Hadron production in high-energy nuclear collisions and the QCD phase diagram

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- Chemical freeze-out of light quark (u,d,s) hadrons
- ...and the connection to the QCD phase diagram
- Chemical freeze-out of heavy quarks (charmonium)

work in collaboration with P. Braun-Munzinger, K. Redlich, J. Stachel

arXiv:1710.09425
• lots of particles, mostly newly created \((m = E/c^2)\)

• a great variety of species:
  \(\pi^\pm (ud, \bar{d}u), m=140 \text{ MeV}\)
  \(K^\pm (u\bar{s}, \bar{u}s), m=494 \text{ MeV}\)
  \(p (uud), m=938 \text{ MeV}\)
  \(\Lambda (uds), m=1116 \text{ MeV}\)
  also: \(\Xi(dss), \Omega(sss)\)...

• 3 decades in energy and 3 decades of experimental effort

mass hierarchy in production ...natural to think of the thermal model
The statistical (thermal) model

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grand canonical partition function for specie $i$ ($\hbar = c = 1$):

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln[1 \pm \exp(-(E_i - \mu_i)/T)]$$

$g_i = (2J_i + 1)$ spin degeneracy factor; $T$ temperature;

$E_i = \sqrt{p^2 + m_i^2}$ total energy; $+$ for fermions $-$ for bosons

$\mu_i = \mu_B B_i + \mu_{I3} I_{3i} + \mu_S S_i + \mu_C C_i$ chemical potentials

$\mu$ ensure conservation (on average) of quantum numbers, fixed by “initial conditions”

i) isospin: $V_{\text{cons}} \sum_i n_i I_{3i} = I_{3}^{\text{tot}}$, with $V_{\text{cons}} = N_B^{\text{tot}} / \sum_i n_i B_i$

$I_{3}^{\text{tot}}$, $N_B^{\text{tot}}$ isospin and baryon number of the system ($\sim 0$ at high energies)

ii) strangeness: $\sum_i n_i S_i = 0$

iii) charm: $\sum_i n_i C_i = 0$. 

a dense system for $T \gtrsim 170$ MeV (for point-like hadrons)

*the usual case is* $R_b = R_m = 0.3$ fm
Thermal fits of hadron abundances

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\[ n_i = \frac{N_i}{V} = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T] \pm 1} \]

Latest PDG hadron mass spectrum ...quasi-complete up to \( m=2 \) GeV; our code: 555 species (including fragments, charm and bottom hadrons)

for resonances, the width is considered in calculations

canonical treatment whenever needed (small abundances)

Minimize: \( \chi^2 = \sum_i \frac{(N_{i,\text{exp}} - N_{i,\text{therm}})^2}{\sigma_i^2} \)

\( N_i \) hadron yield, \( \sigma_i \) experimental uncertainty (stat.+syst.)

\[ (T, \mu_B, V) \quad \text{...tests} \text{ chemical freeze-out} \quad \text{(chemical equilibrium)} \]
Thermal fit – LHC, Pb–Pb, 0-10%

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\[ \frac{dN}{dy} \]

\[ \text{Pb-Pb } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV, 0-10\% centrality} \]

Data, ALICE

Statistical Hadronization

\[ \pi^+, \pi^-, K^\pm, K^0 \text{ from charm included} \]

(0.7\%, 2.9\%, 3.1\% for the best fit)

\[ T_{CF} = 156.5 \pm 1.5 \text{ MeV} \]
\[ \mu_B = 0.7 \pm 3.8 \text{ MeV} \]
\[ V_{\Delta y=1} = 5280 \pm 410 \text{ fm}^3 \]

\[ \chi^2 / N_{df} = 29.3 / 19 \]

remarkably, loosely-bound objects are well described
Thermal fit – LHC, Pb–Pb, 0-10%
Systematic uncertainties in the model

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**hadron spectrum** ...embody low-energy QCD ...**vacuum masses**

well-known for \( m < 2 \text{ GeV} \); many confirmed states above 2 GeV, still incomplete for high \( m \), BR not well known, but can be reasonably guessed

\( T \) found to be robust in fits with spectrum truncated above 1.8 GeV

\( \sigma \left[ f_0(500) \right] \) meson proposed recently to be discarded (3-4% less pions)

Giacosa, Begun, Broniowski, arXiv:1603.07687

\((2J + 1)\) counted in
Systematic uncertainties - hadron spectrum

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contribution of resonances is significant (and particle-dependent)
Systematic uncertainties - hadron spectrum

Fit of $\phi$, $\Omega$, d, $^{3}\text{He}$, $^{3}\Lambda\text{H}$, $^{4}\text{He}$:

$T_{CF} = 156 \pm 2.5$ MeV

($\chi^2/N_{df} = 7.4/8$)

Fit of nuclei (d, $^{3}\text{He}$, $^{4}\text{He}$):

$T_{CF} = 159 \pm 5$ MeV

3-4 MeV upper bound of syst. uncert. due to hadron spectrum

contribution of resonances is significant (and particle-dependent)
Systematic uncertainties in the model

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hadron eigenvolumes ...to mimick interactions (beyond low-density, Dashen-Ma)

we consider that \( R_{\text{meson}} = 0.3, R_{\text{baryon}} = 0.3 \) fm is a reasonable case

point-like hadrons lead to same \( T \), but volume larger by 20-25%

an extreme case, \( R_{\text{meson}} = 0, R_{\text{baryon}} = 0.3 \) fm leads to
\( T = 161.0 \pm 2.0 \) MeV, \( \mu_B = 0 \) fixed, \( V = 3470 \pm 280 \) fm\(^3\)

NB: in this case, the result is rather sensitive on the set of hadrons in the fit
for instance, using hadrons up to \( \Omega \), cannot constrain \( T \) (unphysically large)

...and anything else can be imagined, see \( (R \) dependent on mass & strangeness) Alba, Vovchenko, Gorenstein, Stöcker, arXiv:1606.06542, etc.
Energy dependence of $T$, $\mu_B$ (central collisions)

thermal fits exhibit a limiting temperature:

$$T_{lim} = 158.4 \pm 1.4 \text{ MeV}$$

$$T_{CF} = T_{lim} \frac{1}{1 + \exp(2.60 - \ln(\sqrt{s_{NN}(\text{GeV})})/0.45)}$$

$$\mu_B[\text{MeV}] = \frac{1307.5}{1 + 0.288\sqrt{s_{NN}(\text{GeV})}}$$

The grand (albeit partial) view

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Data:
AGS: E895, E864, E866, E917, E877
SPS: NA49, NA44
RHIC: STAR, BRAHMS
LHC: ALICE

NB: no contribution from weak decays

data consistent with smooth behaviour vs. energy
(fireball is everywhere:)

$\frac{dN}{dy}$ yield ratio

$\sqrt{s_{NN}}$ (GeV)
Connection to the phase diagram of QCD

\[ T_{\text{CF}} \to T_{\text{lim}} \quad \text{...is chemical freeze-out a determination of the phase boundary?} \]

...Yes, at low \( \mu_B \)

Lattice QCD:
Borsanyi et al.,
HotQCD, PRD 90 (2014) 094503, PRD 83 (2011) 014504

Statistical model
Cleymans, Redlich, PRC 59 (1999) 1663
Andronic et al., arXiv:1710.09425
Vovchenko et al., PRC 93 (2016) 064906
Becattini et al., PLB 764 (2017) 241
STAR, PRC 96 (2017) 044904

Are the larger \( T \) values at RHIC significant (physics)?
Proton collisions at the LHC

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pp collision at 7 TeV, “photographed” by ALICE
Proton collisions at the LHC

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pp collision at 7 TeV, “photographed” by ALICE
Strangeness production - from small to large systems

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ALICE, Nature Physics 13 (2017) 535

(big geometric) fireball in Pb–Pb reached with violent pp and p–Pb collisions

(grand canonical) statistical description works well in Pb–Pb (with $T$ of QCD phase boundary)

is the same mechanism at work in small systems (at large multiplicities)?

string hadronization models do not describe data well

...new ideas are being put forward

Fischer, Sjöstrand, arXiv:1610.09818

“thermodynamical string fragmentation”
Strangeness production - from small to large systems

Vislavicius, Kalweit, arXiv:1610.03001

ratios to high multiplicity limit (HML)

canonical statistical hadronization describes data well
We turn now to quarkonium

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"If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region."

Refinements: “sequential suppression”:

Digal et al., PRD 64 (2001) 75

no $q\bar{q}$ bound state if

$r_{q\bar{q}}(T) > r_0(T) \simeq 1/(g(T)T)$

$r_0$ Debye length in QGP

$\Rightarrow q\bar{q}$ “thermometer” of QGP
all charm quarks are produced in primary hard collisions \( (t_{cc} \sim 1/2m_c \approx 0.1 \text{ fm/c}) \)

- **survive** and **thermalize in QGP** (thermal, but not chemical equilibrium)
- charmed hadrons are formed at chemical freeze-out together with all hadrons
- statistical laws, quantum no. conservation; stat. hadronization \( \neq \) coalescence
- is freeze-out at(/the?) phase boundary?
  ...we believe yes ...based on data in the light-quark sector and Lattice QCD

- no J/\( \psi \) survival in QGP (full screening)

  can J/\( \psi \) survive above \( T_c \)? ...yet to be settled (LQCD)


if all this is supported by data, J/\( \psi \) loses status as “thermometer” of QGP
...and gains status as a powerful observable for the phase boundary
Statistical hadronization of charm: method and inputs

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- Thermal model calculation (grand canonical) \( T, \mu_B: \rightarrow n_{th}^X \)

\[
\begin{align*}
N_{\text{dir}}^{cc} &= \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th}) \\
N_{\text{dir}}^{cc} &<< 1 \rightarrow \text{Canonical} (J. Cleymans, K. Redlich, E. Suhonen, Z. Phys. C51 (1991) 137): \\
N_{\text{dir}}^{cc} &= \frac{1}{2} g_c N_{oc}^{th} I_1 (g_c N_{oc}^{th}) + g_c^2 N_{cc}^{th} \rightarrow g_c \text{ (charm fugacity)}
\end{align*}
\]

Outcome: 
\[
N_{D} = g_c V n_{D}^{th} I_1 / I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}
\]

The only specific input parameter: \( N_{\text{dir}}^{cc} \) (from experiment / pQCD)

Minimal volume for QGP: \( V_{QGP}^{min} = 100 \text{ fm}^3 \)

corona contribution considered
Charmonium in the statistical hadronization model

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\[ R_{AA}^{J/\psi} = \frac{dN_{AA}^{J/\psi}/dy}{N_{coll} \cdot dN_{pp}^{J/\psi}/dy} \]

- "suppression" at RHIC (and SPS)
- "enhancement" at the LHC

\[ N_{J/\psi} \sim (N_{cc}^{dir})^2 \]

What is so different at LHC? (compared to RHIC)

\[ \sigma_{cc}: \sim 10x, \ Volume: \sim 2.2x \]

this was for top LHC energy … but is a generic prediction of the model
Charmonium data at RHIC and the LHC

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- "suppression" at RHIC (PHENIX)
- dramatically different at the LHC

Statistical Hadronization Model

\[ N_{J/\psi} \sim (N_{c\bar{c}}^{dir})^2 \]

\( J/\psi \) is another observable (charm) for the phase boundary calculations are for \( T=156 \, \text{MeV} \)

\[ \frac{dN_{ch}}{d\eta} \sim \varepsilon \]

\( (>20 \, \text{GeV/fm}^3, \text{for } \frac{dN_{ch}}{d\eta} \approx 2000) \)
Mean transverse momentum of J/ψ mesons

\[ r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}} \]

**ALICE inclusive J/ψ → μ⁺μ⁻, 2.5<y<4**
- Pb-Pb \( \sqrt{s_{NN}} = 2.76 \) TeV, global syst. = 4%

**PHENIX inclusive J/ψ → μ⁺μ⁻, 1.2<y<2.2**
- Au-Au and Cu-Cu \( \sqrt{s_{NN}} = 0.2 \) TeV, global syst. = 3%

**NA50 inclusive J/ψ → μ⁺μ⁻, 0<y<1**
- Pb-Pb \( \sqrt{s_{NN}} = 0.017 \) TeV, global syst. = 3%

**Transport model calculations**
- TM1: Texas A&M (R.Rapp et al.)
- TM2: Tsinghua (P.Zhuang et al.)

softening of \( p_T \) is significant at the LHC, clear indication of (re)generation thermalization of charm quarks demonstrated by collective flow of D and J/ψ
$\psi(2S)$ production

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arXiv:1710.09425
The data approach the thermal limit for central Pb-Pb coll. fair description by model also for $R_{AA}$ of $\Upsilon(1S)$
• abundance of hadrons with light quarks consistent with chemical equilibration
  there is a variety of approaches ... *a personal bias: the “minimal model”*
  a minimal set of parameters, means a well-constrained model
  the thermal model provides a simple way to access the QCD phase boundary
  ... *at high energies* (at low energies canonical suppression needs more care)

• (I think:) everybody agrees that we see (re)combination of charm quarks at the LHC ... a new observable for the QCD phase boundary?
  not settled yet, as transport models also describe data ... (re)generation in QGP

• interesting (sequential?) “disappearance” pattern in the bottom (ϒ) sector
  do bottom quarks also thermalize at the LHC? (at RHIC?)
  will ϒ add more weight to the phase boundary?
Backup slides
LHC, Pb–Pb, 0-10% - 3 models

ALICE, arXiv:1710.07531
LHC, Pb–Pb, 0-10% - ALICE data

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- $\pi^\pm$, $K^\pm$, $p$, $\bar{p}$, PRC 88 (2013) 044910
- $\phi$, PRC 91 (2015) 024609
- $K^0_S$, $\Lambda$, PRL 111 (2013) 222301
  \(\bar{\Lambda}\) from S. Schuchmann, PhD Thesis, Goethe-University Frankfurt (July 2015)
- $\Xi$, $\Omega$, PLB 728 (2014) 216
- $d$, $^3$He, PRC 93 (2015) 024917
  derive anti-particles from published ratios
- $^3\Lambda H$, $^3\bar{\Lambda}H$, PLB 754 (2016) 360, assume B.R. = 25%
- $^4$He, $^4\bar{\text{He}}$, arXiv:1710.07531
Volume in central collisions

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\[ V_{\Delta y = 1} = \frac{dN_{ch}}{dy}|_{y=0}/n_{ch}^{\text{therm}} \]

\[ V_{kin} = V_{HBT} = (2\pi)^{3/2}R_{side}^2R_{long} \]

HBT data: ALICE, PLB 696, 328 (2011)