



FIAS Frankfurt Institute
for Advanced Studies



Melting and freeze-out conditions of hadrons in a thermal medium



Utrecht 2017

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in collaboration with

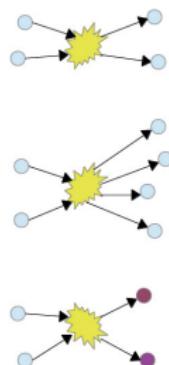
J. Aichelin, H. Petersen, J-B. Rose and J. Tindall

Strangeness in Quark Matter 2017 conference
July 14, 2017

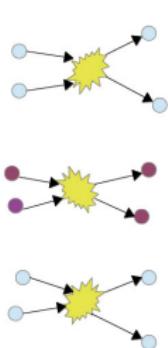


Chemical freeze-out

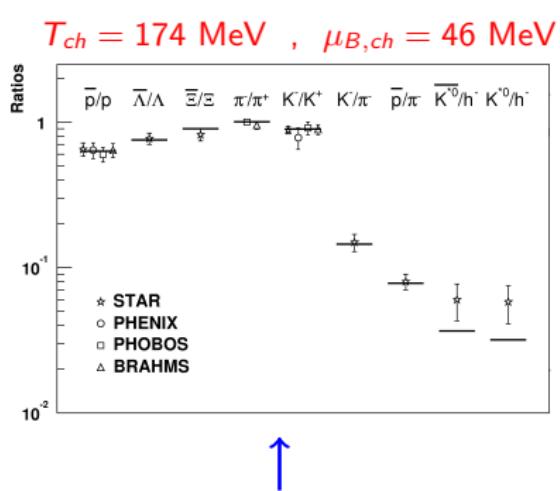
No more inelastic collisions \rightarrow total yield per species (approx.) fixed



Collisions BEFORE
chemical freeze-out



Collisions AFTER
chemical freeze-out

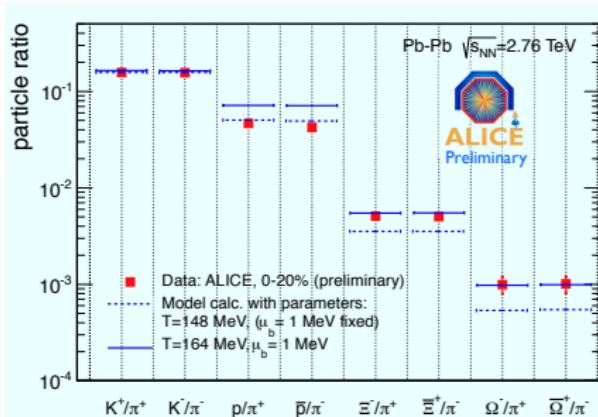


Statistical Thermal Model

Cleymans and Satz, Z.Phys.C57 (1993) 135

Braun-Munzinger et al. PLB518 (2001) 41

Tensions in T_{ch}

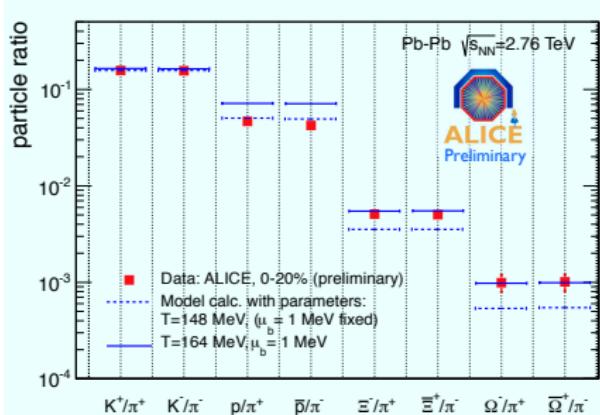


Multistrange hadrons prefer
larger T_{ch}
(also in STAR [▶ data](#))

$$T_{ch} \text{ (nonstrange)} = 148 \text{ MeV}$$
$$T_{ch} \text{ (multistrange)} = 164 \text{ MeV}$$

Preghezna et al. [ALICE Coll.] Acta Phys. Pol.B.43.555 (2012), Abelev et al. [ALICE Coll], PRL109, 252301 (2012)

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- 1 Missing hadronic resonances in thermal models (see S. Chatterjee talk)
- 2 Use of non-equilibrium distributions (see V. Begun talk)
- 3 Flavor-dependent freeze-out temperature
(see S. Chatterjee and P. Alba talks)

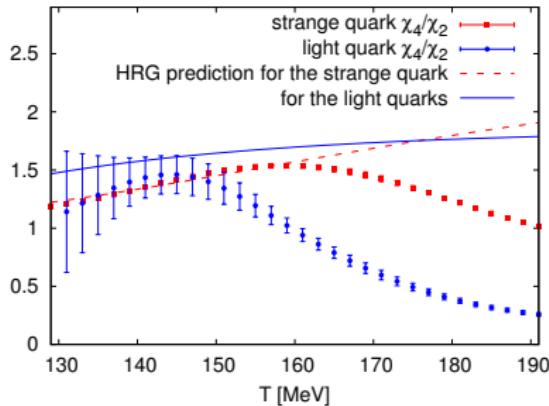
Chatterjee et al. PLB 727 (2013) 554

Alba et al. PLB 738 (2014) 305

Deconfinement transition

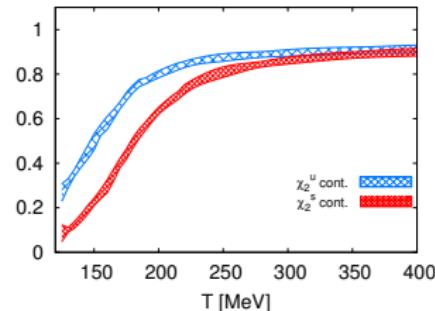
Similar difference in susceptibilities computed by lattice QCD

$$\chi_{ijk}^{uds} = \frac{\partial^{i+j+k}}{\partial (\frac{\mu_u}{T})^i \partial (\frac{\mu_d}{T})^j \partial (\frac{\mu_s}{T})^k} \left(\frac{P}{T^4} \right)$$



Bellwied et al. PRL111 (2013) 202302

$T_{light} \simeq 145$ MeV, $T_{strange} \simeq 160$ MeV



Borsanyi et al. JHEP 1201 (2012) 138
also Bellwied et al. PRD 92, 114505 (2015)

See talk by R. Bellwied

Outline

Question

Additional indications for sequential deconfinement and freeze-out temperatures?



Methodology

Use simple systems where these quantities can be extracted unambiguously



1. Deconfinement temperature

↓
Melting (or Mott) temperature in the PNJL model of QCD

2. Freeze-out temperature

↓
Decoupling temperature in an expanding system using a transport model

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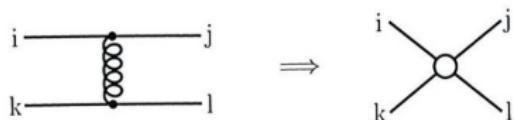
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We use an effective model model of QCD: **Nambu-Jona-Lasinio model**



Limited to low energies, but valid at finite T and μ_B

Effective Lagrangian

$$\mathcal{L}_{int} = -g \quad [\bar{q}_i \gamma^\mu T^a \delta_{ij} q_j] \quad [\bar{q}_k \gamma_\mu T^a \delta_{kl} q_l] + \text{six-point 't Hooft interaction}$$

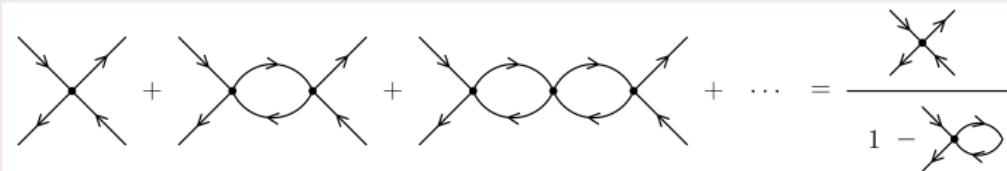
Flavor: $i, j = 1 \dots N_f = 3$; T^a : Gell-Mann matrices $a = 1 \dots N_c^2 - 1 = 8$

Reviews: Vogl, Weise (1991), Klevansky (1992), Ebert, Reinhardt, Volkov (1994), Hatsuda, Kunihiro (1994), Buballa (2004)...

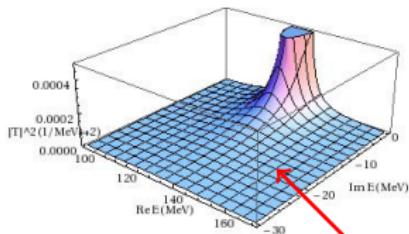
“Gluonic” contribution via the Polyakov loop effective potential: [PNJL model](#)

Generation of mesons

MESONS via Bethe-Salpeter equation for $\bar{q}q$ JMTR, B. Sintes and J. Aichelin, PRC91 (2015), 065206

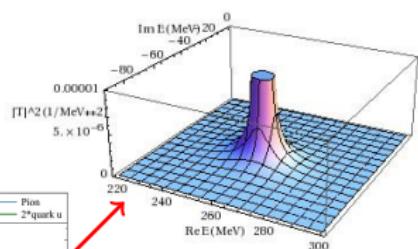
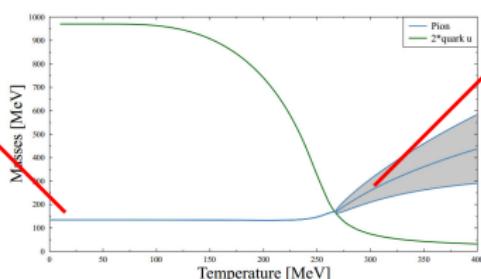


$$G_{meson}(p_0, \mathbf{p}) = \frac{\kappa}{1 - \kappa \Pi(p_0, \mathbf{p})} \rightarrow 1 - \kappa \Pi(M_{meson} - i\Gamma_{meson}/2, \mathbf{0}) = 0$$



pole $\in \mathbb{R}$
Stable meson

$$T < T_{Mott}$$

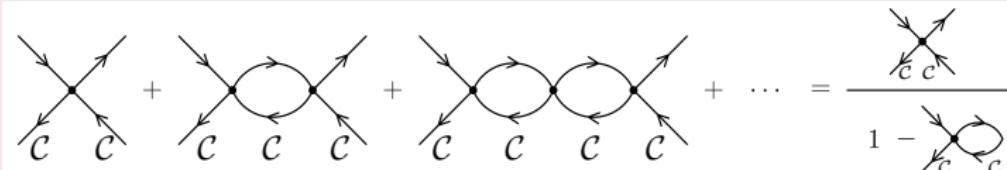


$\text{pole} \in \mathbb{C}$
Unstable meson

$$T > T_{Mott}$$

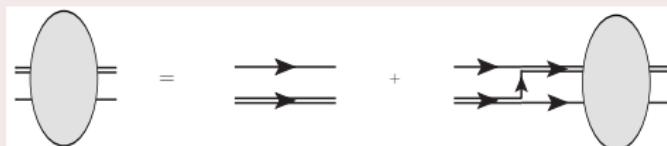
Generation of baryons

DIQUARKS via Bethe-Salpeter equation for qq



Baryon = Diquark + Quark

$$G_{baryon}(p_0, \mathbf{p}) = G_0 + G_0 Z G_{baryon}(p_0, \mathbf{p})$$



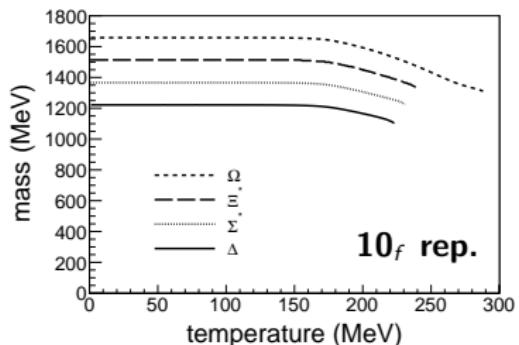
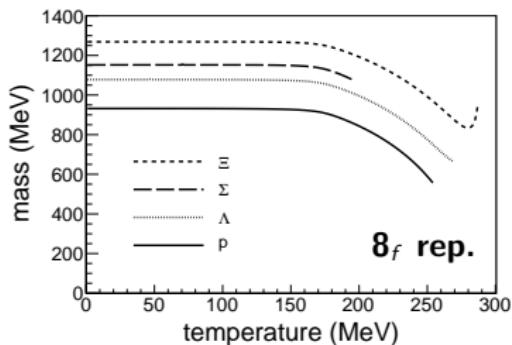
Baryon masses

$$G_{baryon}(p_0, \mathbf{p}) = \frac{G_0}{1 - G_0 Z} \rightarrow 1 - G_0 Z(p_0 = M_{baryon}, \mathbf{p} = \mathbf{0}) = 0$$

JMTR, B. Sintes and J. Aichelin, PRC91 (2015), 065206

Hadron melting temperatures in the PNJL model

JMTR, B. Sintes and J. Aichelin, PRC91 (2015), 065206



Meson	π	K	η	η'	ρ	K^*	ω	ϕ
T_{Mott} (MeV)	282	286	245	0	253	266	253	382
Baryon	p	Λ	Σ	Ξ	Δ	Σ^*	Ξ^*	Ω
T_{Mott} (MeV)	254	269	195	287	223	231	239	288

- $T_{Mott}(\Xi) \sim T_{Mott}(\Omega) > T_{Mott}(p)$ (as suggested by thermal fits)
- $T_{Mott}(\phi)$ abnormally large. Small $T_{Mott}(\Sigma)$ due to threshold proximity
- Multistrange states have larger T_{Mott} (except Ξ^*)

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Freeze-out temperatures

- Realization of freeze-out process in a simple system
- Inspiration comes from Cosmology: thermal history of the universe
- Dynamical extraction of decoupling condition

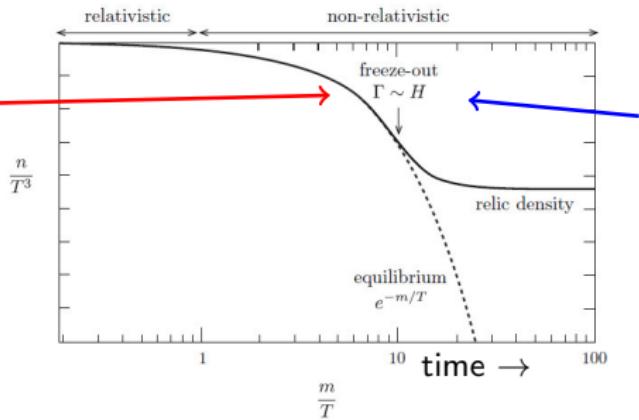
Scattering rate:

$$\Gamma = n\sigma|v|$$

n : density

σ : cross section

$|v|$: relative velocity



Hubble rate:

$$H = \frac{1}{a(t)} \frac{da(t)}{dt}$$

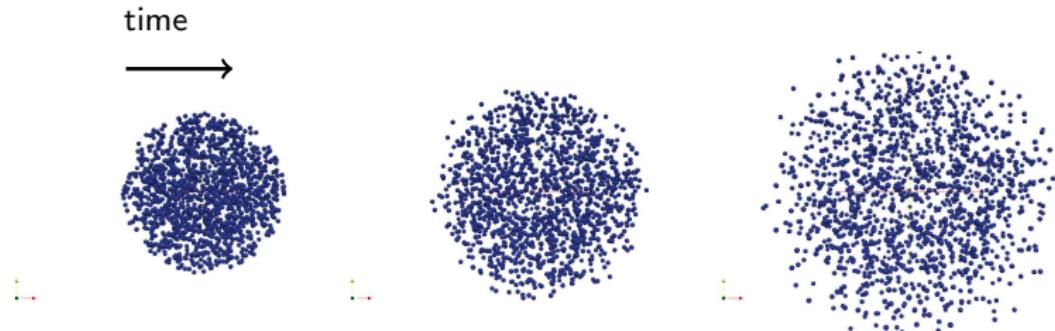
$a(t)$: scale factor

t : time

Friedmann-Robertson-Walker metric: $ds^2 = dt^2 - a^2(t)(dx^2 + dy^2 + dz^2)$

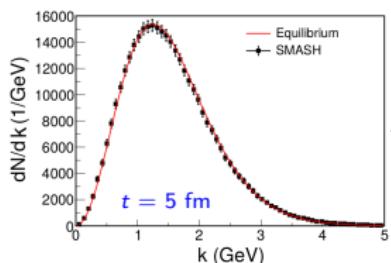
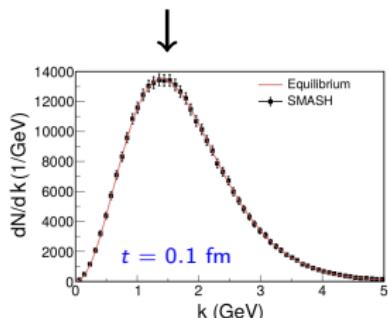
Simulating Many Accelerated Strongly-interacting Hadrons

- **SMASH** is a new transport approach to simulate low-energy HICs
(J. Weil et al. Phys.Rev. C94 (2016) no.5, 054905)
- Applied to strangeness, dileptons+photons, collectivity signatures, transport coefficients...
- HERE: “Expanding box” on a FRW spacetime
- Perfect agreement with known exact solutions of Boltzmann equation
J. Tindall, JMTR, J.B. Rose and H. Petersen, PLB770 (2017) 532
D. Bazow, G.S. Denicol, U. Heinz, M. Martinez and J. Noronha, PRL 116 (2016) 022301

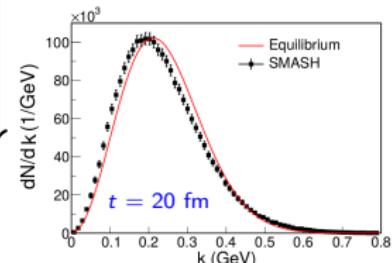


Application: Decoupling of particles

- Single species interacting via binary collisions (constant σ)
- Equilibrium reached and maintained if $\Gamma \gg H$



Freeze-out ($\Gamma = H$) takes place between $t = 5 \text{ fm}$ and $t = 20 \text{ fm}$



Not in equilibrium!

$$\Gamma < H$$

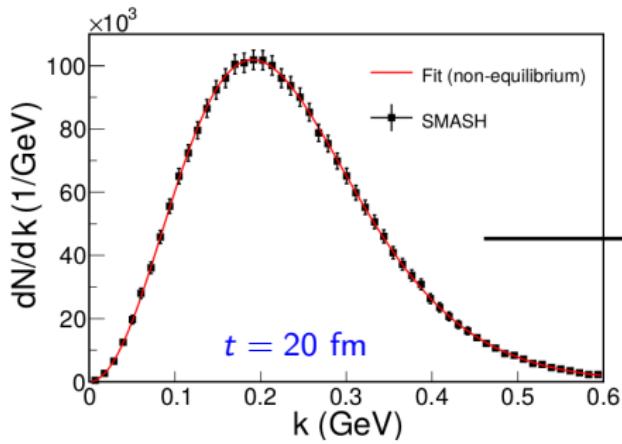
$$f_{\text{equilibrium}}(t, k) = \frac{g}{(2\pi)^3} e^{-\frac{\sqrt{k^2 + m^2} - \mu(t)}{T(t)}}$$

2 parameters fixed by conservation of particle number and entropy per particle

Fit at $t = 20$ fm to

$$f_{\text{freeze-out}}(t, k) = f_{\text{equilibrium}} \left(t_D, k \frac{a(t)}{a_D} \right) \propto \exp \left[-\frac{\sqrt{\left(k \frac{a(t)}{a_D} \right)^2 + m^2}}{T_D} \right]$$

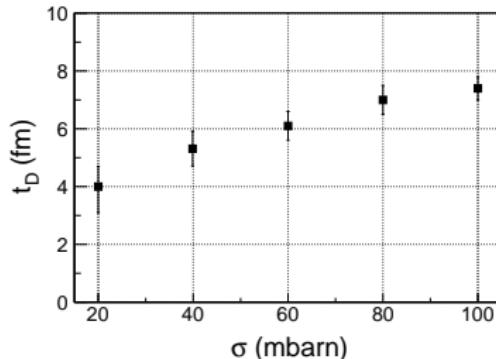
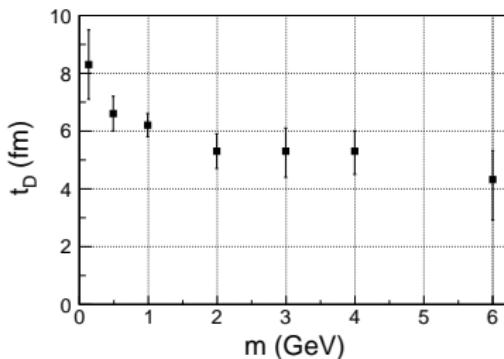
↑
↓
momentum redshift
 $a_D \equiv a(t_D)$; $T_D \equiv T(t_D)$



$$t_D = 5.3 \pm 0.6 \text{ fm}$$

Toy model for freeze-out

Indications for a sequential freeze-out in our toy model:



J. Tindall, JMTR, J.B. Rose and H. Petersen, PLB770 (2017) 532

- Earlier freeze-out (higher temperature) for more massive particles
- Later freeze-out (lower temperature) for states with larger cross section

To improve for HICs:

- 1 Hadronic mixture + physical interactions
- 2 Realistic model for $a(t)$ e.g. Blast-wave model

- Using the PNJL model we have computed the mass of mesons and baryons as functions of the temperature
- Multistrangeness particles (ϕ, Ξ, Ω) have a higher Mott temperatures than nonstrange hadrons
- Melting temperature depends on flavor content but does not follow a clear pattern
- A toy model for decoupling is implemented in SMASH transport code, where freeze-out can be determined with precision
- Clear dependence of the freeze-out time (temperature) on mass and cross section
- We obtain indications for a sequential freeze-out, but more refined investigations are needed to decide how important is the effect in HICs



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Strangeness in Quark Matter 2017 conference
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Tension in multistrangeness multiplicities at STAR

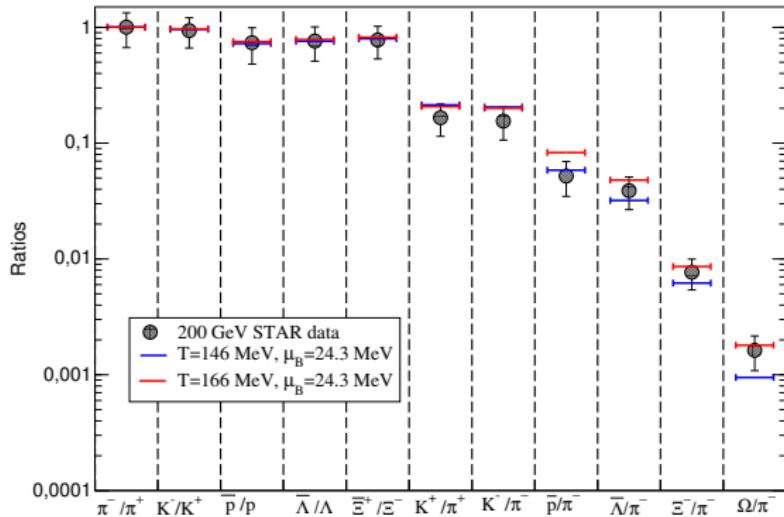


Figure taken from Alba et al. PLB 738 (2014) 305

Feed-down corrected ratios taken from Andronic et al. NPA 904-905 (2013)
535c

Blue param: Cleymans et al. PRC73 (2006) 034905 [\(Go back\)](#)

Tension in multistrangeness multiplicities at ALICE

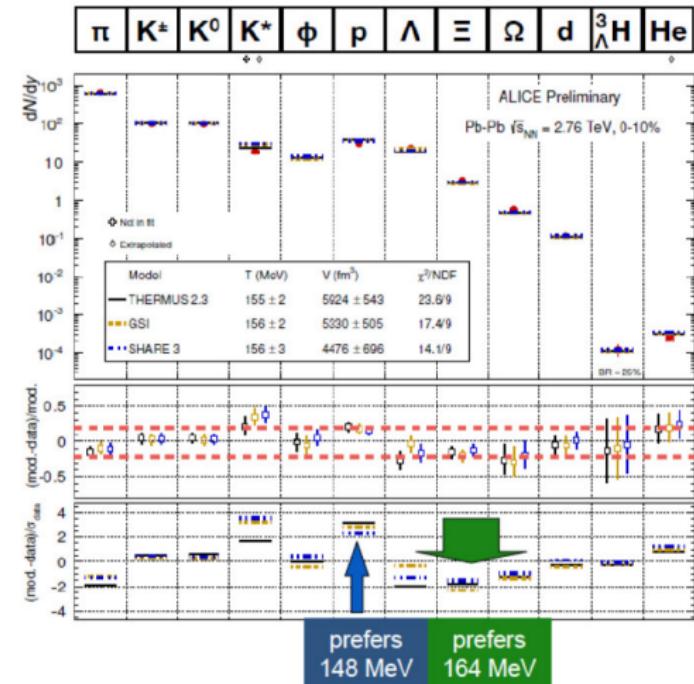


Figure taken from Bellwied, JoP:CS 736 (2016) 012018
LHC Data from Floris: NPA931, 103 (2014)

Exchange Lagrangian: accounts for mesons

Pseudoscalar mesons

$$\mathcal{L}_{\text{ex}} = G (\bar{q}_i \tau_{ij}^a \mathbb{I}_c i\gamma_5 q_j) (\bar{q}_k \tau_{kl}^a \mathbb{I}_c i\gamma_5 q_l); \quad G = (N_c^2 - 1)/N_c^2 g$$

\mathbb{I}_c : color singlet interaction

τ^a : flavor generators $a = 1 \dots 8$ ($N_f = 3$).

(Other terms not shown, e.g. the one accounting for scalar mesons $i\gamma_5 \rightarrow \mathbb{I}$)

The effective Lagrangian should share the global symmetries of (massless) QCD:

Symmetries of massless NJL model

$$SU_V(3) \otimes SU_A(3) \otimes U_V(1) \otimes U_A(1)$$

In our scheme, chiral symmetry is explicitly broken to $SU_V(3)$ by the bare quark masses. We keep an isospin $SU_V(2)$ symmetry. The $U_A(1)$ is broken by quantum effects.

Gluon (static) properties are implemented in the model through an effective potential for the Polyakov loop

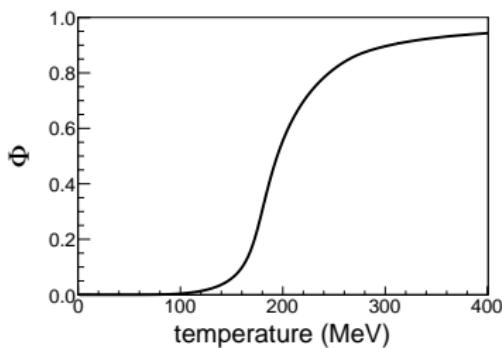
$$\frac{U(T, \Phi, \bar{\Phi})}{T^4} = -\frac{b_2(T)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}\left(\Phi^3 + \bar{\Phi}^3\right) + \frac{b_4}{4}(\bar{\Phi}\Phi)^3$$

$$b_2(T) = a_0 + a_1 \frac{T_0}{T} + a_2 \left(\frac{T_0}{T}\right)^2 + a_3 \left(\frac{T_0}{T}\right)^3$$

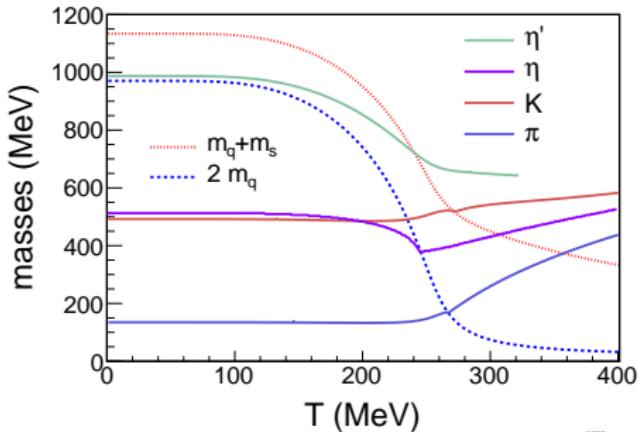
$a_0 = 6.75$, $a_1 = -1.95$, $a_2 = 2.625$, $a_3 = -7.44$, $b_3 = 0.75$, $b_4 = 7.5$ from fit to lattice-QCD results of gluodynamics and $T_0 = 190$ MeV.

Φ is the order parameter
of the deconfinement transition

$$\Phi = \frac{1}{N_c} \text{Tr}_c \langle \mathcal{P} \exp \left(- \int_0^\beta d\tau A_0(x, \tau) \right) \rangle$$

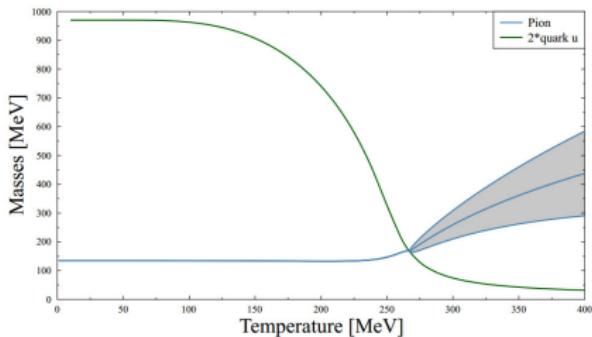


Mesons at finite temperature



Pseudoscalar mesons
in the NJL model at $\mu = 0$

Pion mass (blue line) and
decay width (grey band)



Restoration of chiral symmetry at large temperatures

