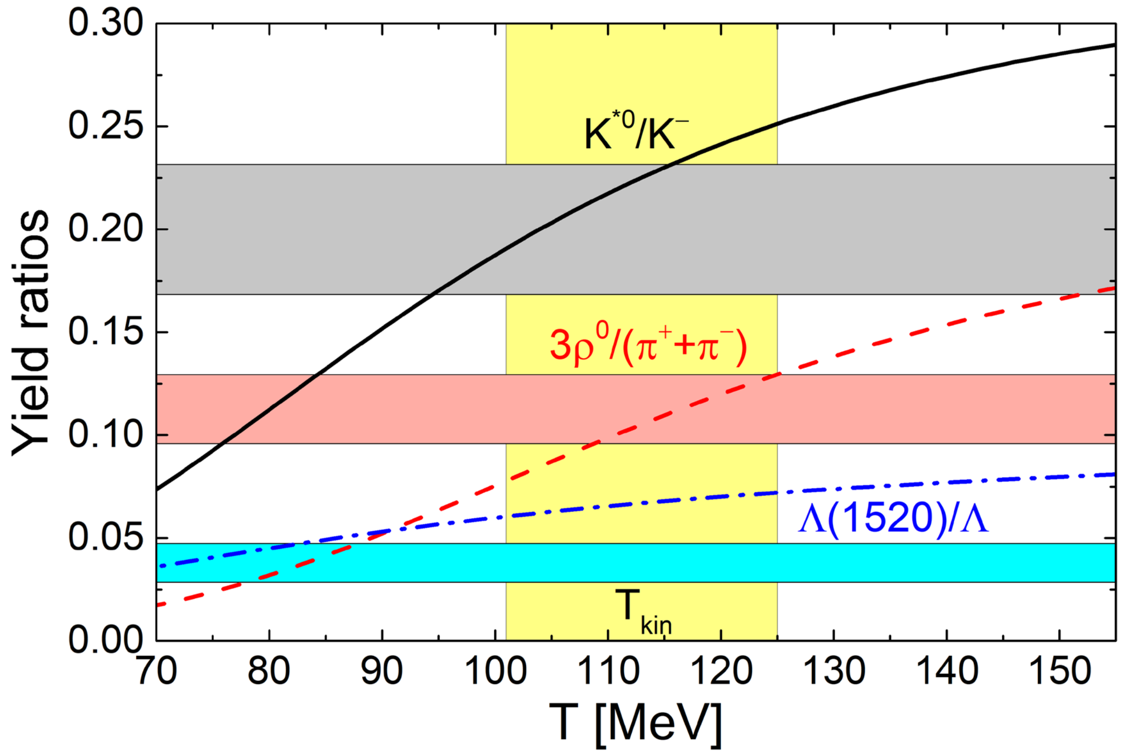
[**VV**, H. Stoecker, *Comput. Phys. Commun.* ***244,*** *295 (2019)*]

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

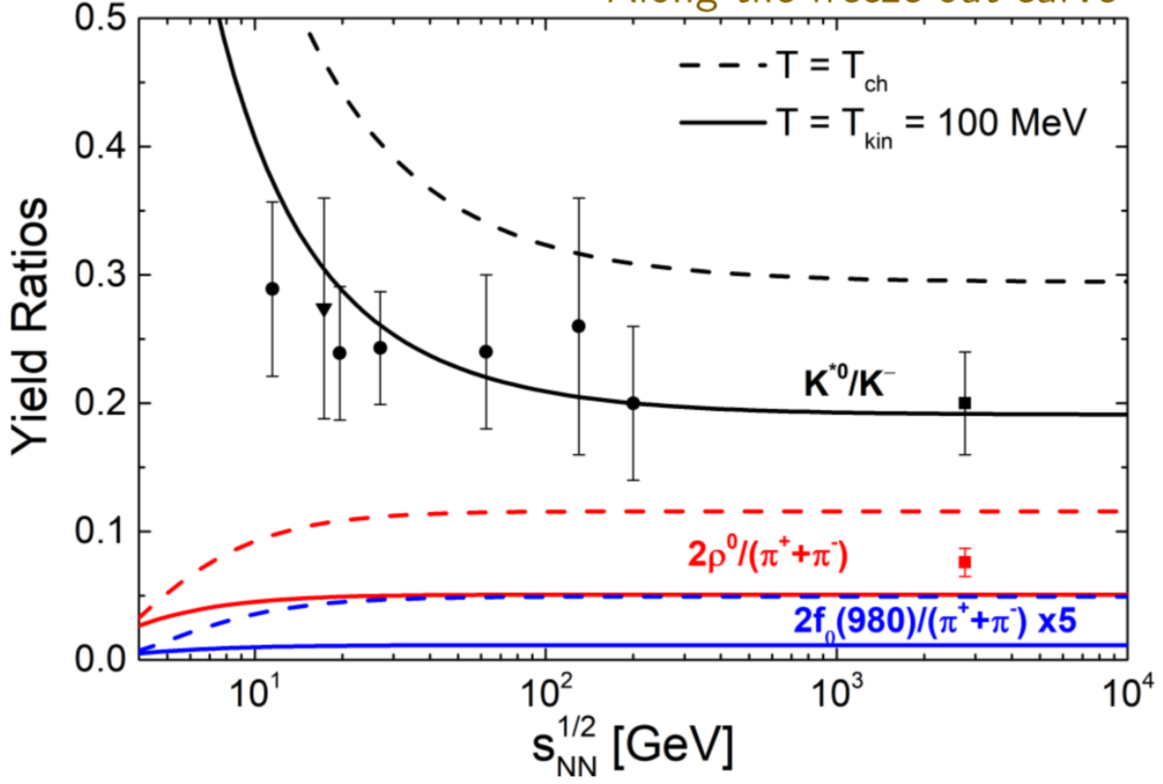
Resonance suppression in hadronic phase

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

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



Along the freeze-out curve

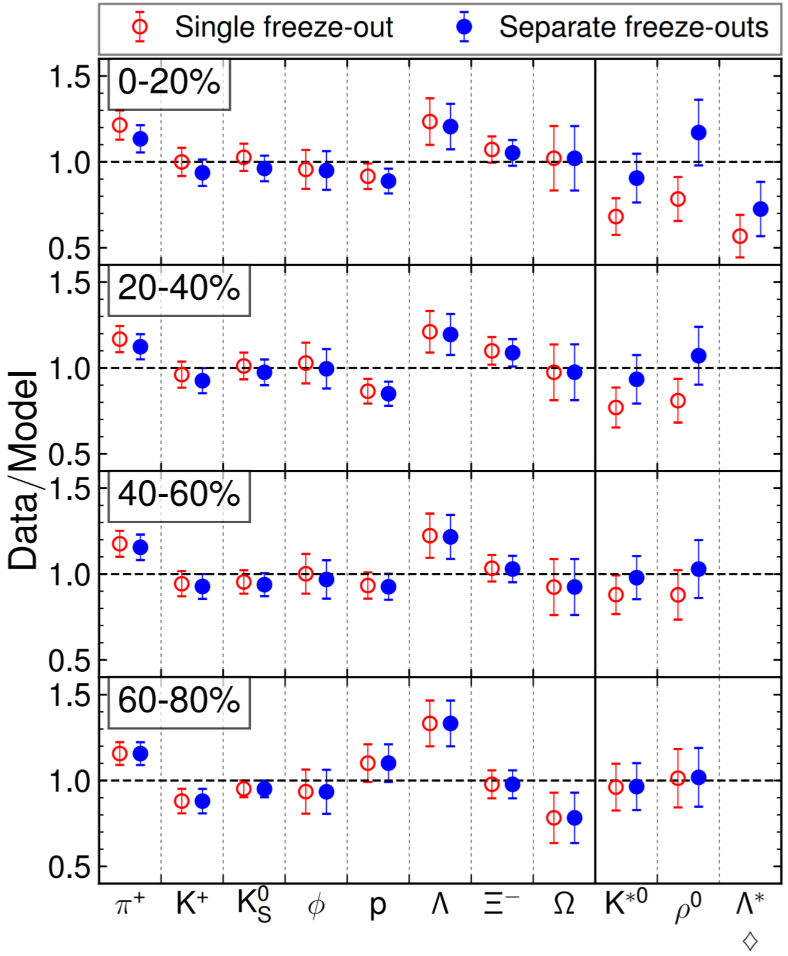


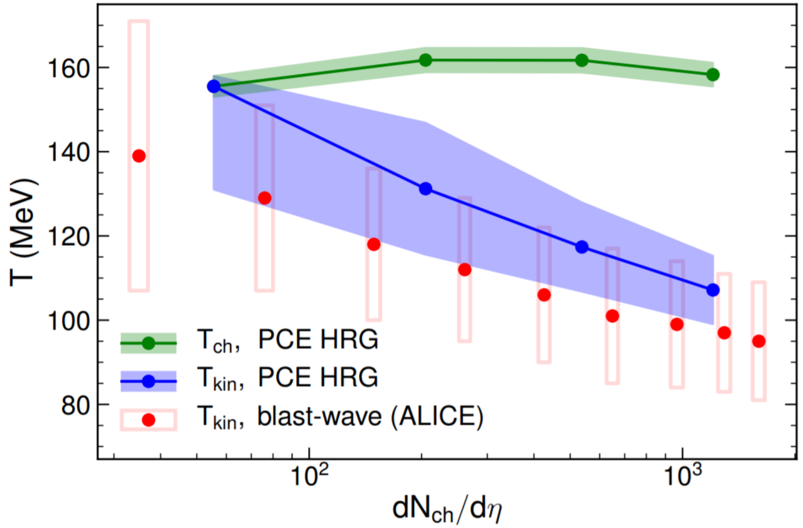
Use the sensitivity of short-lived resonance yields to T_{kin} extract the kinetic freeze-out temperature

A. Motornenko, VV, C. Greiner, H. Stoecker, Phys. Rev. C 102, 024909 (2020)

Kinetic freeze-out temperature from resonances

Thermal fits 2.0: Fit T_{ch} and T_{kin} simultaneously to yields of both stable and short-lived hadrons



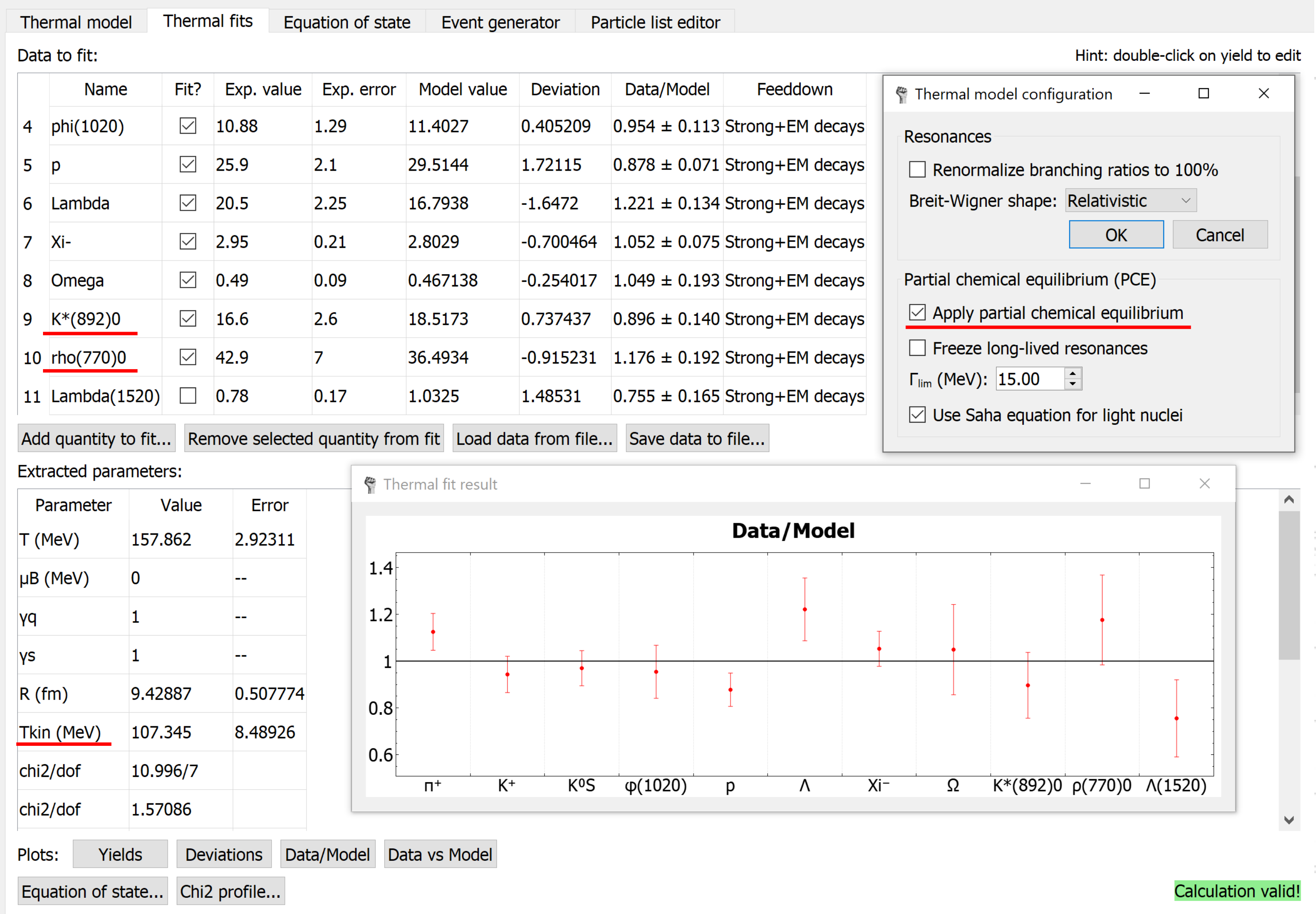


Centrality	T_{ch} (MeV)	T_{kin} (MeV)	χ^2/dof
0-20%	160.2 ± 3.1	–	23.6/8
	158.3 ± 2.8	107.1 ± 8.2	10.5/7
20-40%	162.9 ± 3.1	–	19.5/8
	161.7 ± 2.9	117.3 ± 10.8	12.8/7
40-60%	162.3 ± 3.0	–	12.5/8
	161.8 ± 2.9	131.2 ± 15.9	10.6/7
60-80%	155.5 ± 2.5	–	19.1/8
	155.5 ± 2.5	$155.5^{+2.5}_{-24.5}$	19.1/7

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

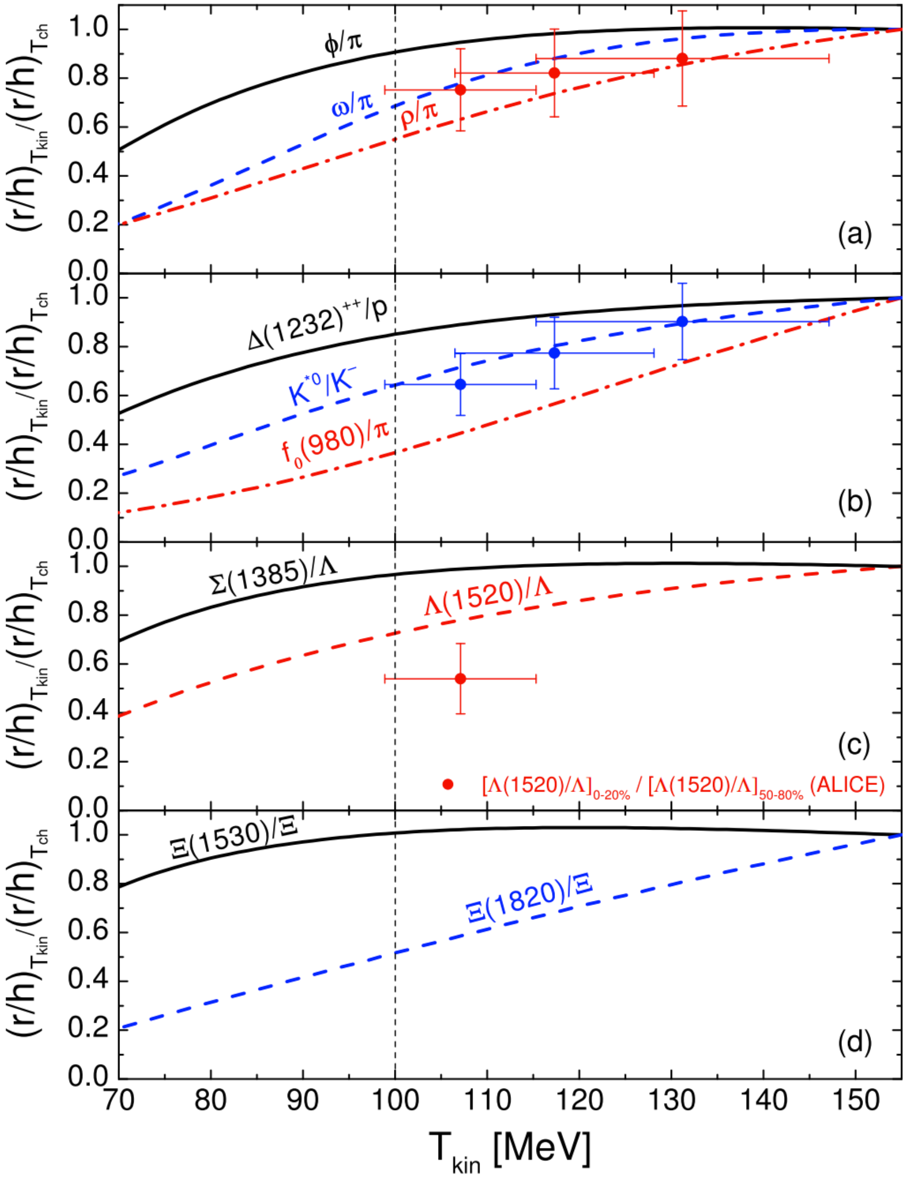
A. Motornenko, **VV**, C. Greiner, H. Stoecker, Phys. Rev. C 102, 024909 (2020)

Kinetic freeze-out temperature from resonances



Available out-of-the box since Thermal-FIST version 1.3!

PCE: predictions for other (short-)lived resonances



- Some resonances suppressed notably, others barely change, none are significantly enhanced

- $\Delta(\tau = 1.7\ fm/c)$ and $\Sigma^*(\tau = 5.5\ fm/c)$ *do not change notably*
  - Similar to transport but may be in tension with data where K^{*0}-like suppression indicated

[ALICE Coll., 2205.13998]

- $f_0 \leftrightarrow \pi\pi$ is in equilibrium (PCE) or not depending on its $\tau =$ 2-20 fm/c lifetime
  - A notable suppression in the hadronic phase predicted by PCE would indicate a short lifetime

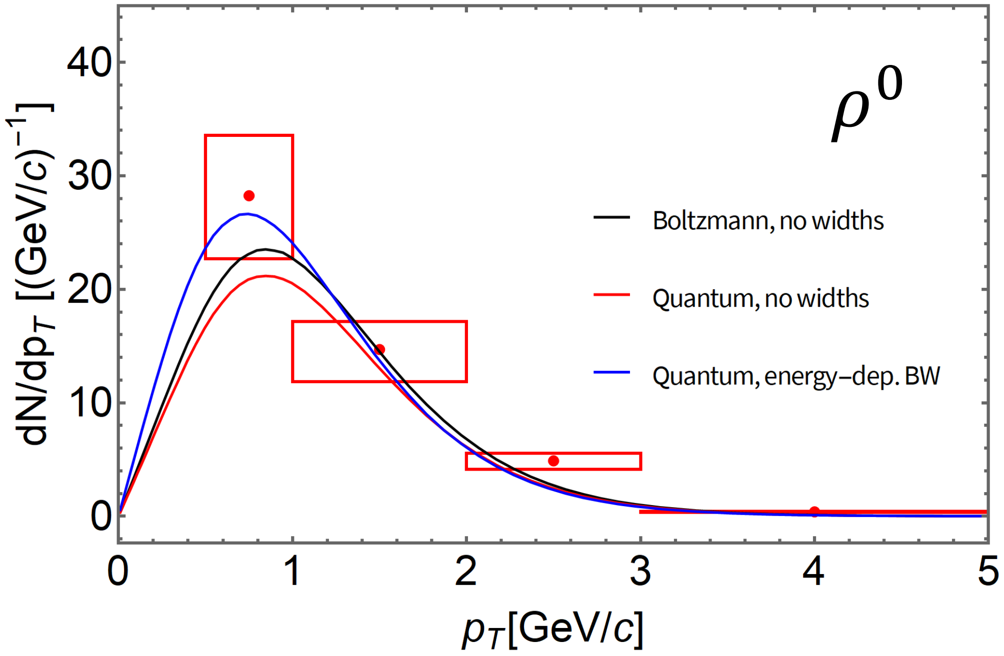
- Transport models yield generally similar results for most resonances

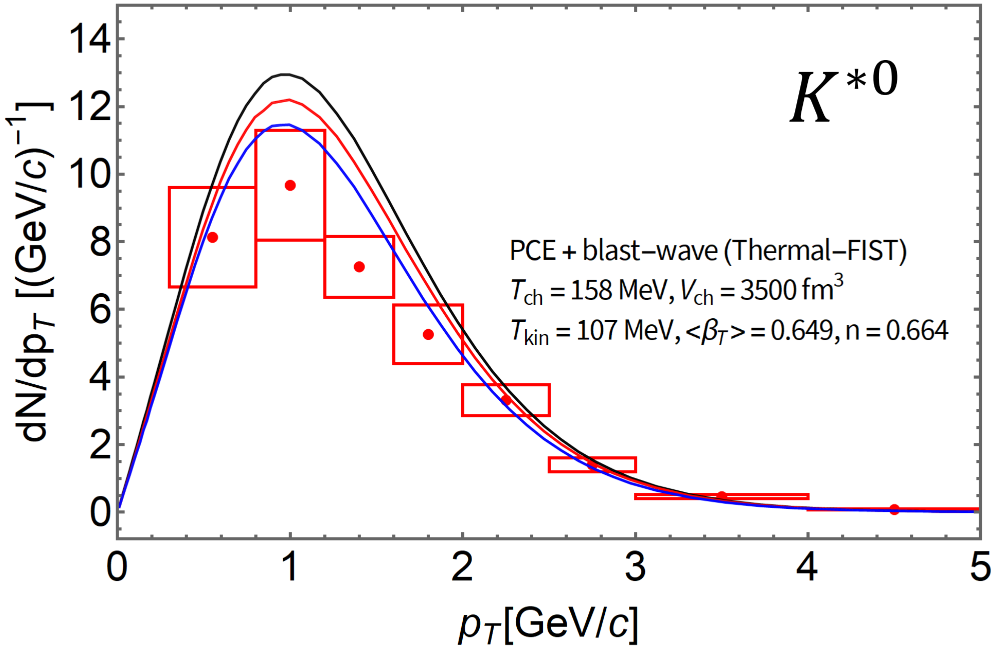
Knospe et al., PRC 93 (2016) 014911
Oliinychenko, Shen, 2105.07539

PCE, resonances and blast-wave event generator

Blast-wave event generator utilizing PCE hadron abundances at $T = T_{kin} = T_{BW}$

Can include effects of quantum statistics, resonance widths, (grand-)canonical treatment of conserved charged on p_T-differential observables





Available in Thermal-FIST since version 1.3!

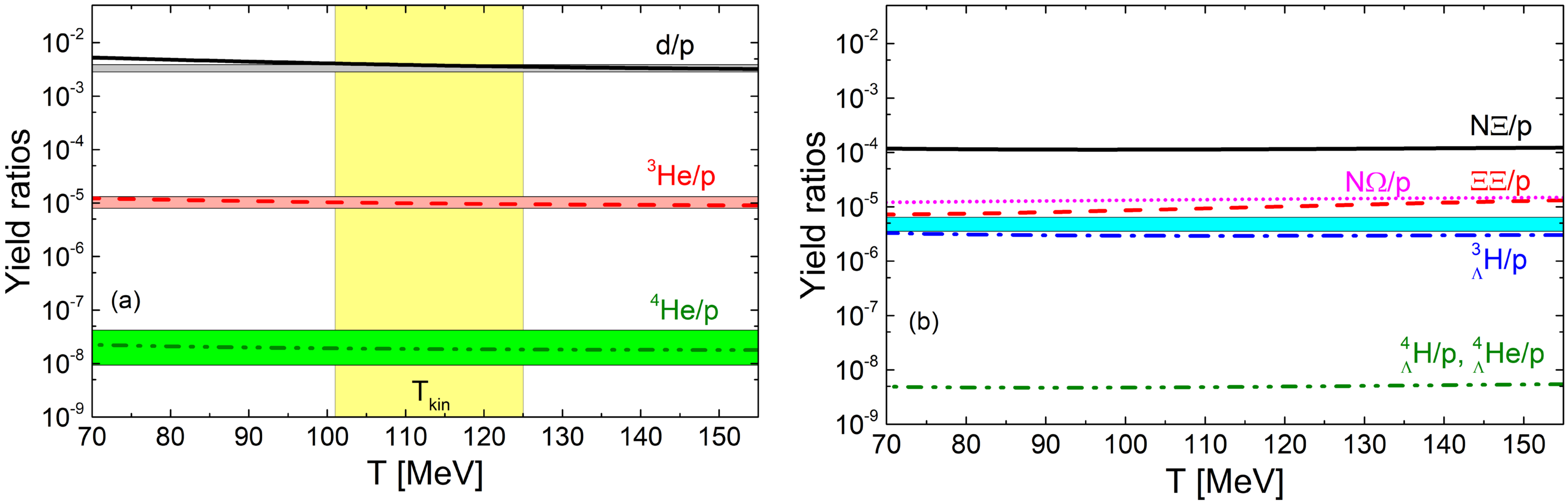
PCE and light (anti-)(hyper-)nuclei: Saha equation

Detailed balance for nuclear reactions

VV, Gallmeister, Schaffner-Bielich, Greiner, PLB 800, 135131 (2020)

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

Saha equation



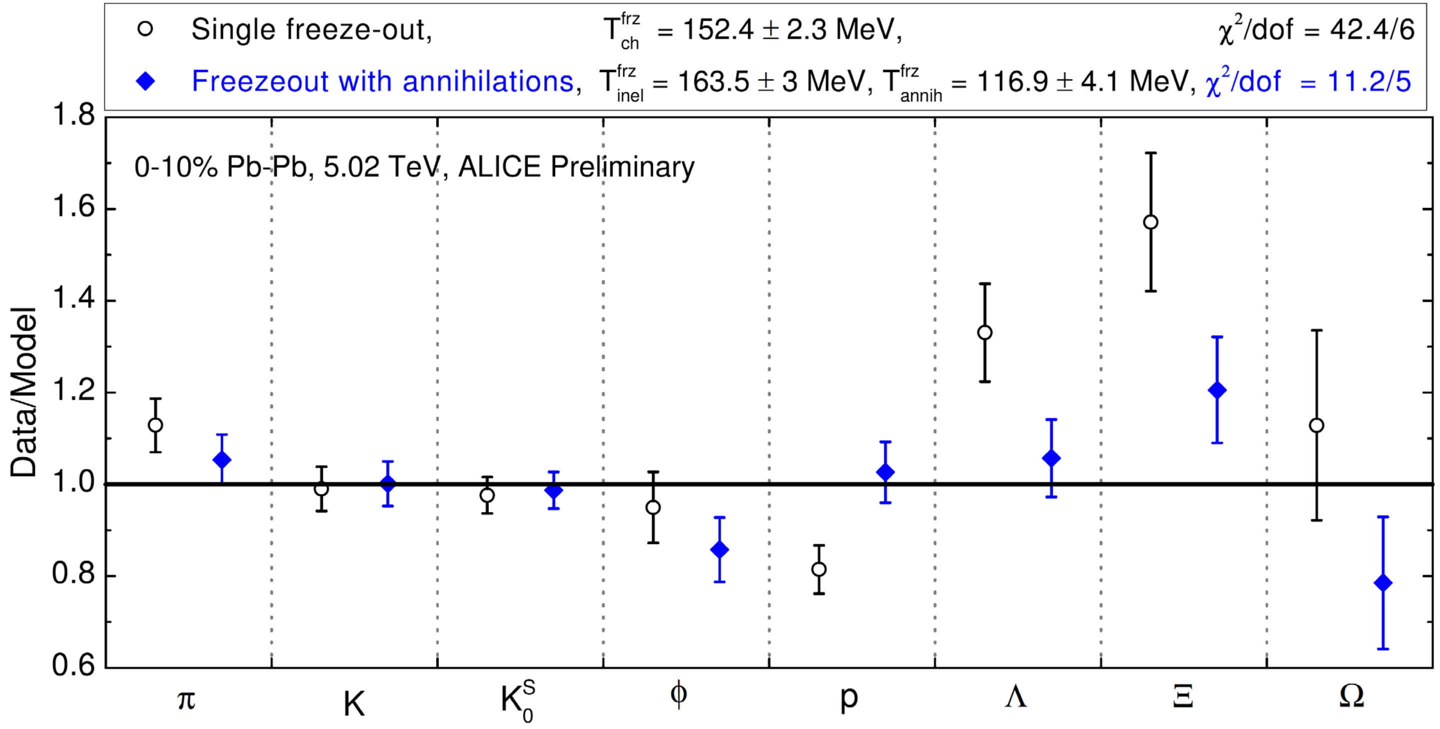
Data permit freeze-out of light (anti-)(hyper-)nuclei at any $T < T_{ch}$ in the hadronic phase!

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

Hadronic phase with annihilations

Add nucleon annihilations $N\bar{N} \leftrightarrow 5\pi$ into the PCE framework

(Anti)nucleon and pions numbers no longer conserved, $N_N, N_{\bar{N}}, N_\pi \neq$ const. but $\frac{N_N + N_{\bar{N}}}{2} + \frac{N_\pi}{5} = \text{const}$



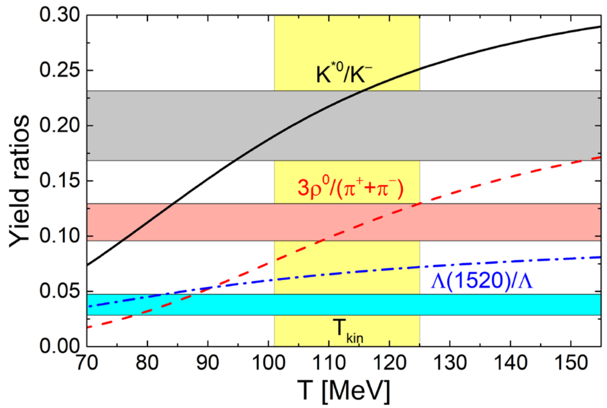
$$\mu_N = \mu_{\bar{N}} = 2.5\mu_\pi$$

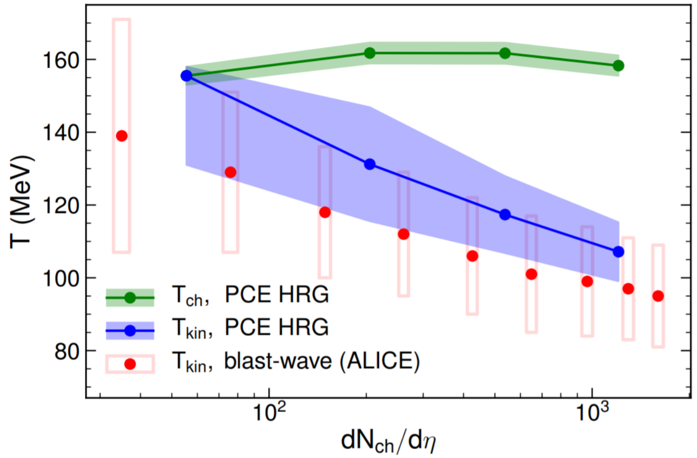
Including annihilations in the hadronic phase leads to a much nicer fit

NB: hyperon annihilations not allowed here

Summary

- **Partial chemical equilibrium** is a thermodynamical approach for resonance abundances in the hadronic phase
  - Short-lived resonances are generally suppressed, stable hadrons unaffected
- **Thermal fits 2.0:** Fit T_{ch} and T_{kin} simultaneously to yields of both stable and short-lived hadrons
  - extract kinetic freeze-out temperature from yields
  - ρ^0 and K^{*0} are particularly sensitive
  - solves the T_{kin}-vs-$\langle\beta_T\rangle$ anticorrelation problem of blast-wave fits
- **Implementation:** Thermal-FIST v1.3+
  - Calculations of abundances and thermodynamic properties
  - Thermal fits 2.0
  - Event generator
  - Saha equation





Thanks for your attention!