Statistical-thermal FIST package

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V.V., H. Stoecker, arXiv:1901.05249, *Computer Physics Communications* (accepted)

Source code: https://github.com/vlvovch/Thermal-FIST

ALICE Physics Week 2019, Prague, Czech Republic

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

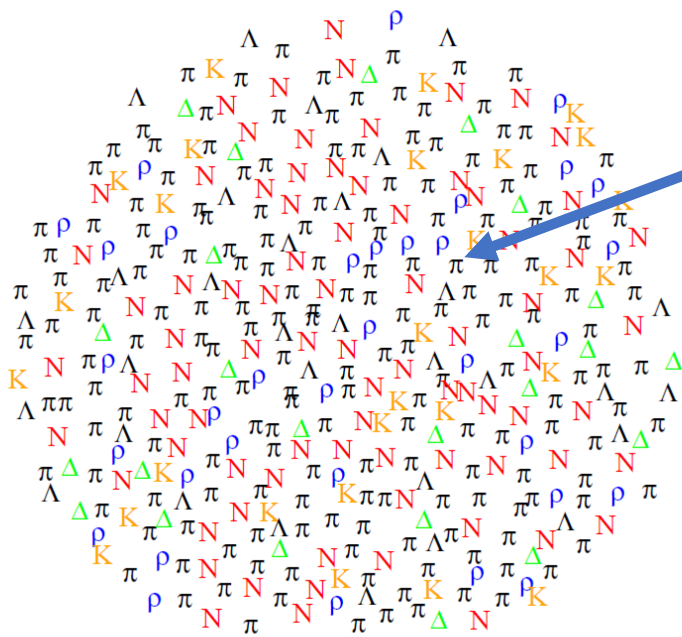
FIAS Frankfurt Institute for Advanced Studies

Hadron resonance gas (HRG) at freeze-out

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

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

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



© J. Cleymans

Thermal model:
Equilibrated hadron resonance gas at the chemical freeze-out stage of high-energy collisions

Model parameters:
T – temperature
μ_B, μ_Q, μ_S – chemical potentials
V – system volume

and many more aspects

Thermal model tools

Available thermal model codes:

1) **SHARE 3** [G. Torrieri, J. Rafelski, M. Petran, et al.] *Since 2003*
Fortran/C++. Chemical (non-)equilibrium, fluctuations, charm, nuclei
open source: http://www.physics.arizona.edu/~gtshare/SHARE/share.html

2) **THERMUS 4** [S. Wheaton, J. Cleymans, B. Hippolyte, et al.] *Since 2004*
C++/ROOT. Canonical ensemble, EV corrections, charm, nuclei
open source: https://github.com/thermus-project/THERMUS

New development:

Thermal-FIST* (current version: v1.2.1) [**V.V.**, H. Stoecker]
C++. Chemical (non-)equilibrium, EV/vdW corrections, Monte Carlo, (higher-order) fluctuations, canonical ensemble, combinations of effects
open source: https://github.com/vlvovch/Thermal-FIST
physics manual: arXiv:1901.05249 *Since 2018*

__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**

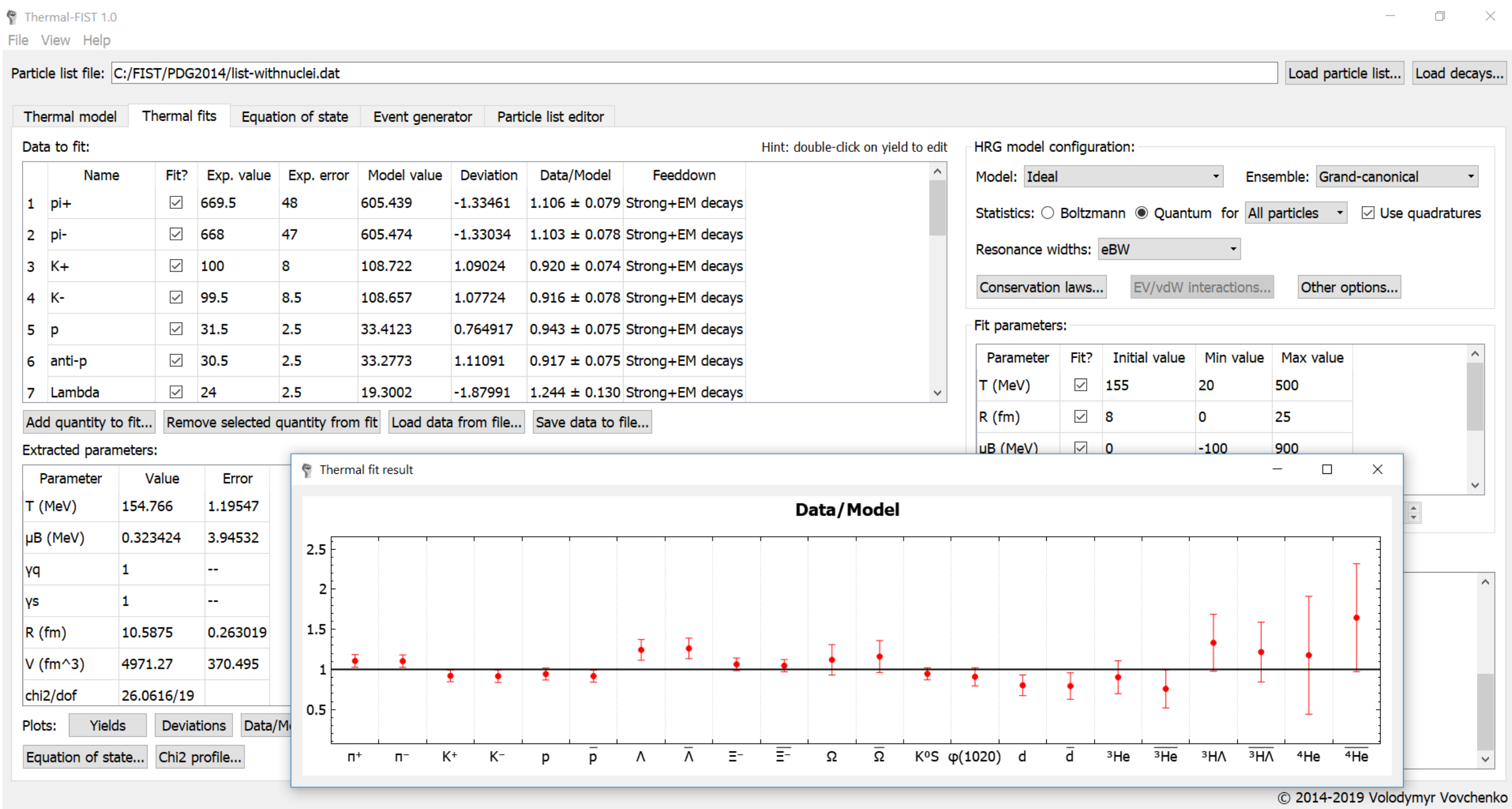
```
# Clone the repository from GitHub
git clone https://github.com/vlvovch/Thermal-FIST.git
cd Thermal-FIST

# 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*

Thermal-FIST

Graphical user interface for *general-purpose* thermal model applications



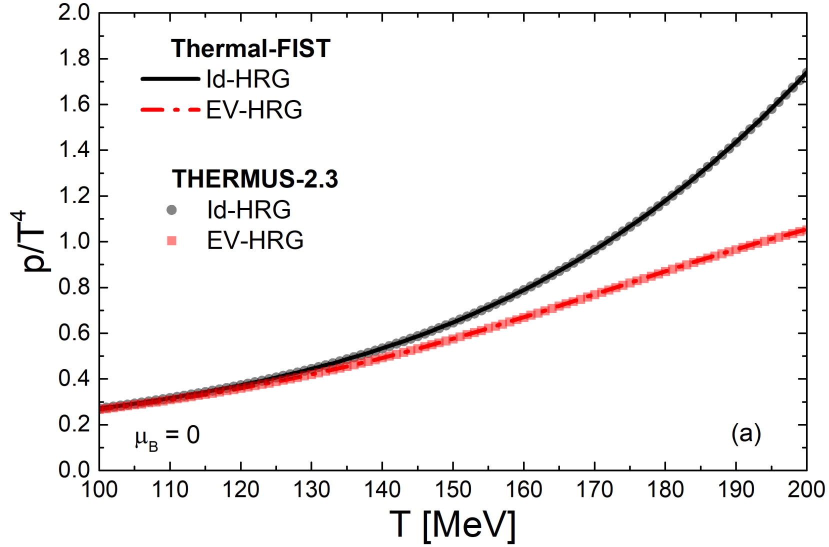
"So that's how you get your results so quickly!"

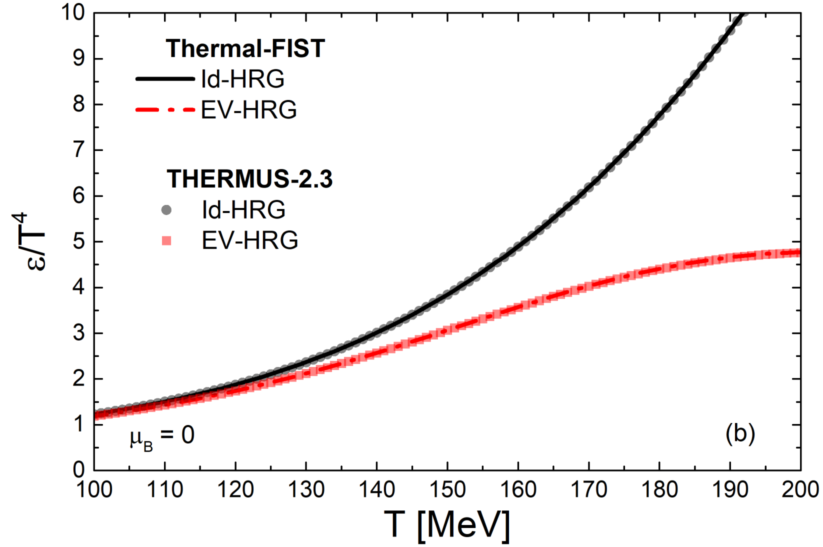
J. Cleymans

"Thanks for reproducing my results!"

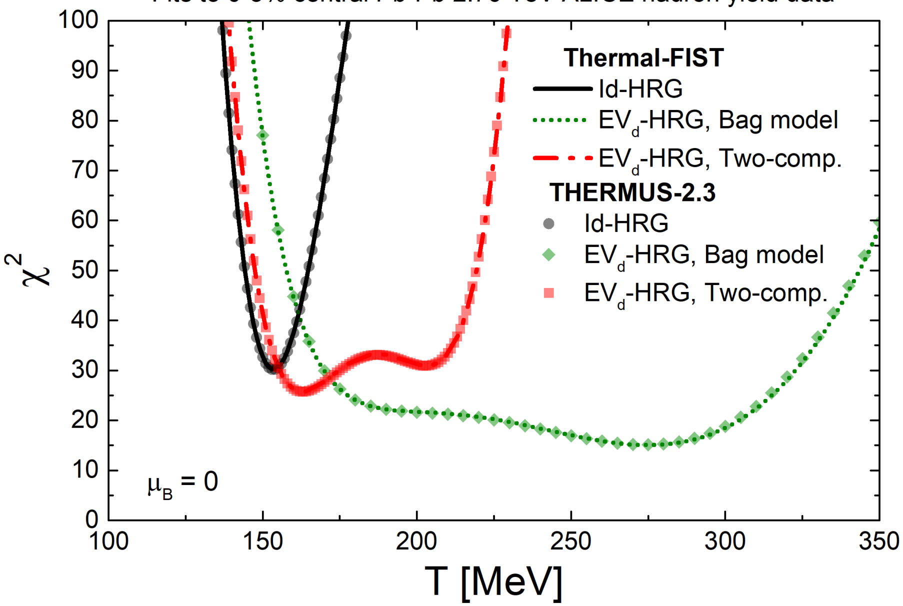
F. Becattini

FIST in THERMUS mode: cross-check





Fits to 0-5% central Pb-Pb 2.76 TeV ALICE hadron yield data



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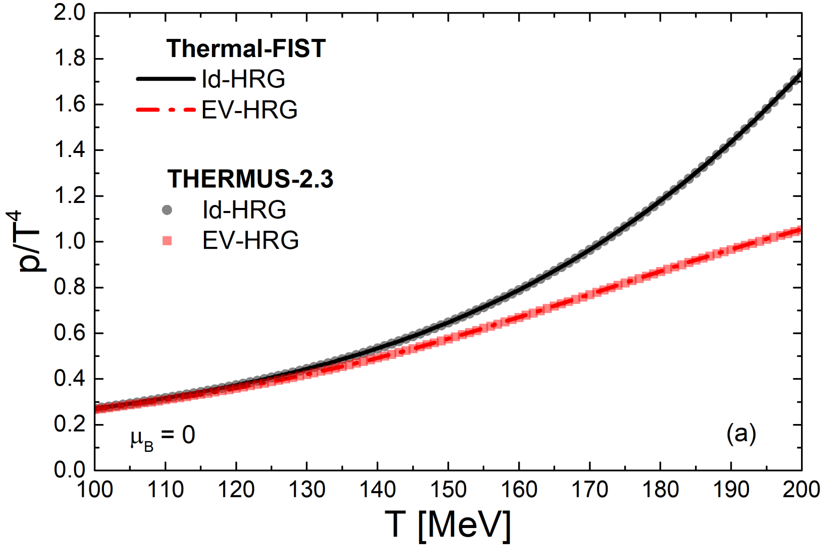
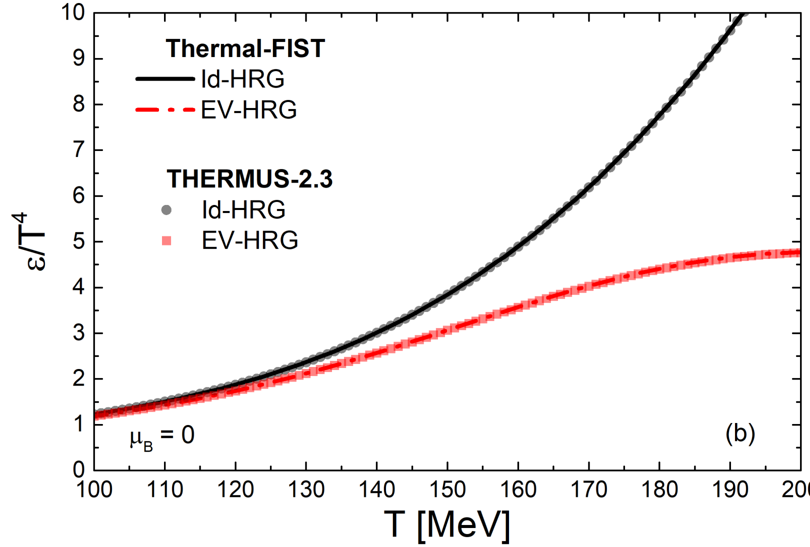
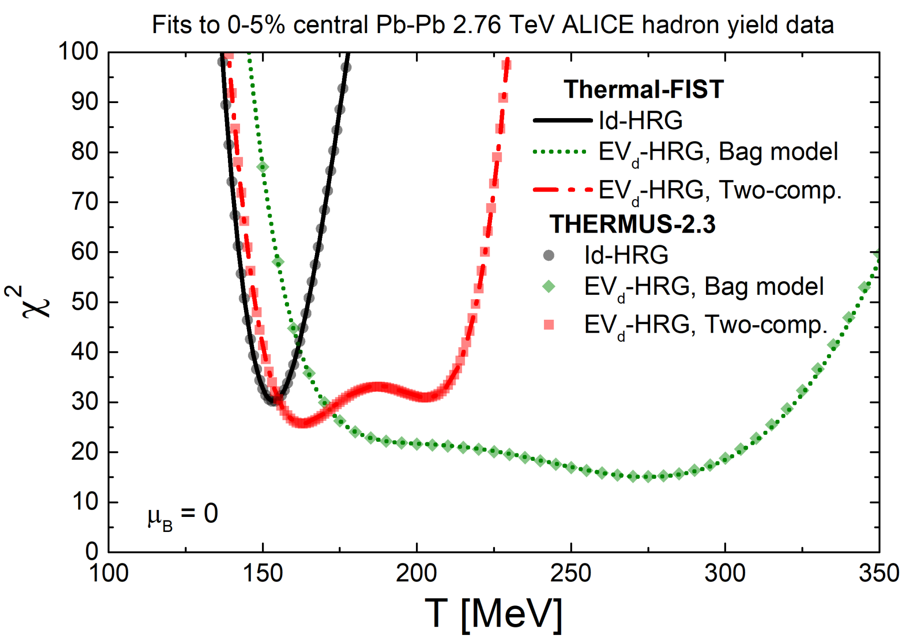
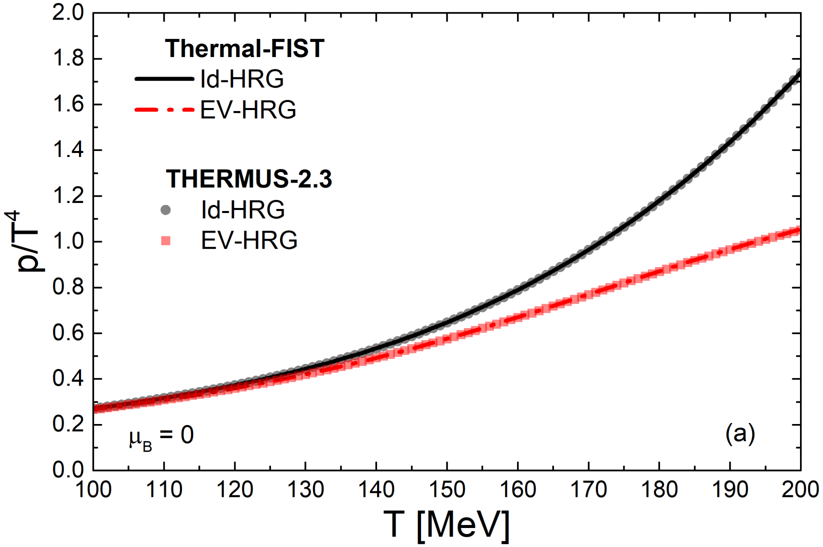


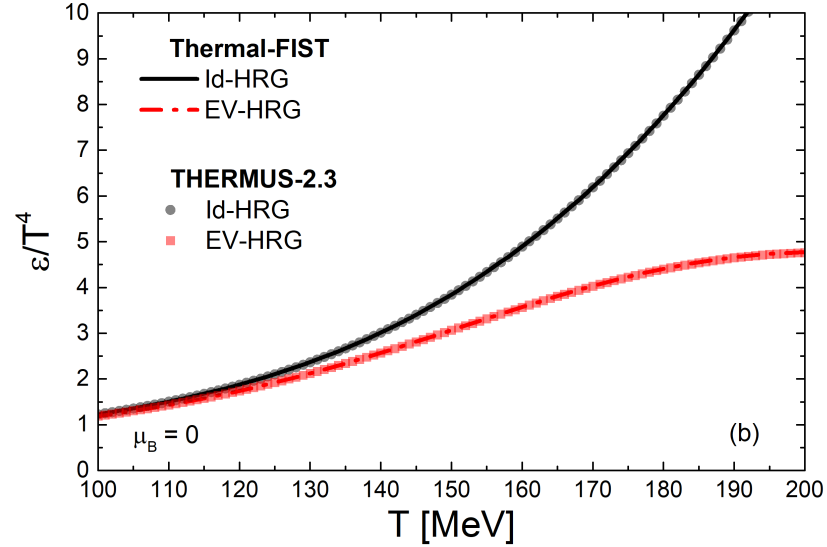


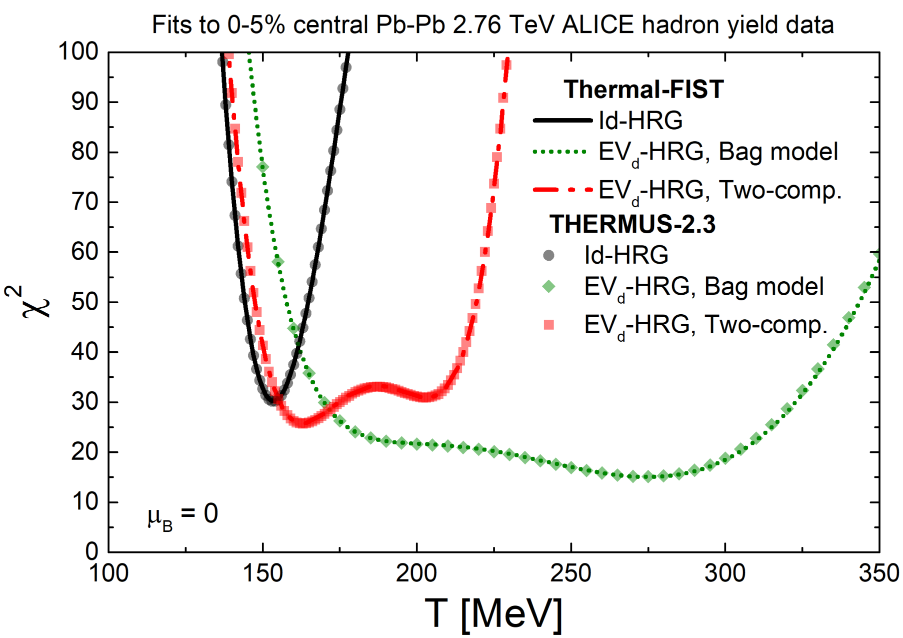


FIST: Fist IS Thermus

FIST in THERMUS mode: cross-check







FIST: Fist IS Thermus

and more...

FIST and Jupyter notebooks

Usual usage: through GUI or compiled C++ macros

NEW: Interactive notebooks through Jupyter (xeus kernel and ROOT-cling)*

jupyter FitExample Last Checkpoint: несколько секунд назад (unsaved changes) Logout

File Edit View Insert Cell Kernel Widgets Help Trusted C++14

Run Code

Initialize and run the fitter

In [7]:
```
// Set chemical potentials to zero
model.SetBaryonChemicalPotential(0.0);
model.SetElectricChemicalPotential(0.0);
model.SetStrangenessChemicalPotential(0.0);
model.SetCharmChemicalPotential(0.0);
model.FillChemicalPotentials();

// Initialize the fitter
ThermalModelFit fitter(&model);

// Do not fit muB, it is zero at LHC
fitter.SetParameterFitFlag("muB", false);

// Pass the data to the fitter
fitter.SetQuantities(dataPbPb010);

// Perform the fit
ThermalModelFitParameters fitResult = fitter.PerformFit(false);
```

Print the fitted parameters and the χ^2

In [8]:
```
cout << "Extracted parameters:" << endl;
cout << setw(15) << "T [MeV]" << " = " << setw(15) << 1.e3 * fitResult.T.value << " +- " << 1.e3 * fitResult.T.error <<
cout << setw(15) << "R [fm]" << " = " << setw(15) << fitResult.R.value << " +- " << fitResult.R.error << endl;
cout << setw(15) << "chi2/dof" << " = " << setw(15) << fitResult.chi2 << "/" << fitResult.ndf << endl;
```

```
Extracted parameters:
        T [MeV] =         155.28 +- 2.78665
         R [fm] =        10.3342 +- 0.545205
       chi2/dof =        15.3832/6
```

*Since version 1.2.1, example at github.com/vlvovch/FIST-jupyter

Thermal model aspects in FIST

- Extensions of the HRG model
  - finite resonance widths
  - repulsive interactions (excluded volume)
  - van der Waals interactions (*criticality*)
  - particle number fluctuations and correlations
  - chemical non-equilibrium (γ_q , γ_s) a la Rafelski
- Equation of state
- Canonical statistical model (CSM)
  - (local) (selective) exact conservation of conserved charges
  - uniform description of hadrochemistry from small to large systems
- 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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Finite resonance widths

$$n_i(T,\mu;m_i) \to \int_{m_i^{\min}}^{m_i^{\max}} dm\, \rho_i(m)\, n_i(T,\mu;m)$$

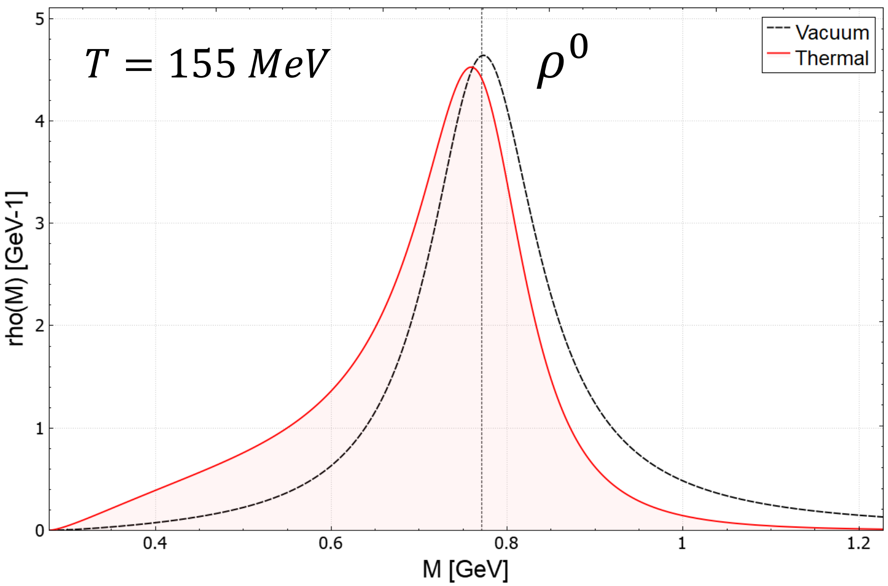
1) Zero-width approximation

Simplest and common possibility

2) Energy-(in)dependent Breit-Wigner

$$\rho_i^{\mathrm{BW}}(m) = A_i \frac{2\, m\, m_i\, \Gamma_i}{(m^2 - m_i^2)^2 + m_i^2 \Gamma_i^2}$$

$$\Gamma_{i\to j}(m) = b_{i\to j}\, \Gamma_i \left[1 - \left(\frac{m^{\mathrm{thr}}_{i\to j}}{m}\right)^2\right]^{L_{i\to j}+1/2}$$



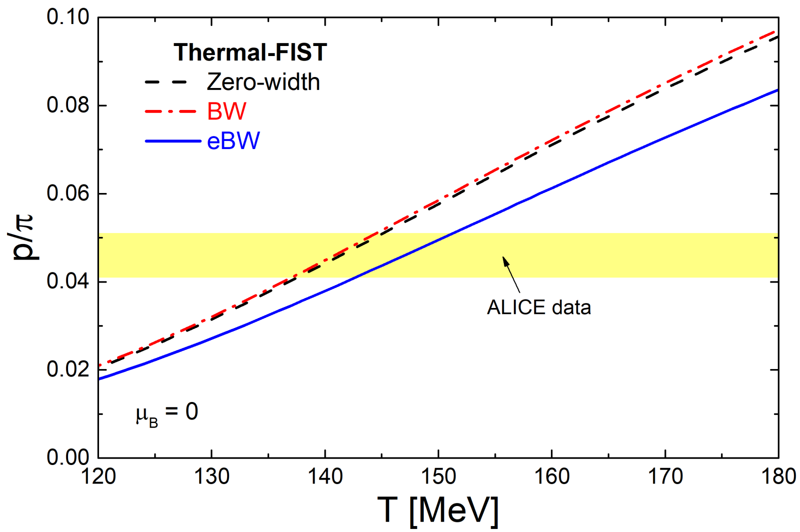
suppression of the spectral strength at the threshold

Alternative: S-matrix approach using phase shifts $\rho_i(m) \propto \frac{\partial \delta(m)}{\partial m}$

Usually based on measured scattering phase shifts

[cf. Huovinen et al., PLB '17; P.M. Lo et al, PLB '19]

Finite resonance widths: data description

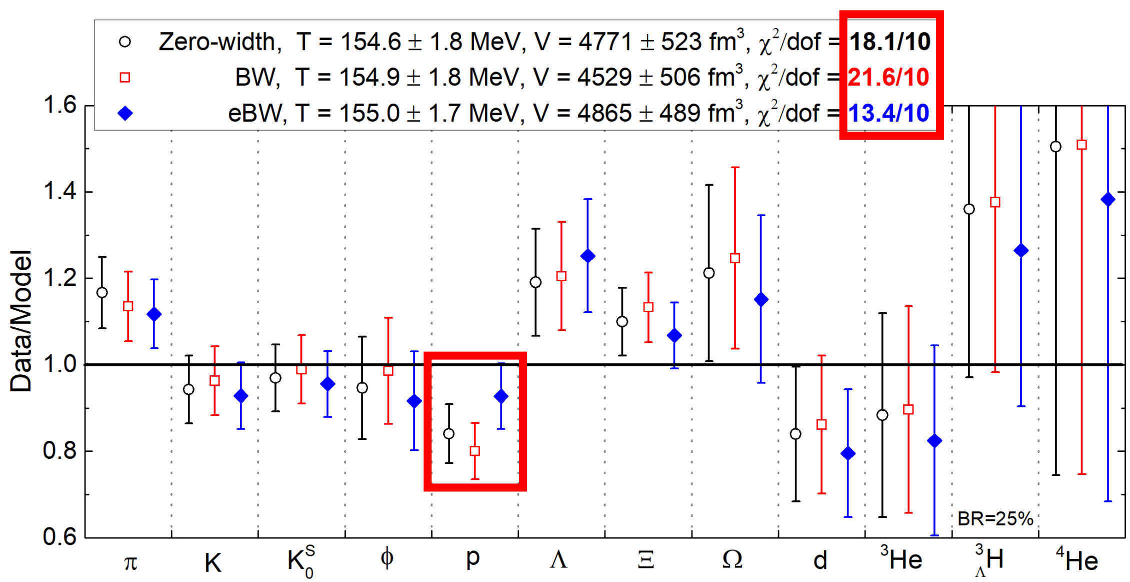


Energy-dependent Breit-Wigner leads to a 15% suppression of proton yields

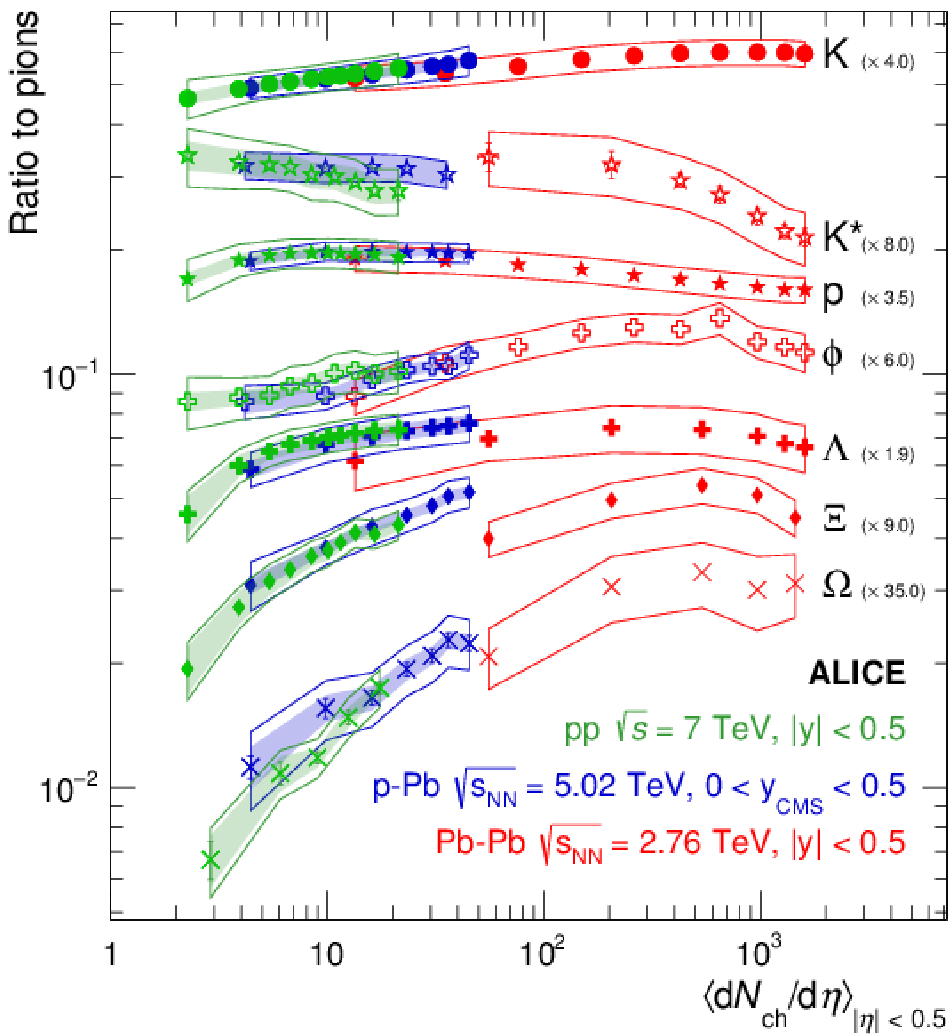
also affected: 10% decrease of Λ

This is enough to describe the 'proton yield anomaly' at 2.76 TeV*

**but beware of the 5 TeV data, see below*



Multiplicity dependence of hadrochemistry



[ALICE collaboration, 1807.11321]

- Hadron yield ratios exhibit multiplicity dependence
- Grand-canonical picture predicts no multiplicity dependence
- Ratios appear to approach a plateau at high-multiplicities → grand-canonical plateau?
- Can multiplicity-dependence be considered in a macroscopic 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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[Becattini et al., ZPC '95, ZPC '97]

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Exact conservation around midrapidity, $V_C = k dV/dy$. How large is k?

Net-proton fluctuations affected by baryon number conservation

[Braun-Munzinger, Rustamov, Stachel, 1612.00702]

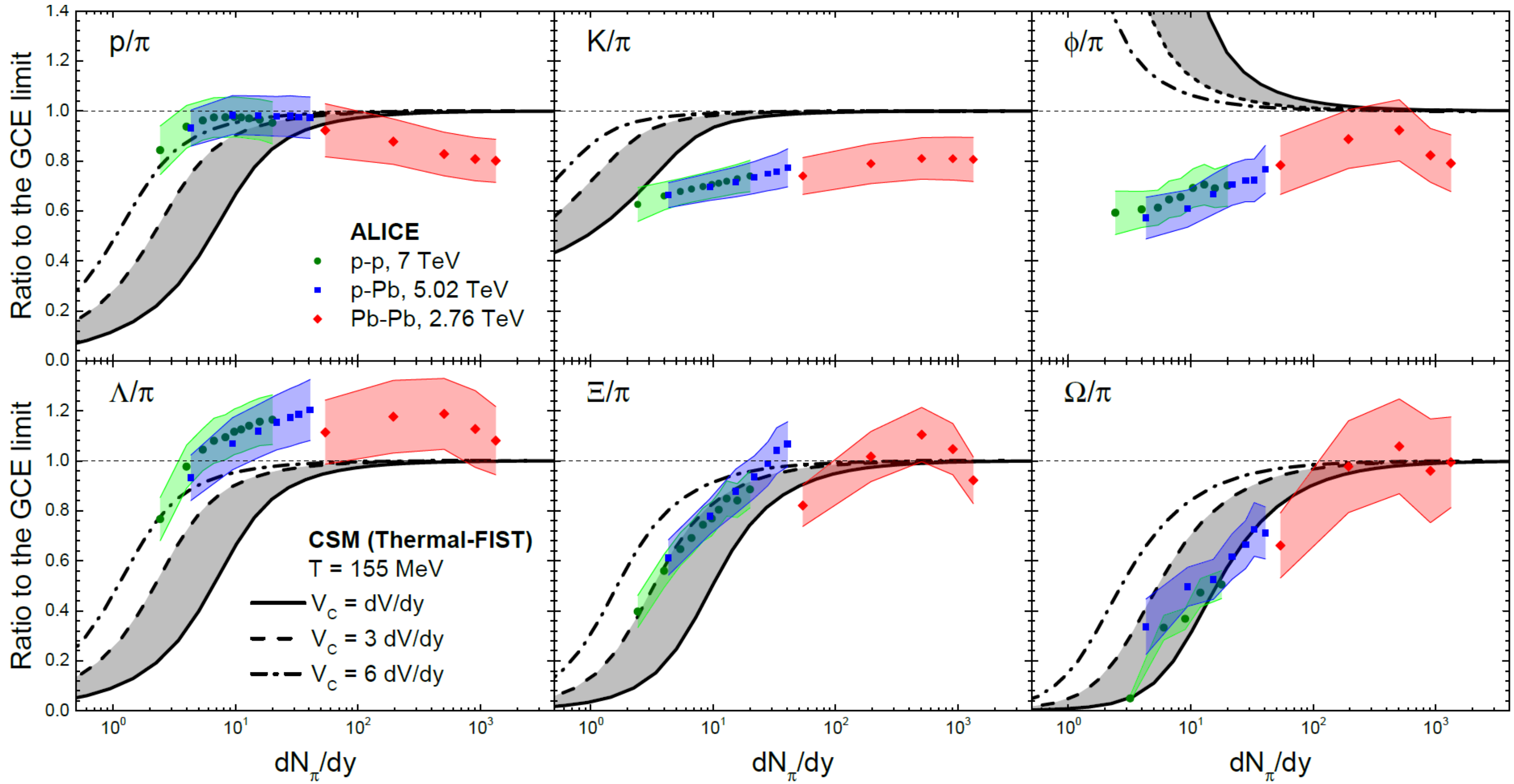
$$\frac{\kappa_2(\mathrm{p}-\bar{\mathrm{p}})}{\langle \mathrm{p} \rangle + \langle \bar{\mathrm{p}} \rangle} \simeq 1 - \frac{\langle \mathrm{p} \rangle}{k \, dN_B/dy}$$

Using ALICE preliminary data for net-p fluctuations [Rustamov, 1704.05329] one obtains $k \sim$ 3-4 for most centrality bins in Pb-Pb collisions

[**V.V.**, Dönigus, Stoecker, 1906.03145]

“Vanilla” CSM at LHC

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



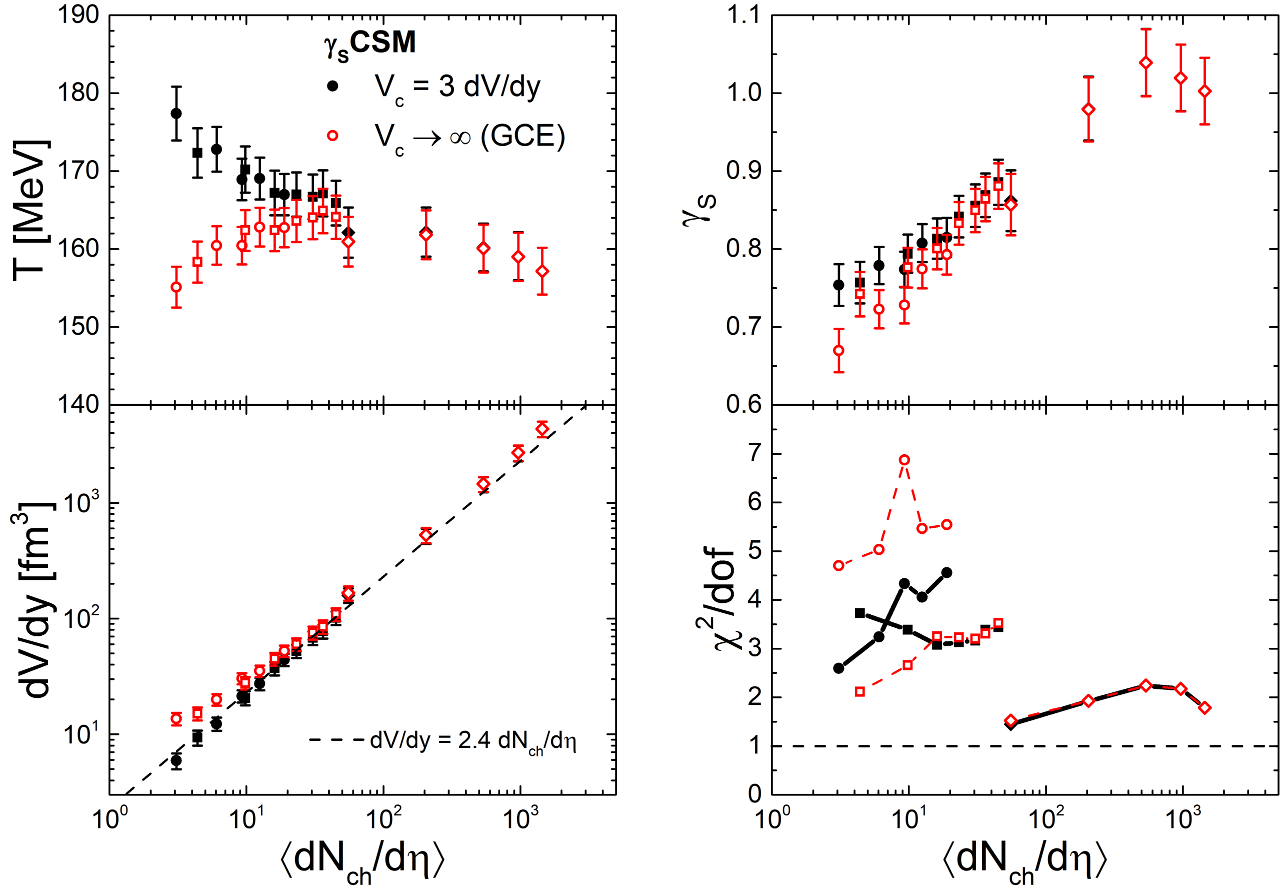
Fair for hyperons, protons and kaons worse, ϕ goes in the opposite direction

[**V.V.**, Dönigus, Stoecker, 1906.03145]

for light nuclei see [**V.V.**, Dönigus, Stoecker, 1808.05245]

Full CSM analysis

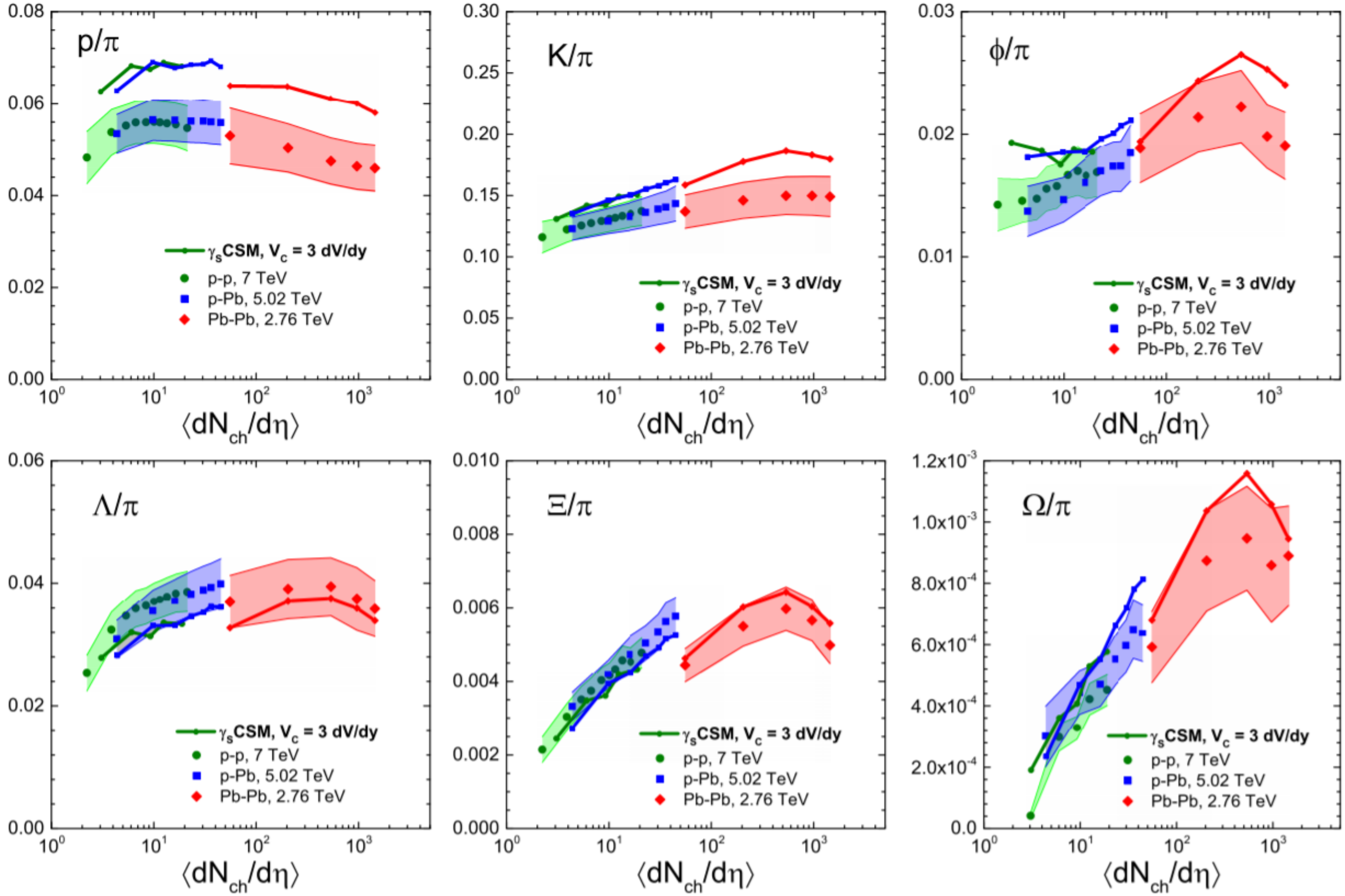
$\boldsymbol{\gamma_S}$**CSM:** $V_C = 3dV/dy$, fit T_{ch} and γ_S at each centrality in p-p, p-Pb, Pb-Pb



Canonical suppression and strangeness saturation important below $dN_{ch}/d\eta \cong 100$

[**V.V.**, Dönigus, Stoecker, 1906.03145]

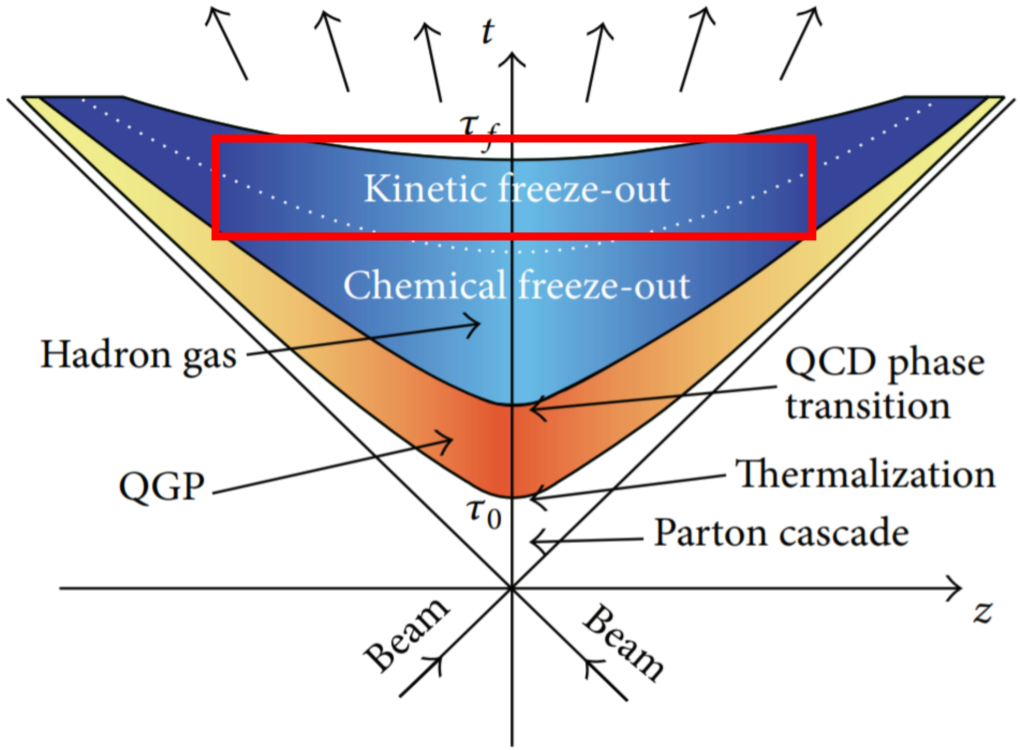
Full CSM analysis: yields



Relative accuracy of γ_SCSM is ~15% across all multiplicity bins

[**V.V.**, Dönigus, Stoecker, 1906.03145]

Hadronic phase



- 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

[e.g., E. Shuryak, Rev. Mod. Phys. 89, 035001 (2017)]

Partial chemical equilibrium

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 $\pi\pi \leftrightarrow \rho$, $\pi K \leftrightarrow K^*, \pi N \leftrightarrow \Delta$, etc.

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:

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

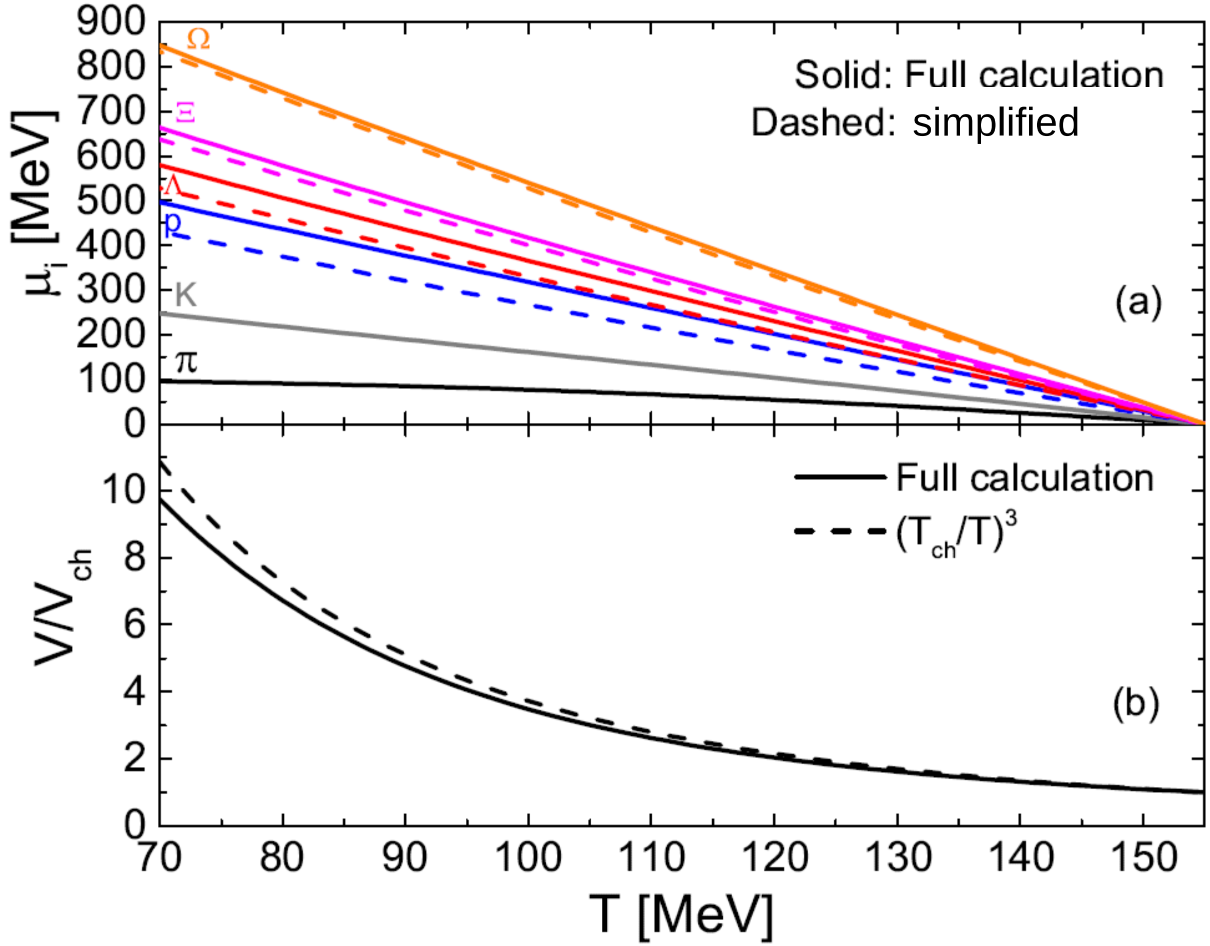
$$\sum_{j \in \text{hrg}} s_j(T, \tilde{\mu}_j) \, V = S(T_{\text{ch}})$$

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

Numerical implementation is in Thermal-FIST development branch

https://github.com/vlvovch/Thermal-FIST/tree/pce

Partial chemical equilibrium at the LHC



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

"Initial conditions" from thermal fits with Thermal-FIST to 0-10% ALICE hadron yields

$T_{ch} = 155$ MeV, $V_{ch} = 4700$ fm^3

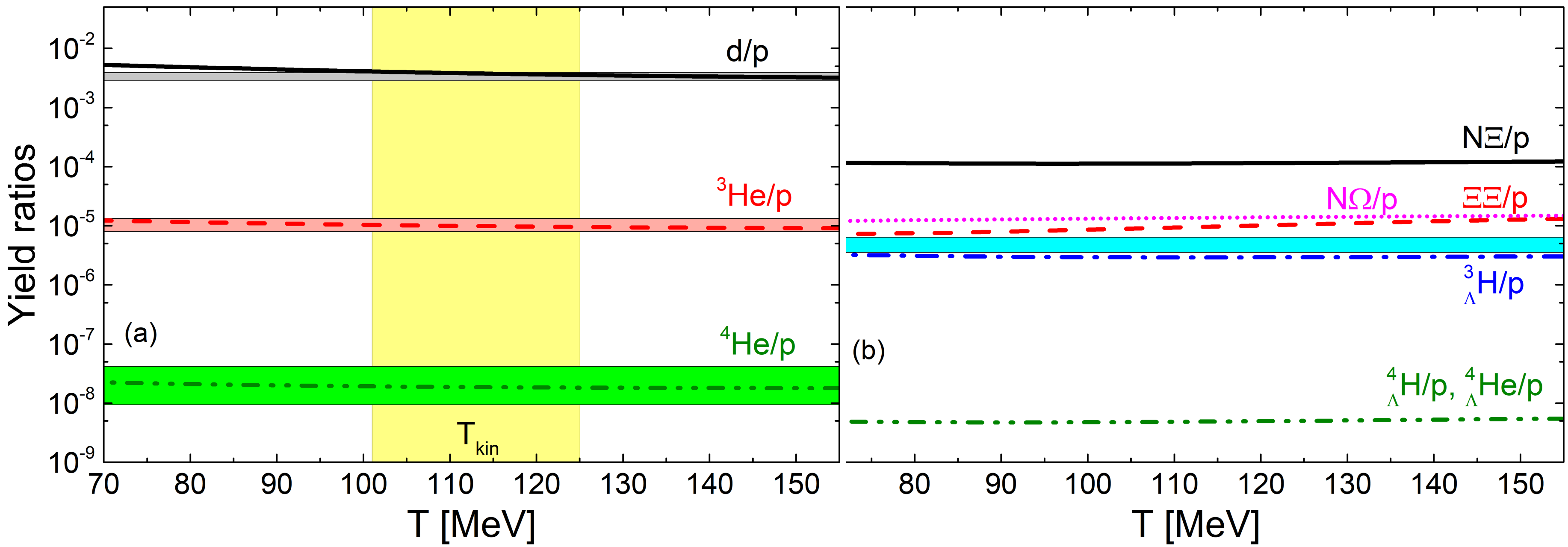
Light nuclei in the hadronic phase

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

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

Saha equation

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



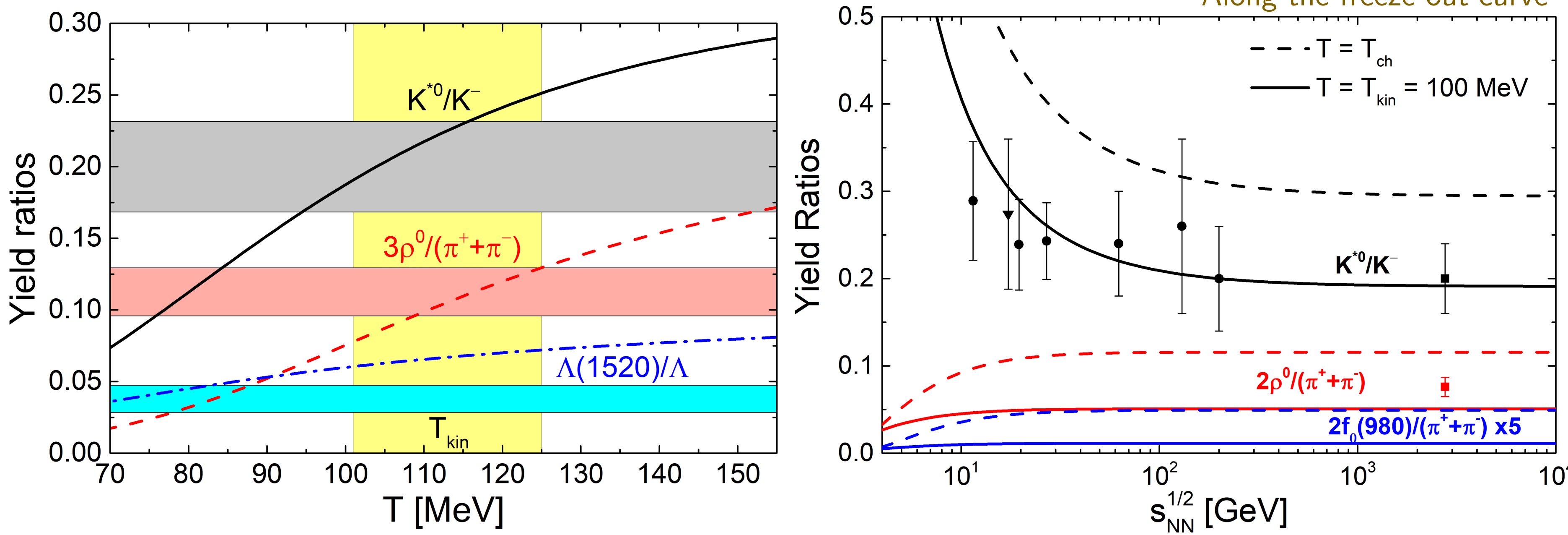
Deviations from thermal model predictions are moderate despite significant cooling and dilution. Is this the reason for why thermal model works so well?

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

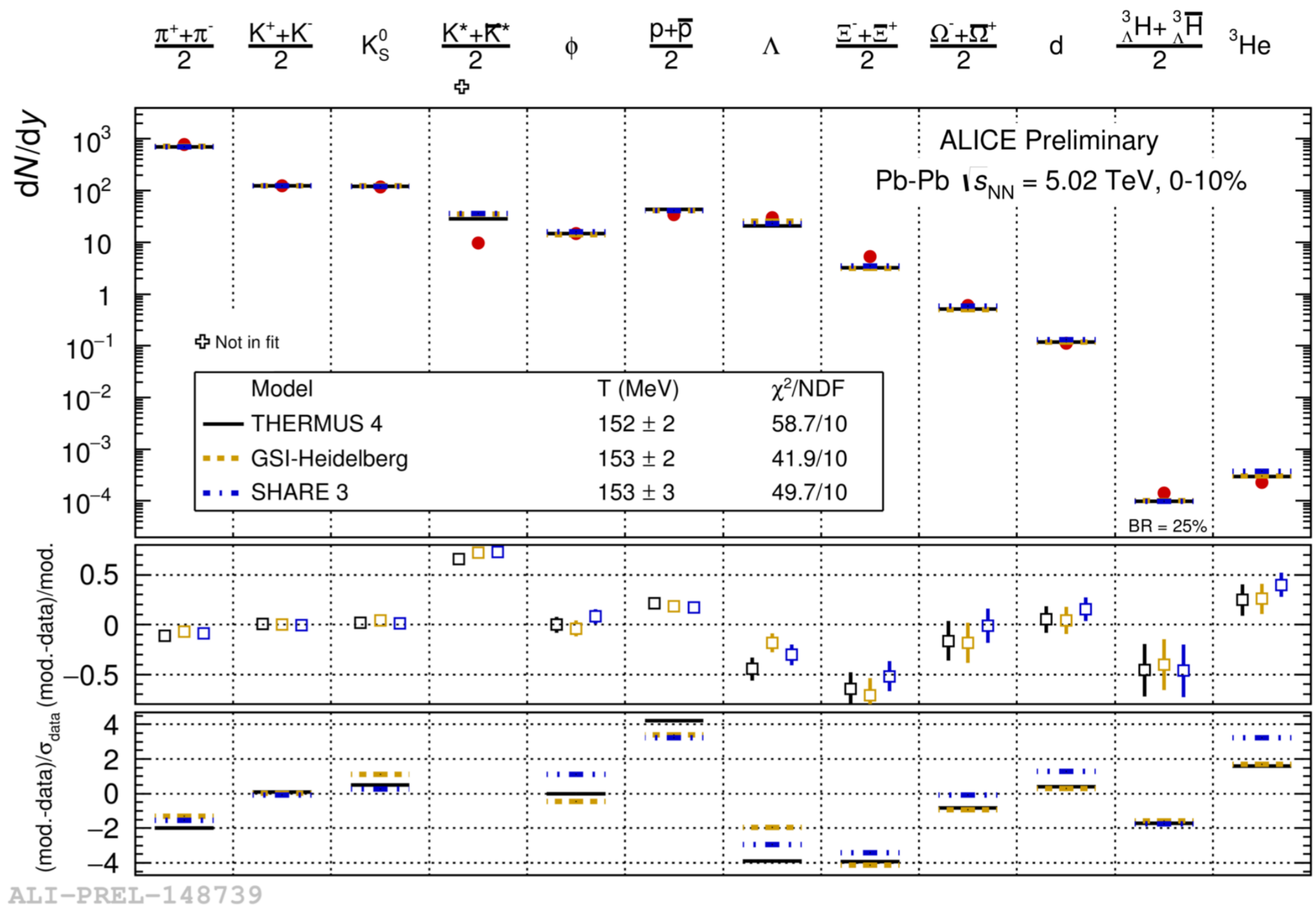


with A. Motornenko

At $T \approx T_{kin}$ the suppressed resonance yields agree quite well with ALICE/RHIS/SPS data for central A+A collisions

This implies significant resonance regeneration in the hadronic phase

5 TeV Pb-Pb data



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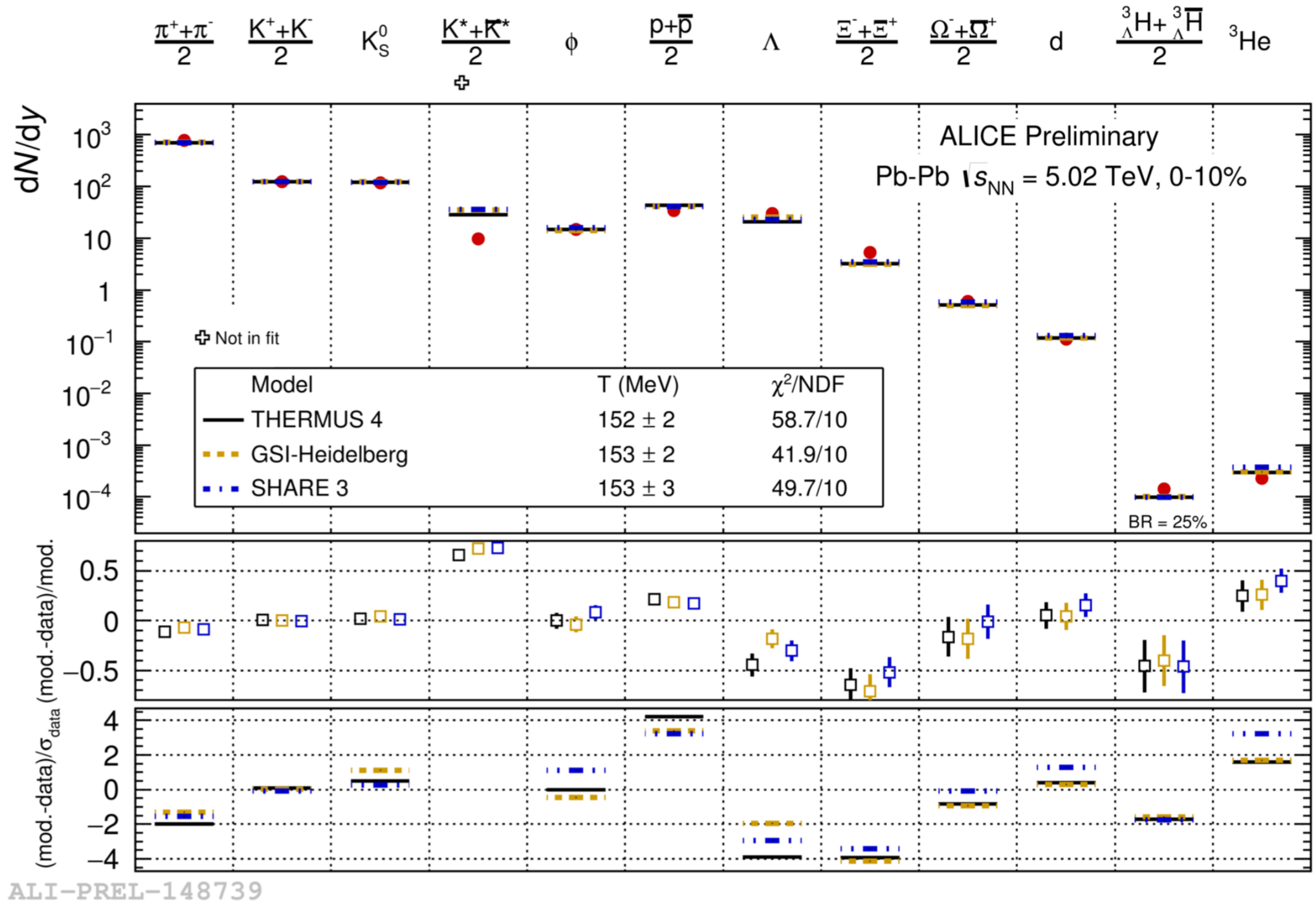


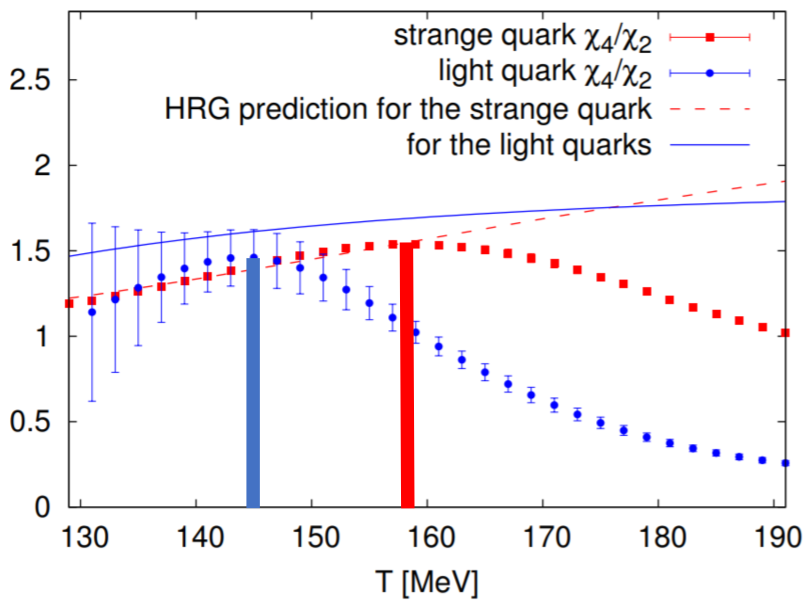
FIST v1.2 (zero-width): $T_{ch} = 151 \pm 2$ MeV, $\chi^2/NDF = 47.4/9$

FIST v1.2 (eBW): $T_{ch} = 152 \pm 2$ MeV, $\chi^2/NDF = 41.9/9$

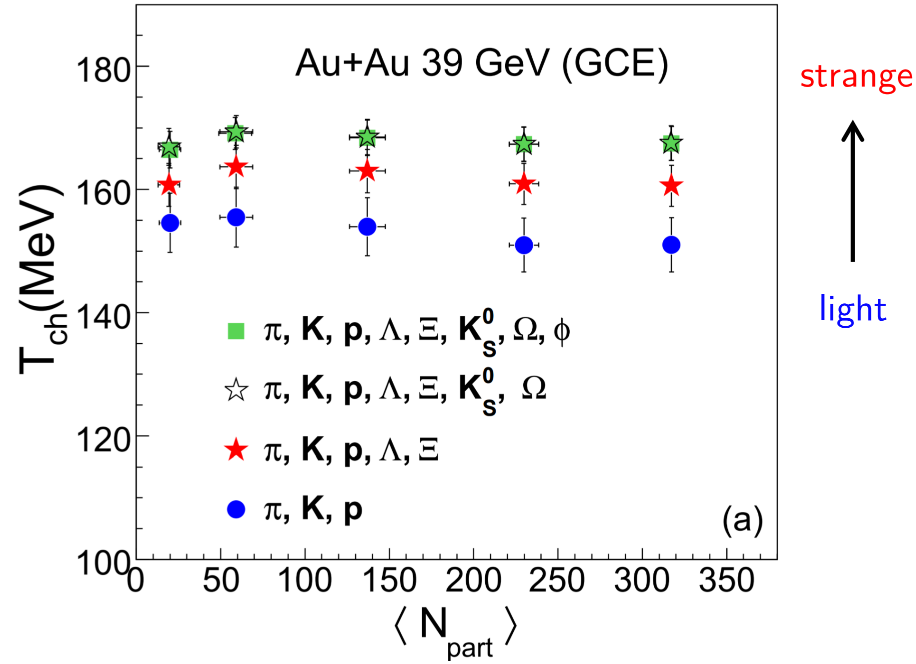
Flavor hierarchy at freeze-out

QCD transition is a broad crossover => different "T_c" for different observables?

strange vs light number susceptibility



[R. Bellwied et al., 1305.6297]



[STAR collaboration, 1701.07065]

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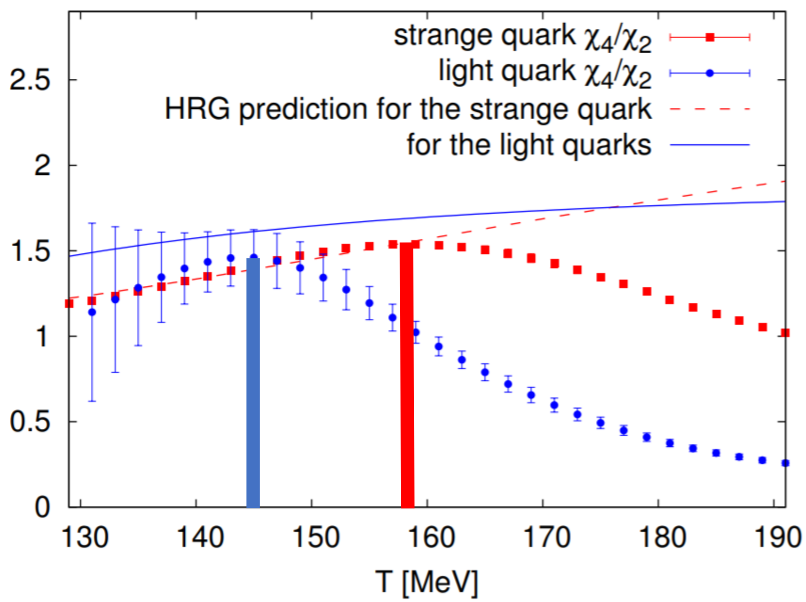

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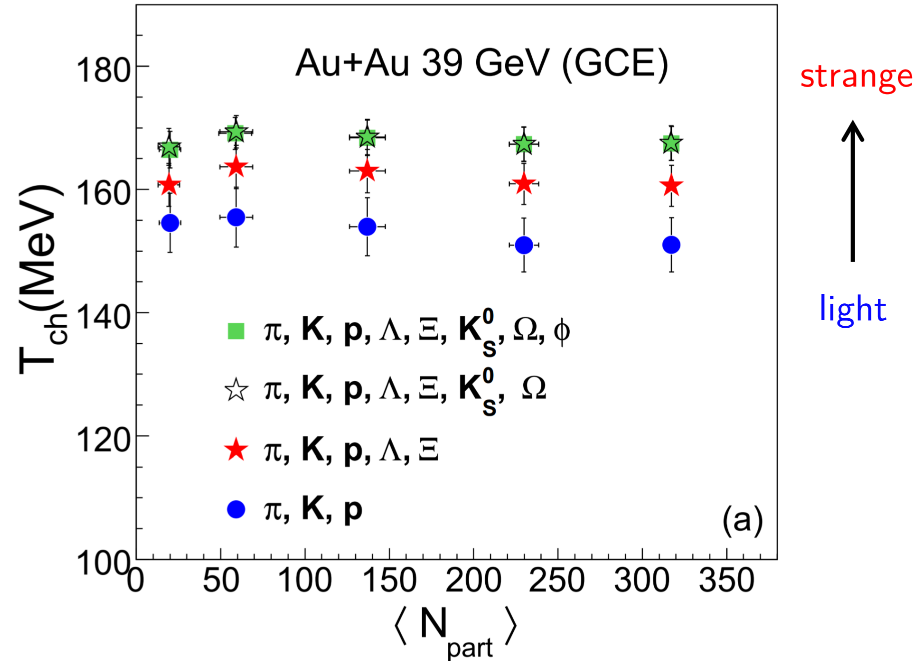


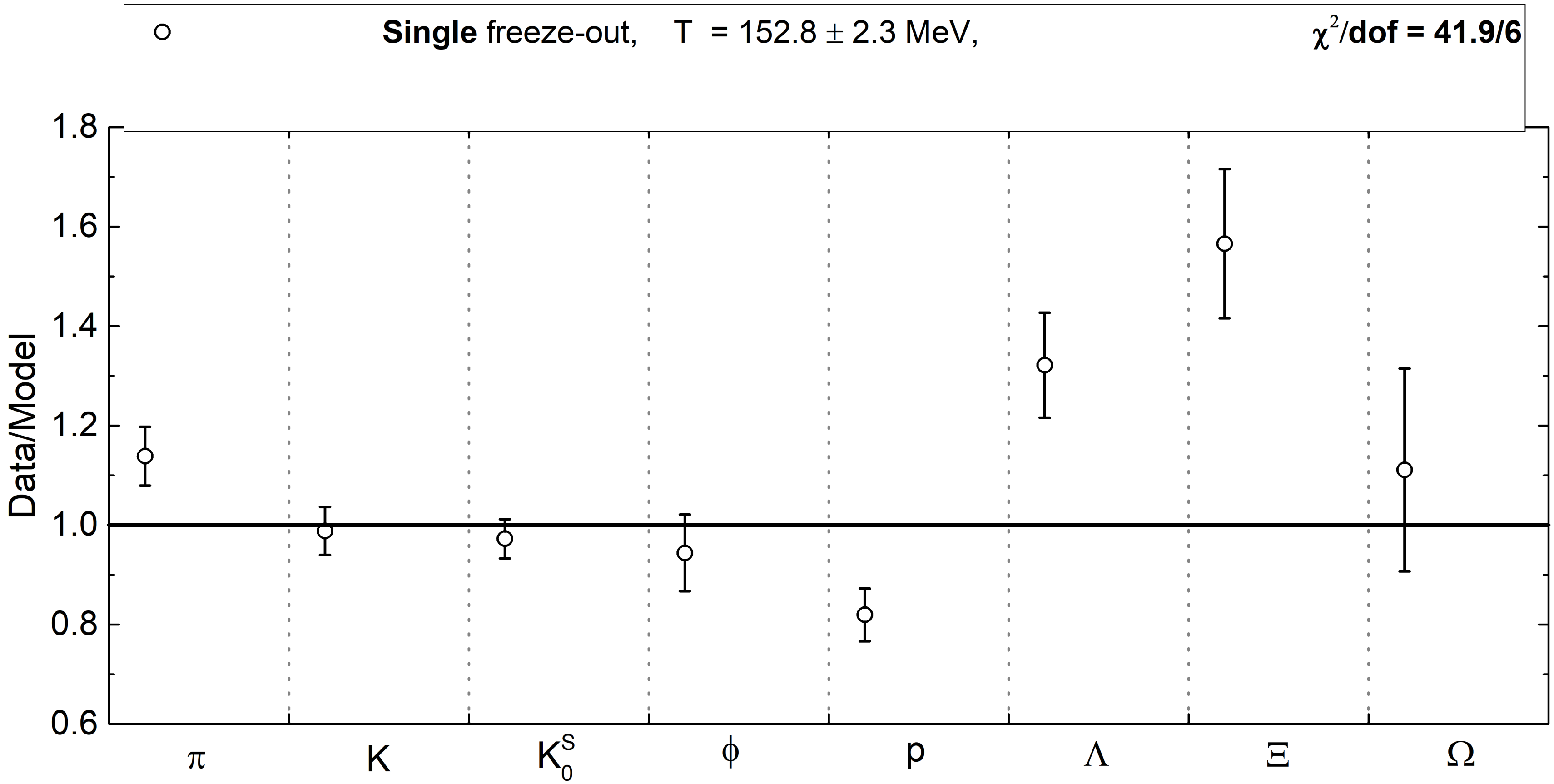
[STAR collaboration, 1701.07065]

Flavor hierarchy implementation in FIST:

- At $T = T_S$ inelastic strangeness reactions freeze, yields of strange hadrons frozen
- At $T_{NS} < T_S$ yields of all light-flavored stable hadrons freeze out
- From T_S to T_{NS} evolution in partial chemical equilibrium of strangeness, strange hadrons, and resonances decaying into them, attain fugacity factors

Flavor hierarchy at freeze-out: Fits

Three global fit parameters: T_S, V_S, and T_{NS}



**no light nuclei here*

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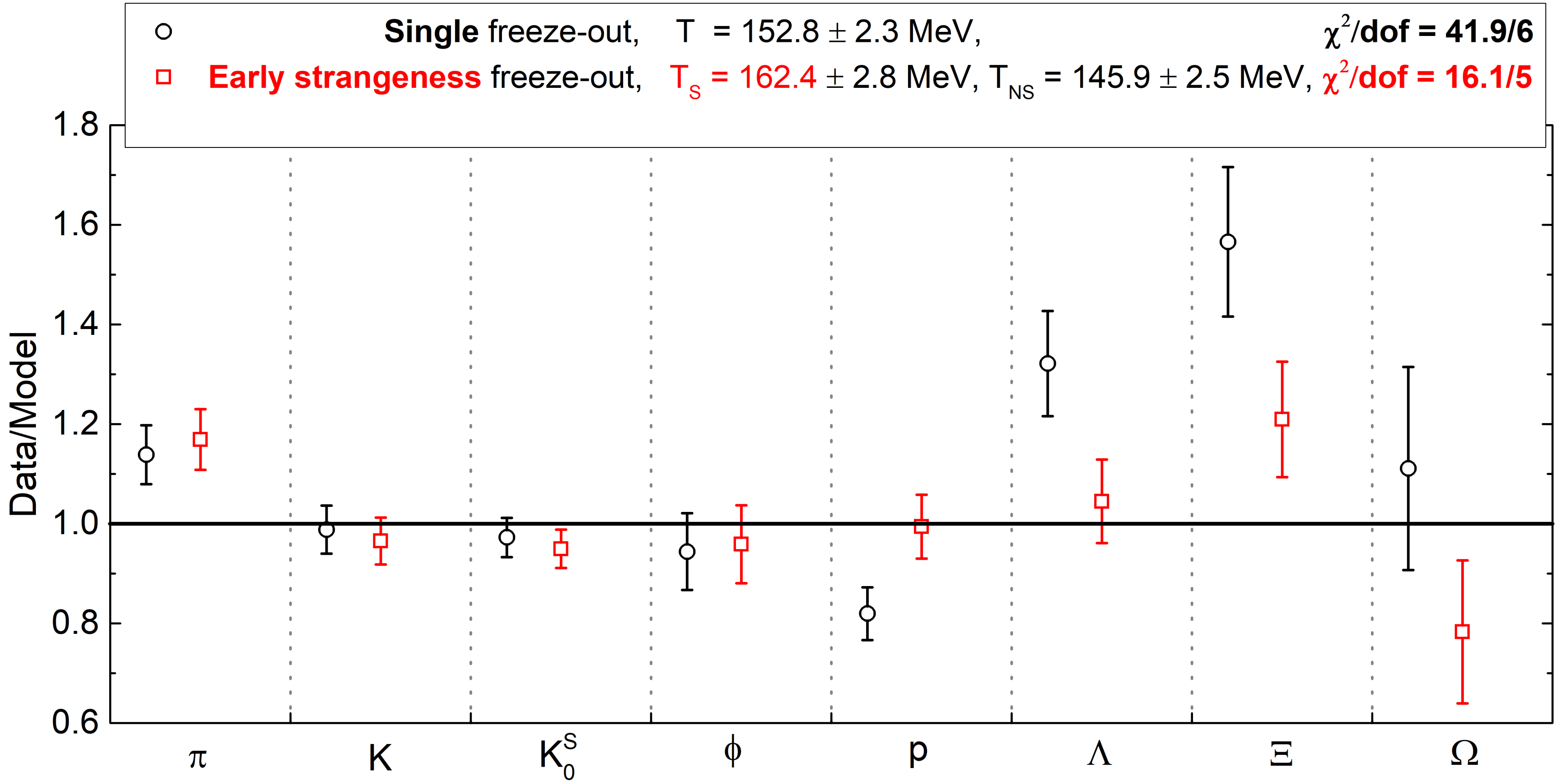

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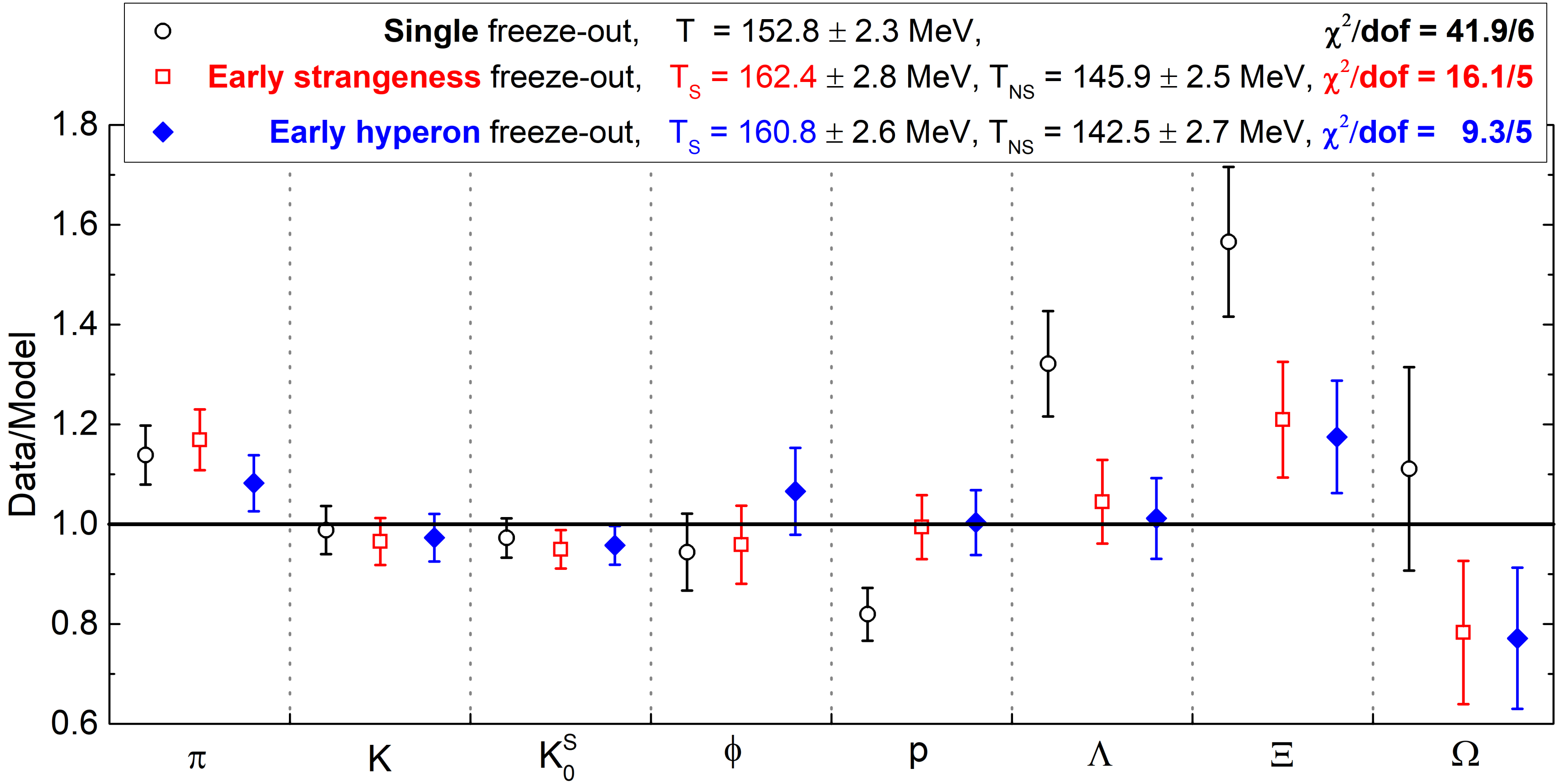

Precision data paves the way to test new scenarios

**no light nuclei here*

Summary and outlook

- **Thermal-FIST** is a user-friendly open source package for general purpose thermal model applications with a modular structure.
- **Usage:**
  - Graphical user interface
  - C++ scripts
  - Jupyter notebooks
- **Highlights of FIST results for ALICE**
  - Resonance widths as a possible solution to ‘proton yield anomaly’
  - Canonical statistical model description of p-p, p-Pb, and Pb-Pb collisions
  - Formation of light nuclei deep in the hadronic phase via the Saha equation
  - Suppression of resonance yields as a consequence of partial chemical equilibrium
  - A unified description of the flavor hierarchy in the chemical freeze-out

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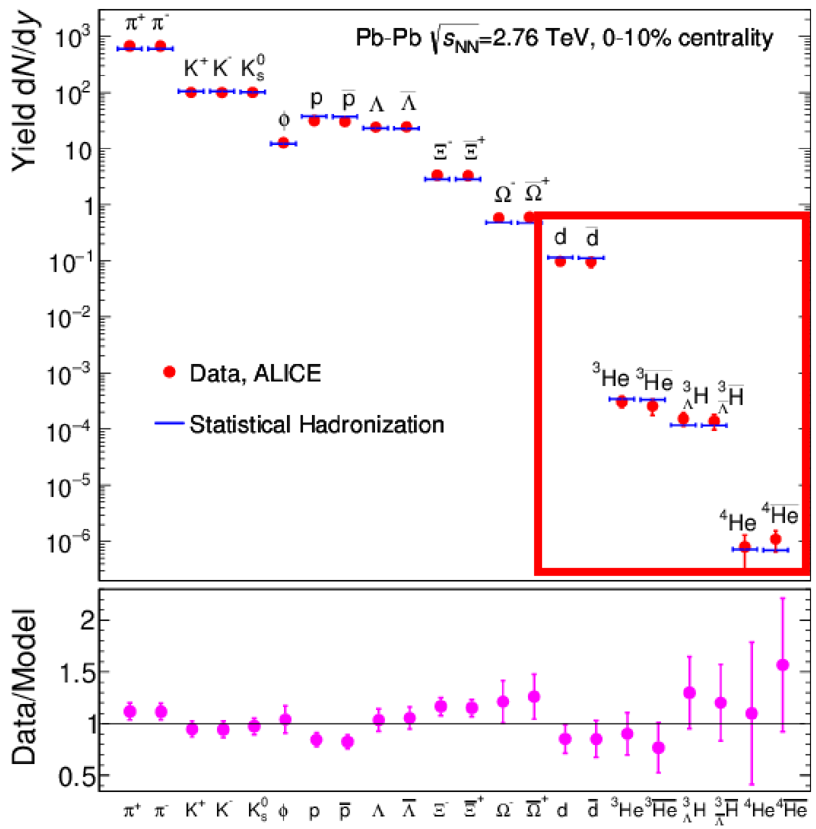
Thanks for your attention!

Backup slides

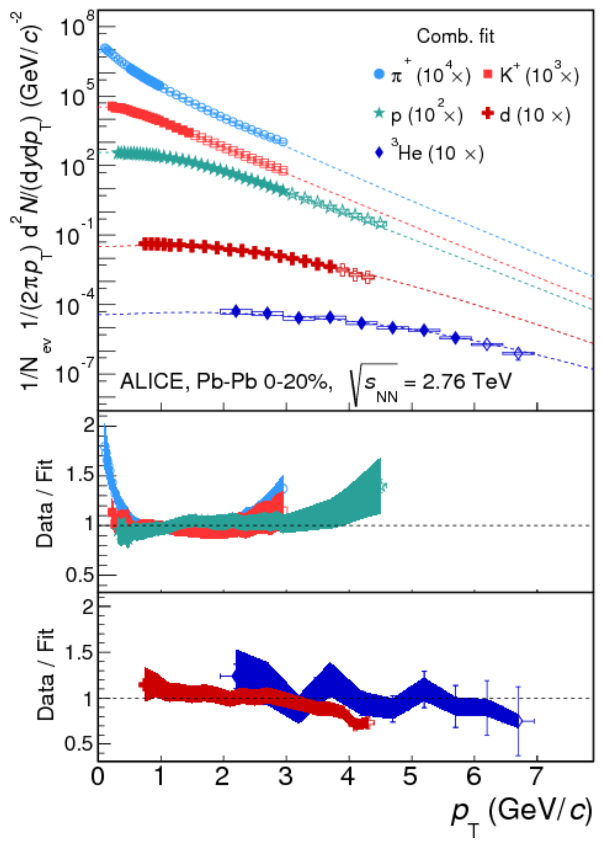
Two experimental observations at the LHC

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



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

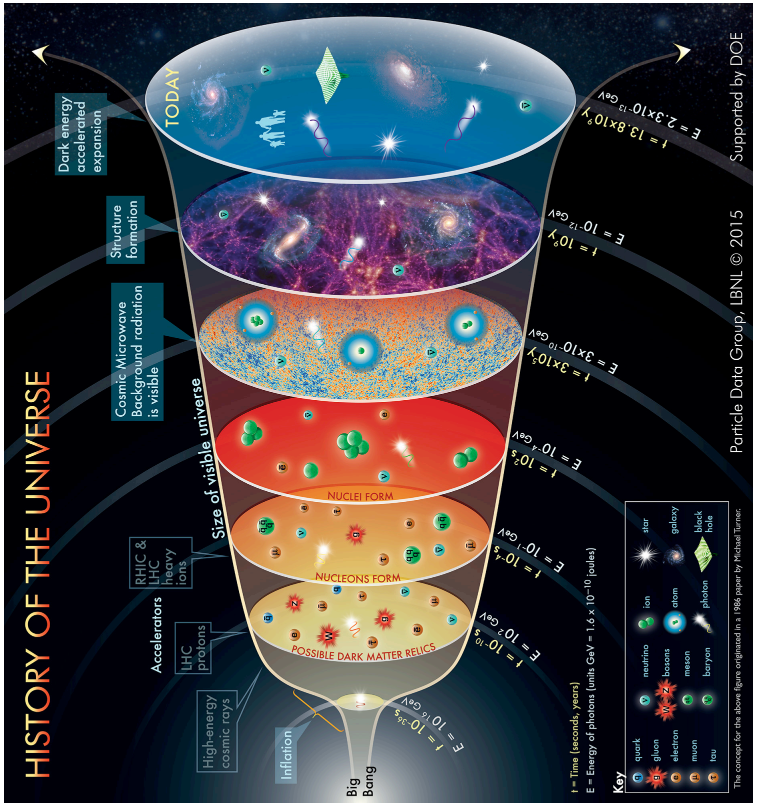
2. Spectra described by blast-wave model at $T_{kin} \approx 100 - 120$ MeV*

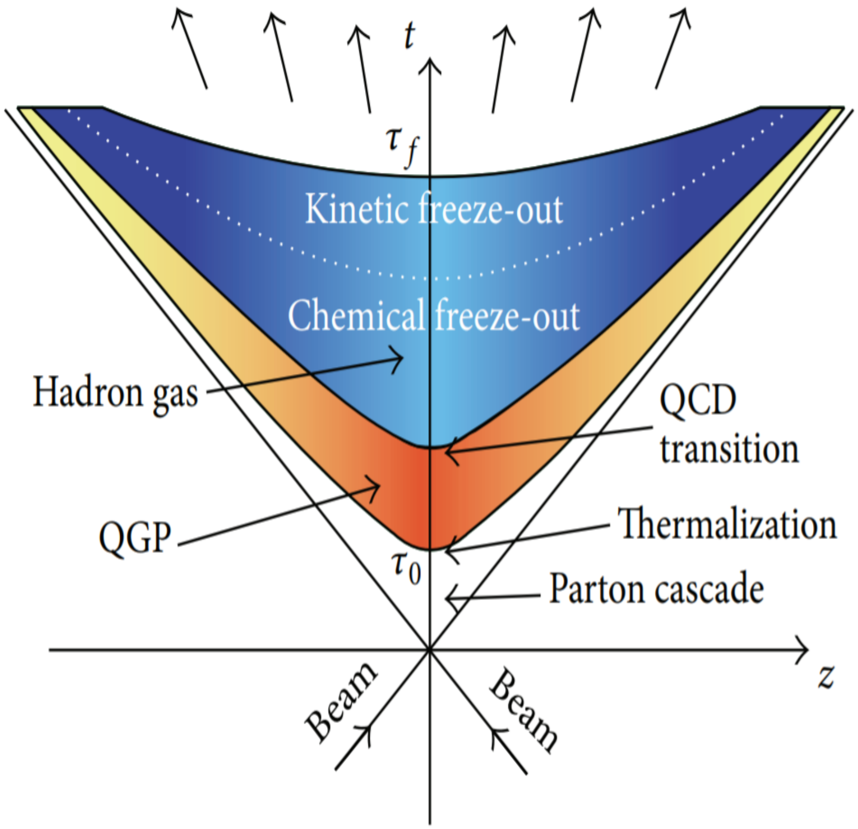


[ALICE collaboration, PRC **93**, 024917 (2016)]

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

Big Bang vs "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 $p + n + \pi \leftrightarrow d + \pi$

LHC nucleosynthesis: simplified 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

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

$d_M \sim 11 - 13, \quad \eta_B \simeq 0.03$

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)]

(Simplified) Saha equation vs thermal model

Saha equation:

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

Thermal model:

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

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

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

Dmytro Oliinychenko,[1] Long-Gang Pang,[1,2] Hannah Elfner,[3,4,5] and Volker Koch[1]

[1]*Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, California 94720, USA*

[2]*Physics Department, University of California, Berkeley, California 94720, USA*

[3]*Frankfurt Institute for Advanced Studies, Ruth-Moufang-Strasse 1, 60438 Frankfurt am Main, Germany*

[4]*Institute for Theoretical Physics, Goethe University, Max-von-Laue-Strasse 1, 60438 Frankfurt am Main, Germany*

[5]*GSI Helmholtzzentrum für Schwerionenforschung, Planckstr. 1, 64291 Darmstadt, Germany*

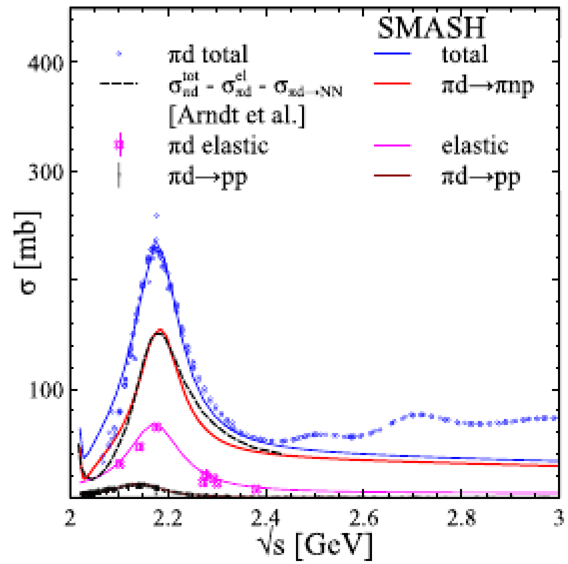


FIG. 1. Deuteron-pion interaction cross sections from SAID database [40] and partial wave analysis [41] are compared to our parametrizations (Tables II and III in the Appendix). Inelastic $d\pi \leftrightarrow$

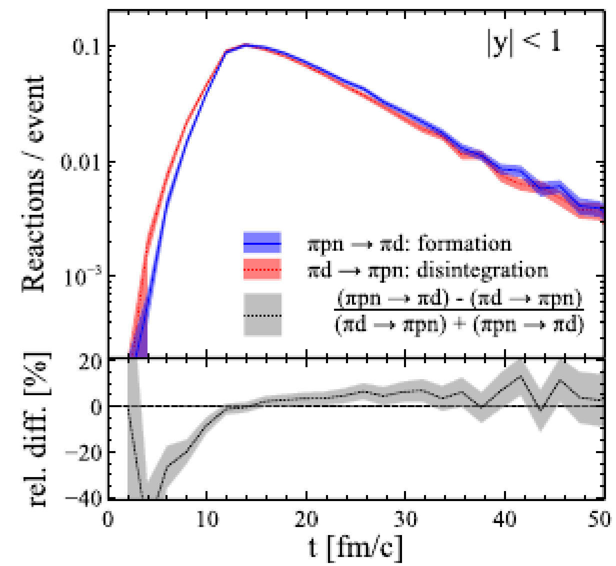
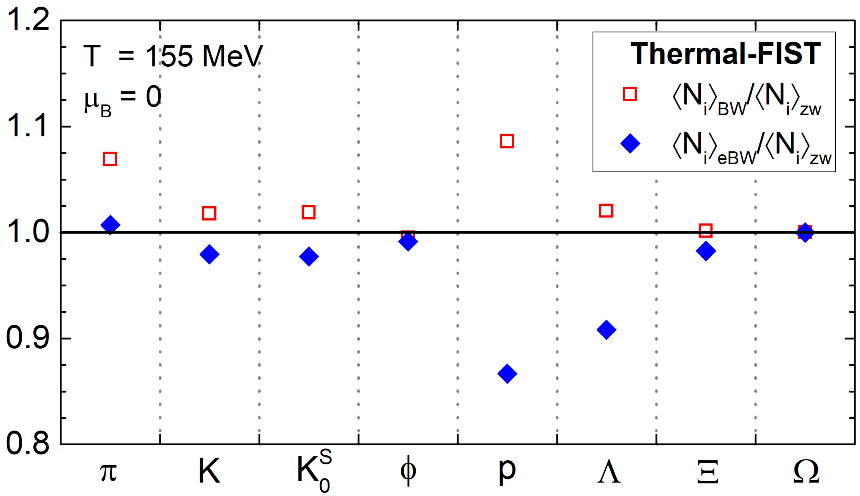


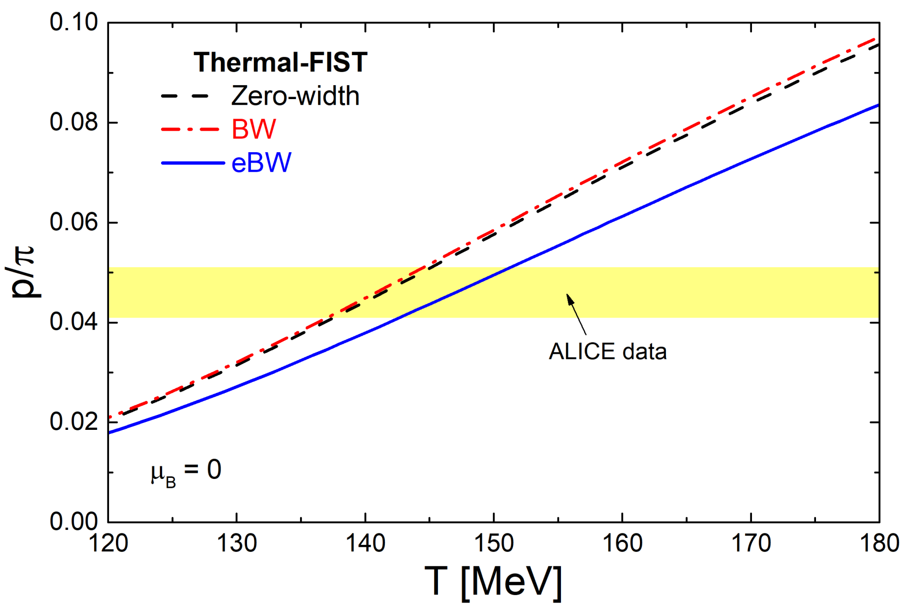
FIG. 5. Reaction rates of the most important $\pi d \leftrightarrow \pi pn$ reaction in forward and reverse direction.

- **Law of mass action at work**

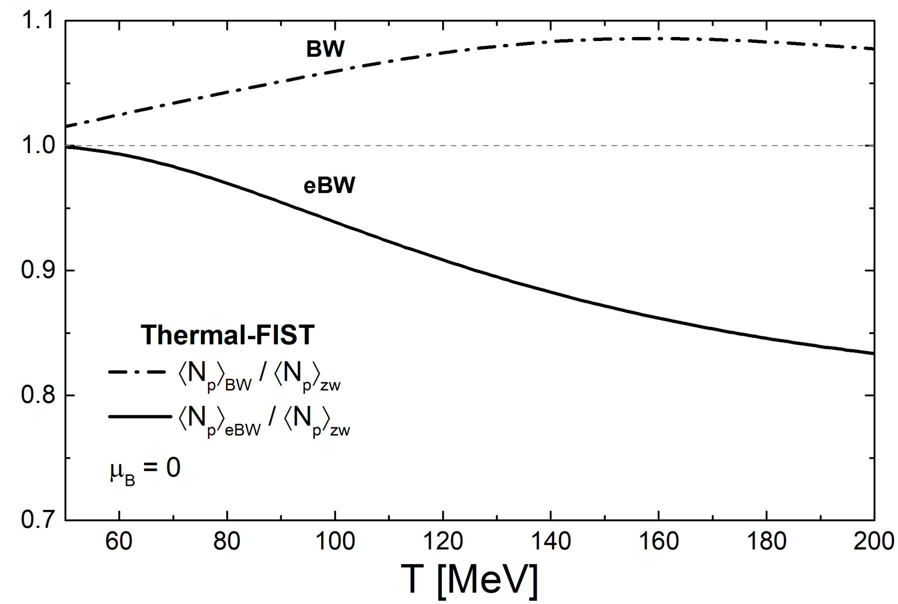
Modeling widths: Effect on hadron yields

Modification of final hadron yields





protons



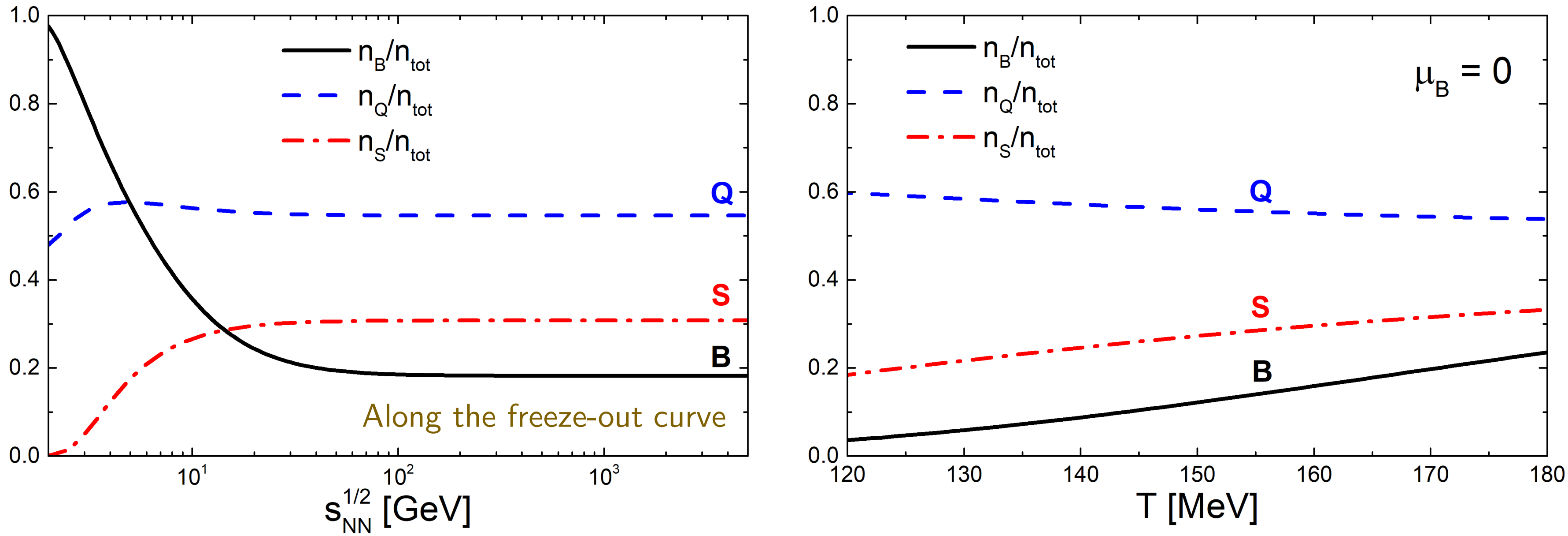
- BW enhances, eBW suppresses feeddown
- Strongest effect for protons & Λ
- p/π ratio suppressed in eBW

When is the canonical treatment necessary?

Normally, when the total number of particles carrying a conserved charge is smaller or of the order of unity

The canonical treatment is often restricted to strangeness only (SCE)

[STAR collaboration, 1701.07065; ALICE collaboration, 1807.11321]



- **Strangeness** conservation is most important at low energies (**HADES**, **CBM**)
- *Small systems at **RHIC** and **LHC**:* exact **baryon** conservation at least as important as **strangeness**

CSM at LHC

Enforce exact conservation of charges, $B = Q = S = 0$, in a *correlation volume* V_C around midrapidity

In general, $\boldsymbol{V_C \neq dV/dy}$

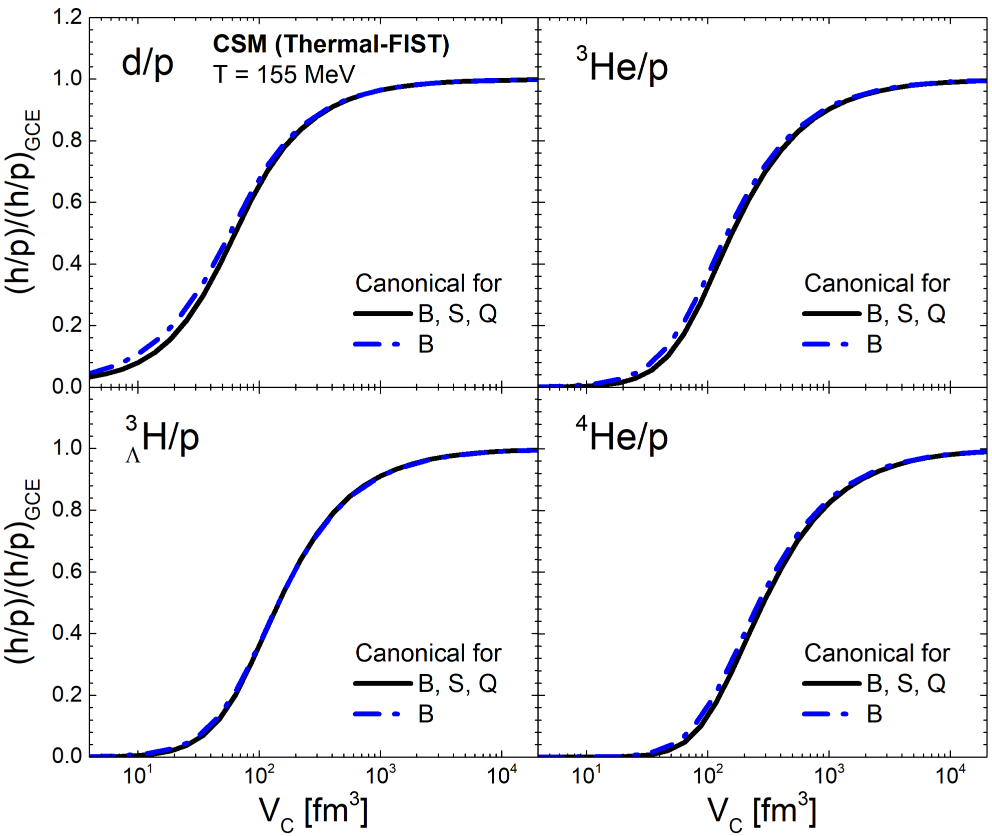
Causality argument: exact conservation across a few units of rapidity?

[Castorina, Satz, 1310.6932]

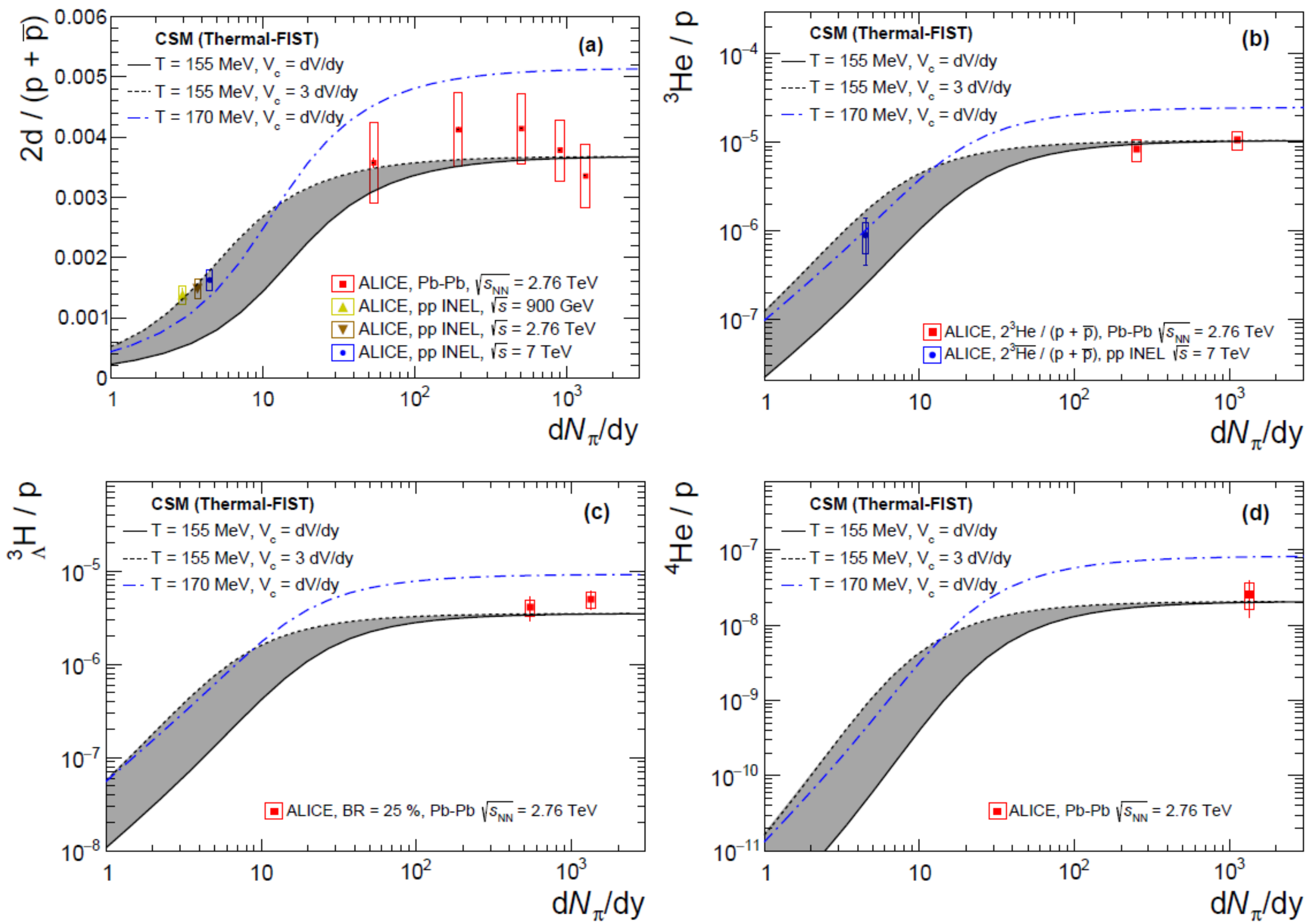
New application:

CSM for **light nuclei**

- Suppression of nuclei-to-proton ratios at low multiplicities
- For these observables sufficient to enforce exact baryon conservation only



CSM at LHC: light nuclei



[**V.V.**, B. Doenigus, H. Stoecker, 1808.05245]

- **CSM** qualitatively captures the behavior seen in the data
- Data prefers $V_C > dV/dy$ and/or $T_{p+p} > T_{Pb+Pb}$

Excluded volume corrections

Notion that hadrons have finite eigenvolume suggested a while ago

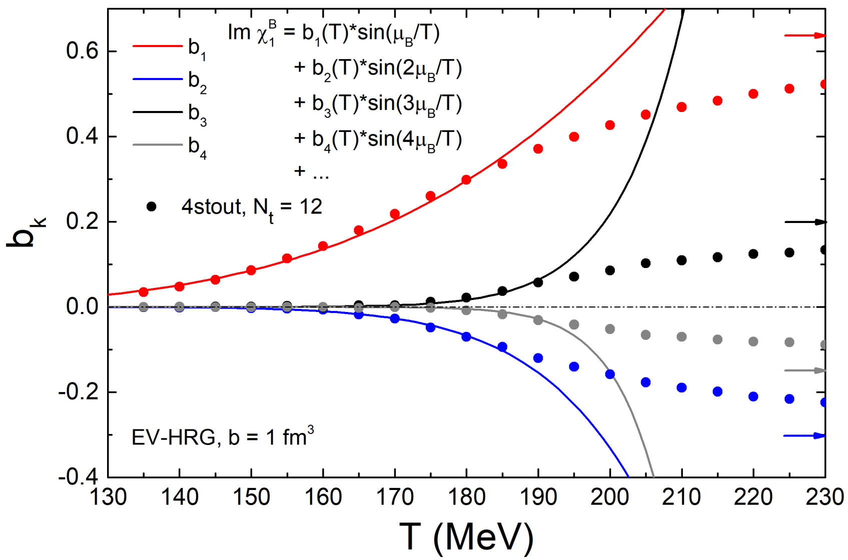
[R. Hagedorn, J. Rafelski, PLB '80]

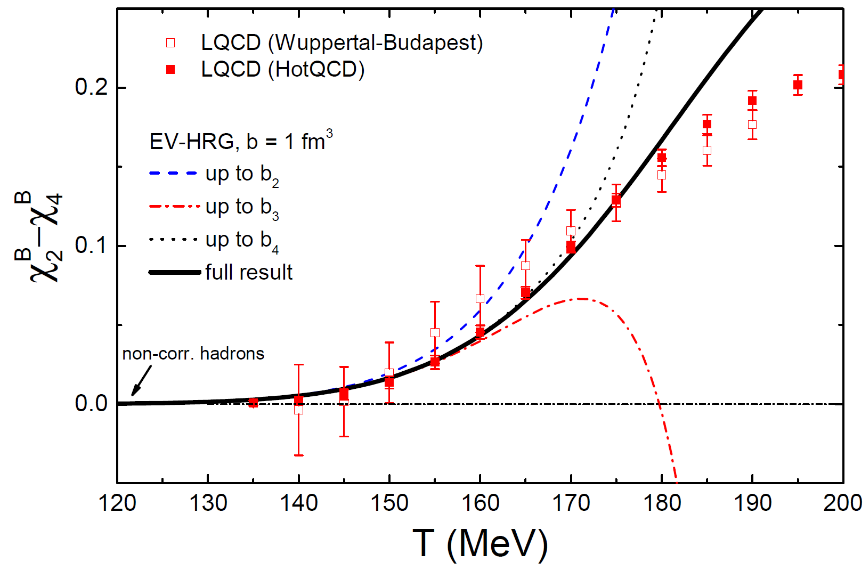
Excluded volume model: $V \to V - bN$ $\Rightarrow$ repulsive interactions

[D. Rischke et al., Z. Phys. C '91]

Whether EV corrections are needed at all has been debated...

Recent lattice data favor EV-like effects in baryonic interactions



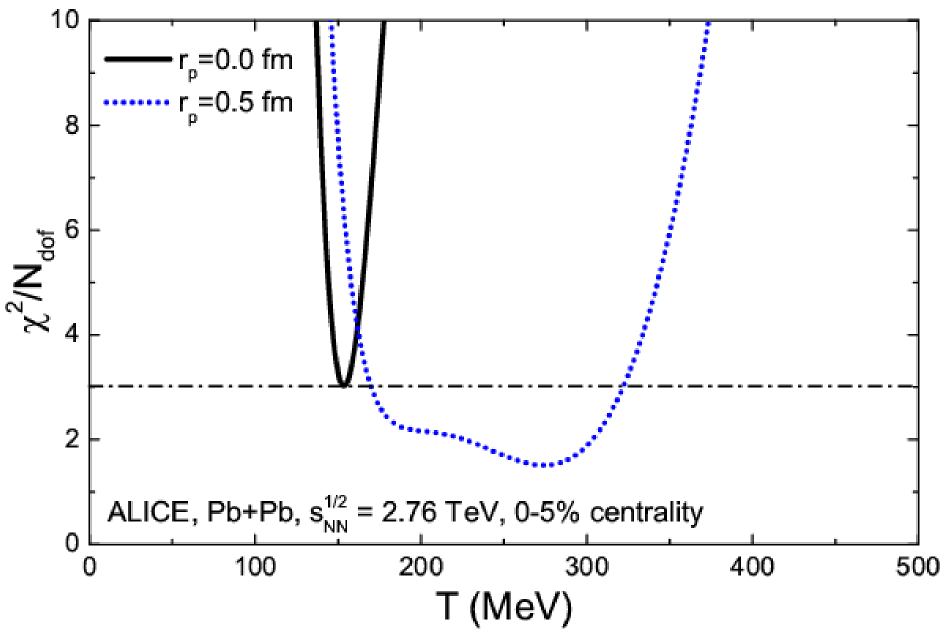


V.V., A. Pasztor, Z. Fodor, S.D. Katz, H. Stoecker, 1708.02852

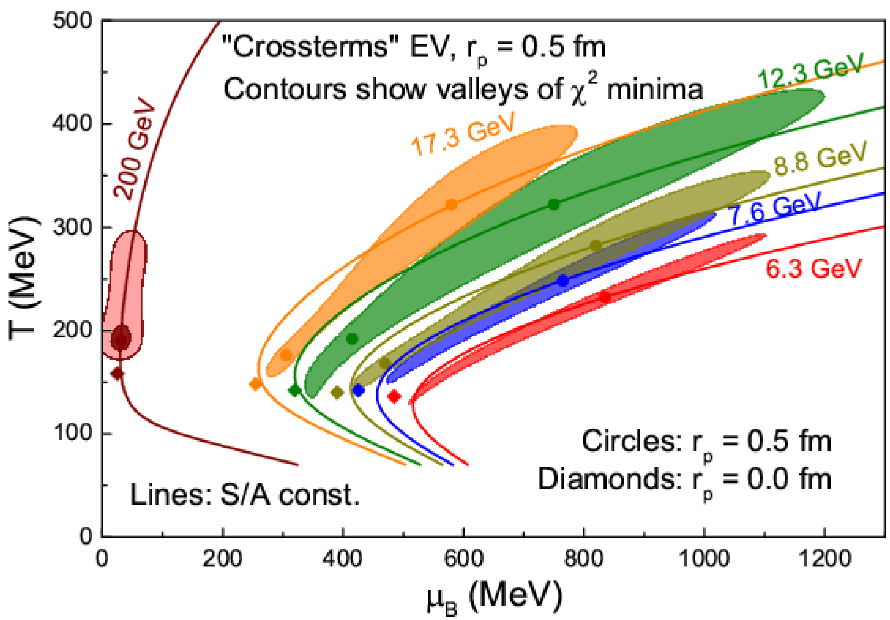
but not much info regarding (non-)existence of EV effects for mesons

Another extreme: bag model scaling

Bag model: $v_i \propto m_i$ [Chodos et al., PRD '74; Kapusta et al., NPA '83, PRC '15]



[**V.V.**, H. Stoecker, 1512.08046]



[**V.V.**, H. Stoecker, 1606.06218]

Extraction of T and μ can be quite sensitive w.r.t EV corrections, *but entropy per baryon, S/A, is a robust observable*

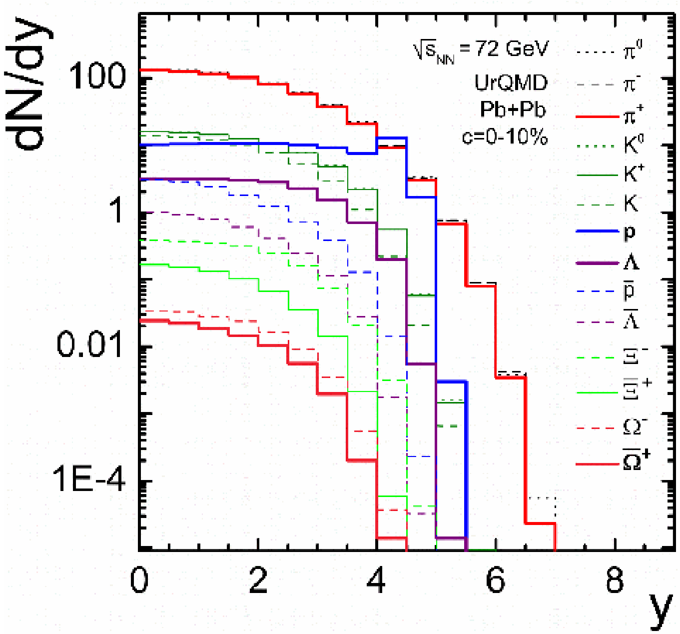
NB: This calculation disregards Hagedorn states needed to model the crossover transition

Rapidity scan

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

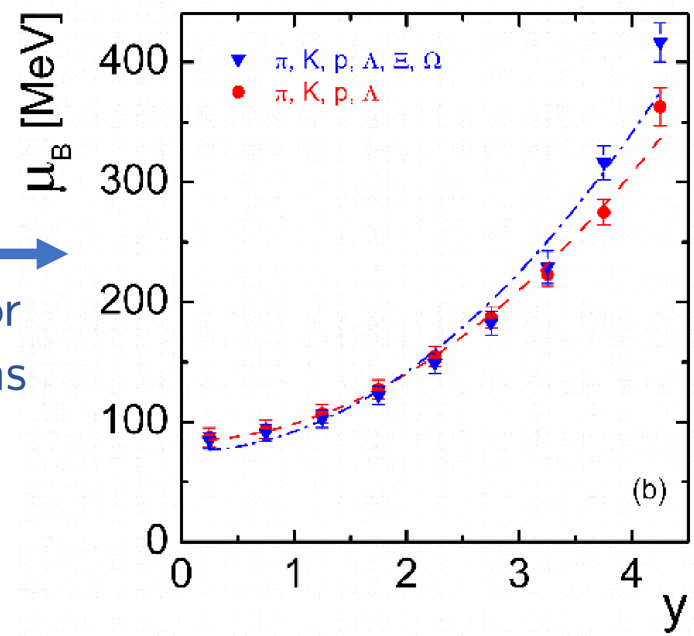
RHIC @ $\sqrt{s_{NN}} = 200$ GeV: $\mu_B(y_s) \approx 25 + 11 y_s^2$ [MeV] [Becattini et al., 0709.2599]

Example: AFTER@LHC project: Pb+Pb collisions @ $\sqrt{s_{NN}} = 72$ GeV



[Begun, Kikola, **V.V.**, Wielanek, 1806.01303]

Thermal fits for different dy bins



Rapidity scan: complementary approach to scan QCD phase diagram

see also Li, Kapusta, 1604.08525; Brewer, Mukherjee, Rajagopal, Yin, 1804.10215