Linking the particle yields data in HIC with lattice QCD

Krzysztof Redlich, University of Wroclaw & EMMI/GSI

- Probing thermalization, composition and parameters of the collision fireball in HIC

  Longstanding collaboration with

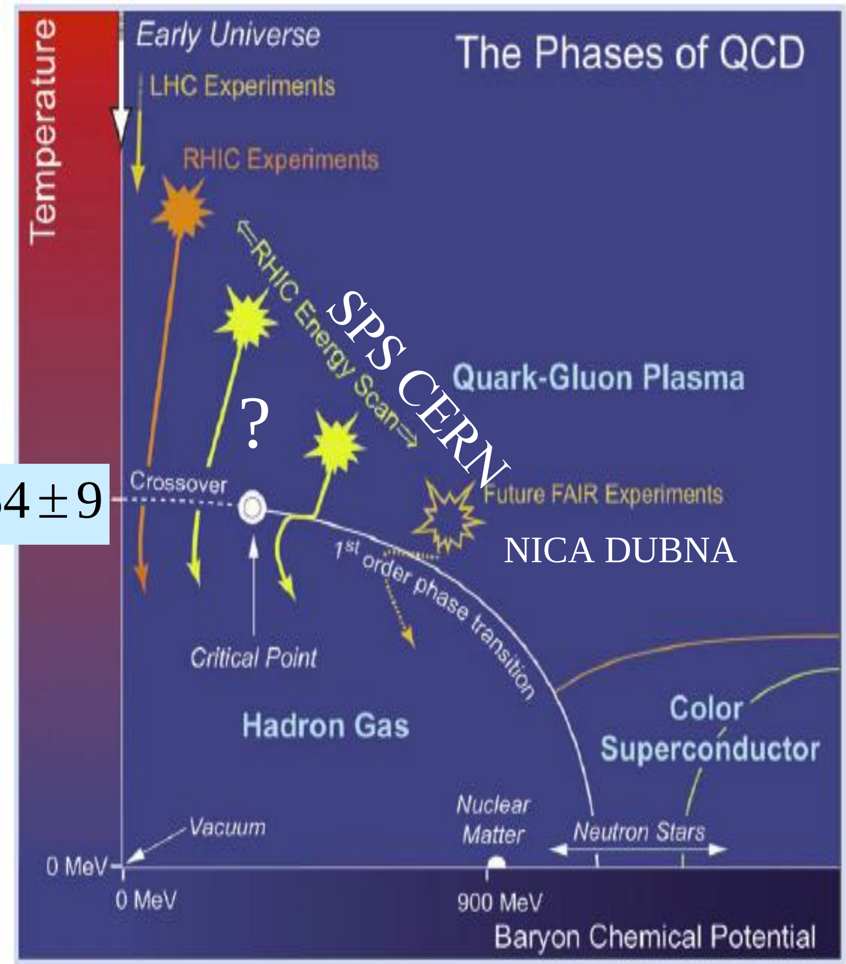
  Helmut Oeschler & Jean Cleymans

  ⇨ linking LQCD results to HIC data of ALICE coll.

- Modelling QCD thermodynamic ? potential within HRG

  ⇨ importance of dynamical widths of resonances: the S-matrix approach

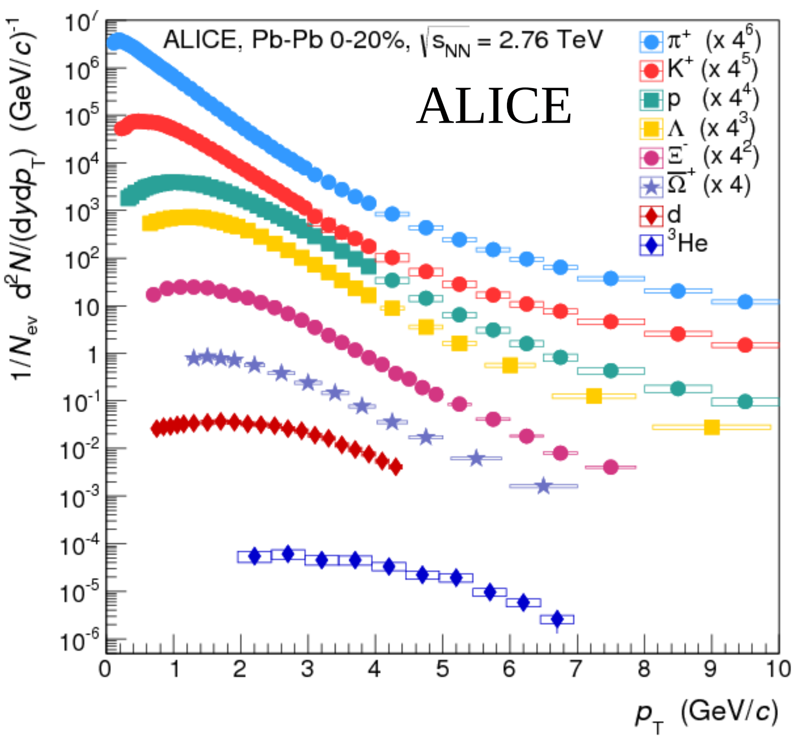
$T_c = 154 \pm 9$



Compare HIC data and Lattice QCD results

Can the thermal nature and composition
of the collision fireball in HIC be verified ?
Jean Cleymans, Helmut Oeschler & K.R

HIC → **Lattice QCD**



- The strategy:
  - Construct the 2nd order fluctuations and correlations from measured yields and compare with LGT

P. Braun-Munzinger, A. Kalweit, J. Stachel, K.R. Phys. Lett. B 47, 292 (2015), Nucl.Phys. A956, 805 (2016)

  - Compare directly measured fluctuations and correlations with LGT and chiral models

F. Karsch and K. R, Phys. Lett. B 695, 136 (2011)
F. Karsch, Central Eur. J. Phys. 10, 1234 (2012)
A. Bazavov et al., Phys. Rev. Lett. 109, 192302 (2012)
G Almasi, B. Friman and K.R. Phys. Rev. (2017)

Consider fluctuations and correlations of conserved charges to be compared with LQCD

Excellent probe of:

- QCD criticality
  - A. Asakawa at. al.
  - S. Ejiri et al.,…
  - M. Stephanov et al.,
  - K. Rajagopal et al.
  - B. Frimann et al.
- freezeout conditions in HIC
  - F. Karsch &
  - S. Mukherjee et al.,
  - C. Ratti et al.
  - P. Braun-Munzinger et al.

- They are quantified by susceptibilities:

  If $P(T,\mu_B,\mu_Q,\mu_S)$ denotes pressure, then

$$\frac{\chi_N}{T^2}=\frac{\partial^2(P)}{\partial(\mu_N)^2} \qquad \frac{\chi_{NM}}{T^2}=\frac{\partial^2(P)}{\partial\mu_N\partial\mu_M}$$

$$N=N_q-N_{-q},\quad N,M=(B,S,Q),\quad \mu=\mu/T,\quad P=P/T^4$$

- Susceptibility is connected with variance

$$\frac{\chi_N}{T^2}=\frac{1}{VT^3}(<N^2>-<N>^2)$$

- If $\mathrm{P}(N)$ probability distribution of N then

$$<N^n>=\sum_N N^n\mathrm{P}(N)$$

Consider special case:

- Baryon and anti-antibaryon Poisson distributed, then for the net charge N
- $\mathrm{P}(N)$ is the Skellam distribution

$$\mathrm{P}(N) = \left(\frac{N_q}{N_{-q}} \right)^{N/2} I_N(2\sqrt{N_q N_{-q}}) \exp[-(N_q + N_{-q})]$$

$< N_q > \equiv N_q$ =>

Charge carrying by particles $q = \pm 1$

- The susceptibility

$$\frac{\chi_N}{T^2} = \frac{1}{VT^3}(< N_q > + < N_{-q} >)$$

Consider special case: particles carrying $q=\pm 1,\pm 2,\pm 3$

- The probability distribution

P. Braun-Munzinger,
B. Friman, F. Karsch,
V Skokov &K.R.
Phys .Rev. C84 (2011) 064911
Nucl. Phys. A880 (2012) 48)

$$< S_{-q} > \equiv S_{-q}$$

$$q=\pm 1,\pm 2,\pm 3$$

$$P(S)=\left(\frac{S_1}{S_{\bar{1}}}\right)^{\frac{S}{2}} \exp\left[\sum_{n=1}^{3}\left(S_n+S_{\bar{n}}\right)\right]$$

$$\sum_{i=-\infty}^{\infty}\sum_{k=-\infty}^{\infty}\left(\frac{S_3}{S_{\bar{3}}}\right)^{\frac{k}{2}} I_k\left(2\sqrt{S_3 S_{\bar{3}}}\right)\left(\frac{S_2}{S_{\bar{2}}}\right)^{\frac{i}{2}} I_i\left(2\sqrt{S_2 S_{\bar{2}}}\right)$$

$$\left(\frac{S_1}{S_{\bar{1}}}\right)^{-i-\frac{3k}{2}} I_{2i+3k-S}\left(2\sqrt{S_1 S_{\bar{1}}}\right)$$

Fluctuations

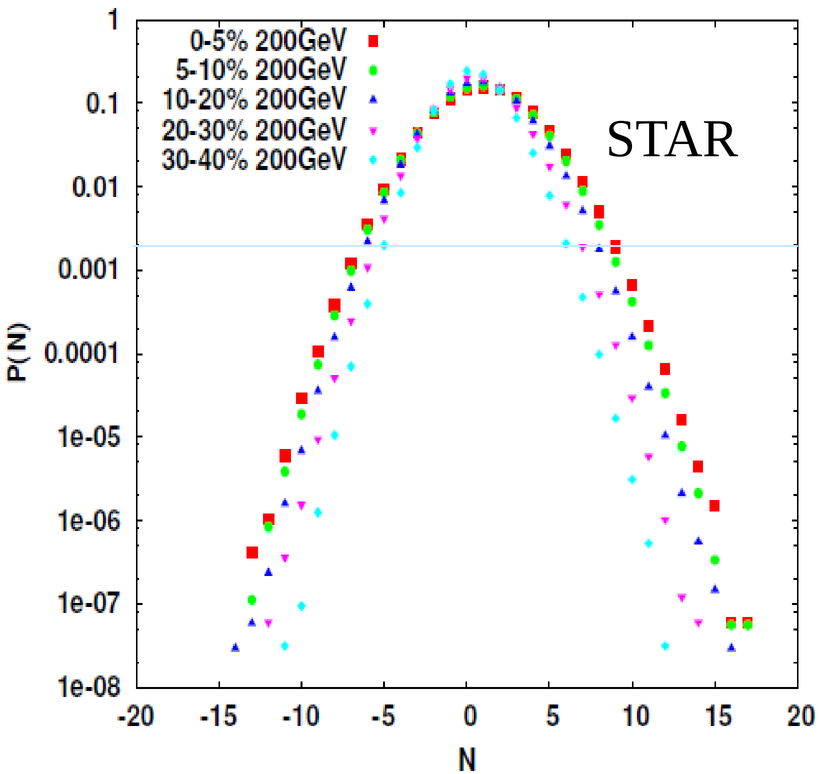
$$\frac{\chi_S}{T^2}=\frac{1}{VT^3}\sum_{n=1}^{|q|} n^2\left(\langle S_n\rangle+\langle S_{-n}\rangle\right)$$

Correlations

$$\frac{\chi_{NM}}{T^2}=\frac{1}{VT^3}\sum_{m=-q_M}^{q_M}\sum_{n=-q_N}^{q_N} nm\langle S_{n,m}\rangle$$

$\langle S_{n,m}\rangle$ is the mean number of particles carrying charge $N=n$ and $M=m$

Variance at 200 GeV AA central coll. at RHIC

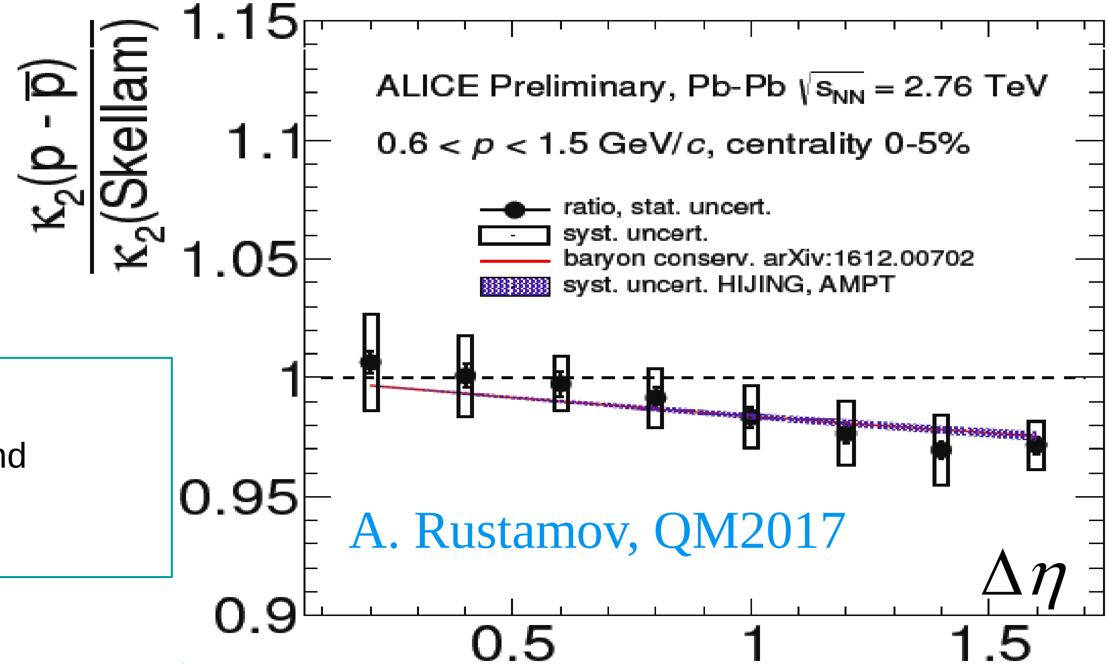


STAR Collaboration data in central coll. 200 GeV

- Consistent with Skellam distribution

$$\frac{<p>+<\bar{p}>}{\sigma^2} = 1.022 \pm 0.016 \qquad \frac{\chi_1}{\chi_3} = 1.076 \pm 0.035$$

- ALICE data consistent with Skellam $\Delta\eta < 1$



- Skellam distribution is a good approximation to calculate the 2nd order charge fluctuations in HIC

The influence of baryon number conservation: P. Braun-Munzinger, A. Rustamov, J. Stachel. Nucl Phys. A960 (2017) 114

Variance at 200 GeV AA central coll. at RHIC

K. Morita, B. Friman and K.R. Redlich
Phys.Lett. B741 (2015) 178

STAR Collaboration data in central coll. 200 GeV

Consistent with Skellam distribution

$$\frac{<p>+<\bar{p}>}{\sigma^2}=1.022\pm0.016$$

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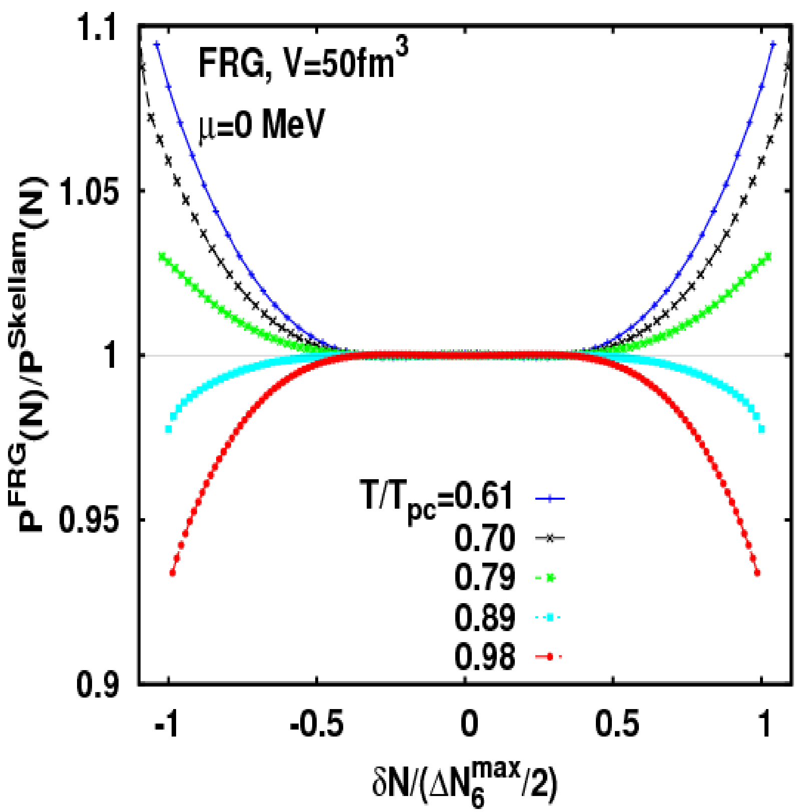
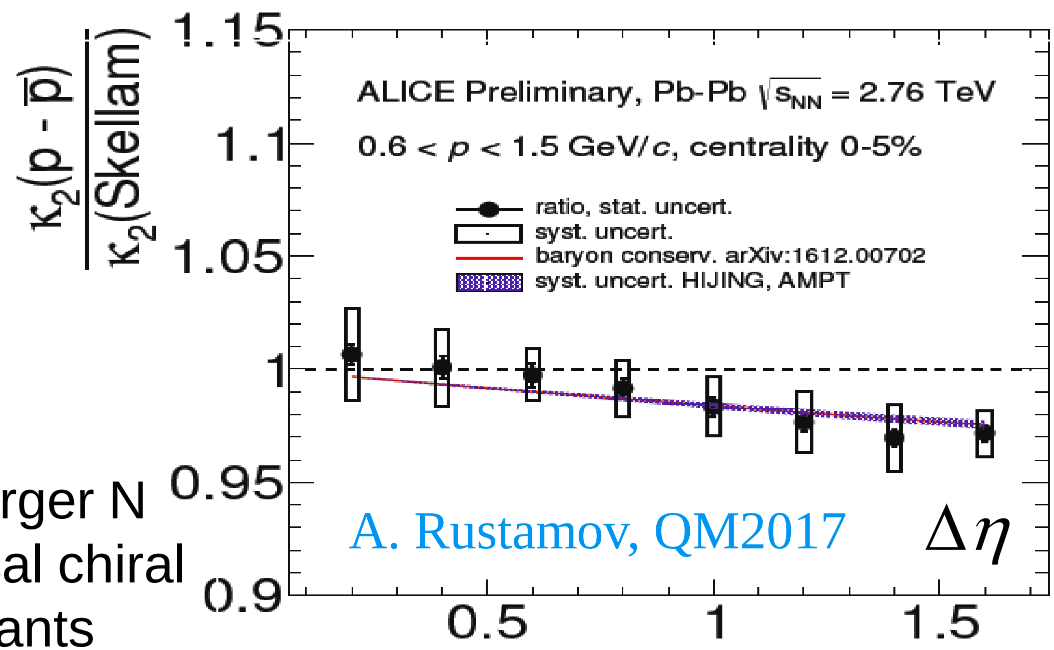




- Shrinking of Skellam distr. at larger N needed to capture the O(4) critical chiral properties of higher order cumulants

Direct comparisons of Heavy ion data at LHC with LQCD

χ_{NM} with $N,M=\{B,Q,S\}$ are expressed by particle yields

$$\frac{\chi_B}{T^2} \approx \frac{1}{VT^3}\left(\langle p\rangle + \langle N\rangle + \langle \Lambda + \Sigma_0\rangle + \langle \Sigma^+\rangle + \langle \Sigma^-\rangle + \langle \Xi^-\rangle + \langle \Xi^0\rangle + \langle \Omega^-\rangle + \overline{par}\right)$$

LQCD From ALICE DATA

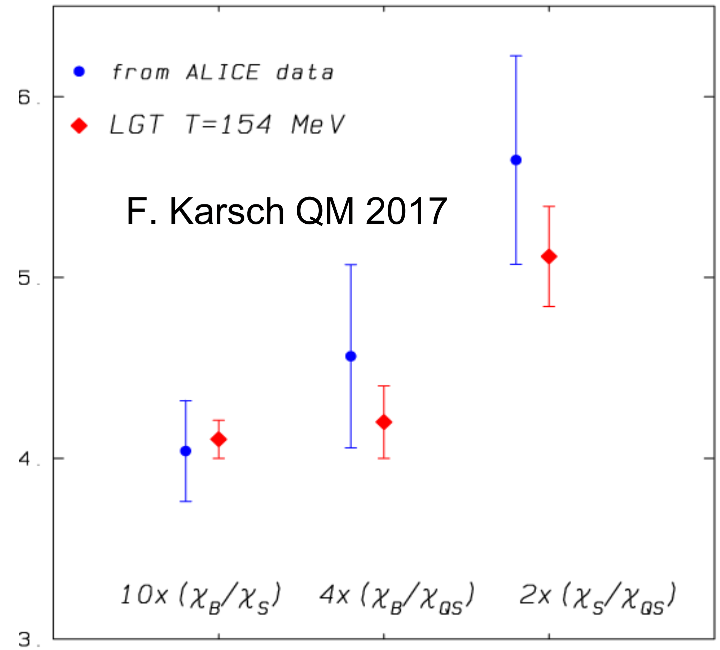
$$\frac{\chi_B}{T^2} = \frac{1}{VT^3}(203.7 \pm 11.4)$$

$$\frac{\chi_S}{T^2} = \frac{1}{VT^3}(504.2 \pm 16.8)$$

$$\frac{\chi_{QS}}{T^2} = \frac{1}{VT^3}(191.1 \pm 12)$$

- The Volume at

$$V_{T_c} = 3800 \pm 500 \quad fm^3$$

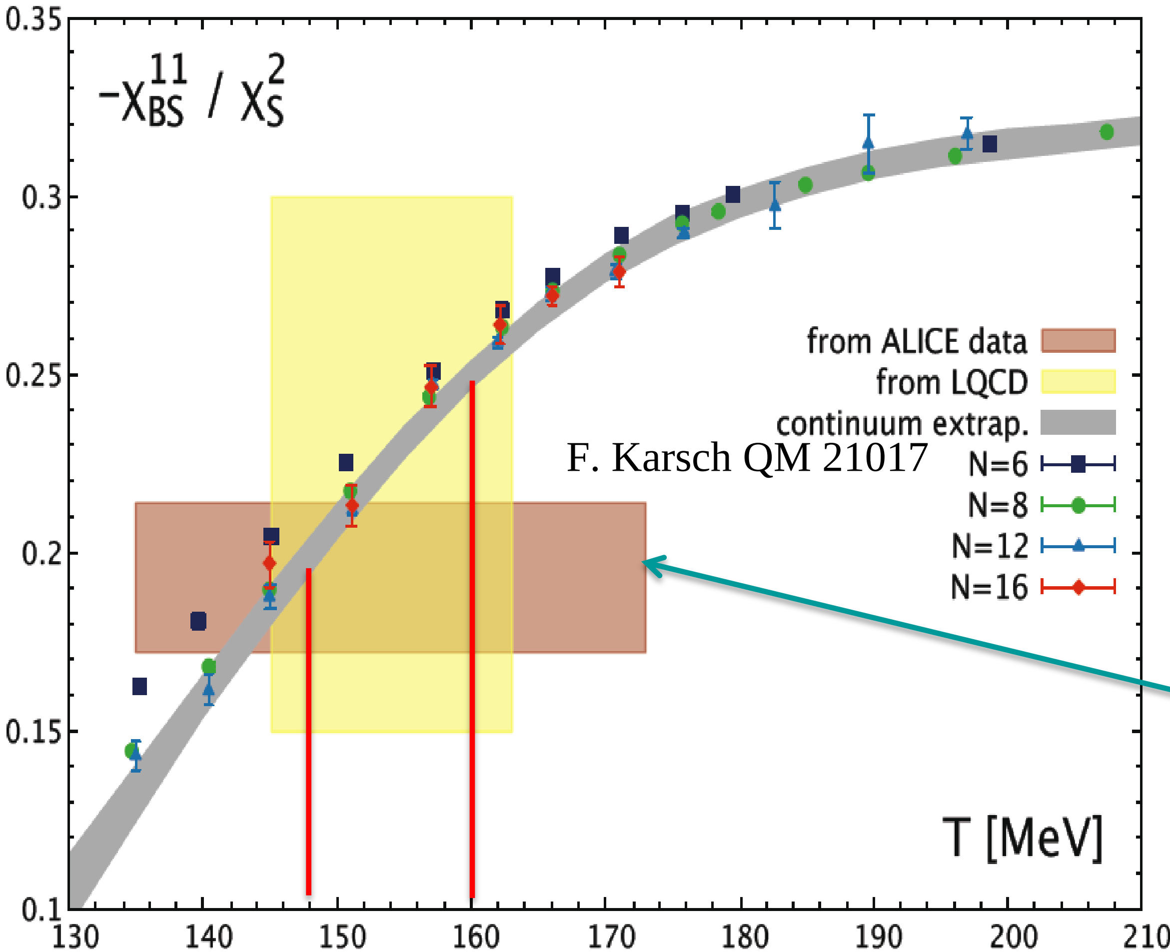


The cumulant ratios extracted from ALICE data are consistent with LQCD at

$$0.148 \le T_f < 160 \quad MeV$$

Evidence for thermalization at the phase boundary

Constraining chemical freezeout temperature at the LHC



At the LHC energy the fireball created in HIC is a QCD medium at the chiral cross over temperature.

$$C_{BS} = -\frac{<(\delta B)(\delta S)>}{<(\delta S)^2>} = -\frac{\chi_{BS}}{\chi_S}$$

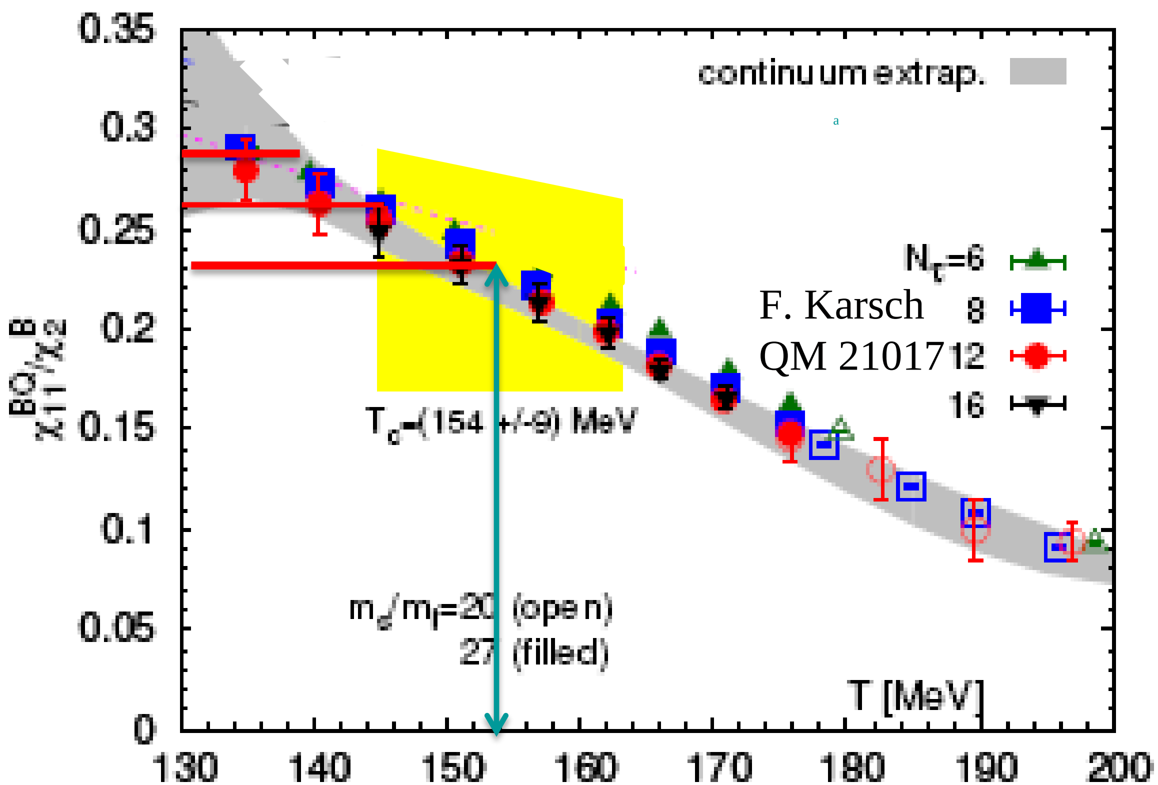
- Excellent observable to fix the temperature

$$-\frac{\chi_{BS}}{T^2} \approx \frac{1}{VT^3}[2<\Lambda+\Sigma^0>+4<\Sigma^+>$$
$$+8<\Xi>+6<\Omega^->] = (97.4\pm 5.8)/VT^3$$

However, this is the lower limit since e.g. $\Sigma^*(\geq 1660) \to N\overline{K}$ $\Lambda^*(\geq 1520) \to N\overline{K}$ are not included

- Data on χ_B / χ_S and χ_B / χ_{QS} consistent with LQCD results for $0.148 \leq T_f < 160\ MeV$

Constraining the upper value of the chemical freeze-out temperature at the LHC



- Considering the ratio

$$\frac{<(\delta B)(\delta Q)>}{<(\delta B)^2>} = \frac{\chi_{BQ}}{\chi_B} = 0.26 \pm 0.03$$

one gets $T < 156\ MeV$

- From the comparison of 2nd order fluctuations and correlations observables constructed from ALICE data and LQCD, one gets agreement at

$$148 \le T_f < 156\ MeV$$

Particle yields data at the LHC consistent with LQCD at the phase boundary

Thermal origin of particle yields with respect to HRG

Rolf Hagedorn => the Hadron Resonace Gas (HRG):

"uncorrelated" gas of hadrons and resonances

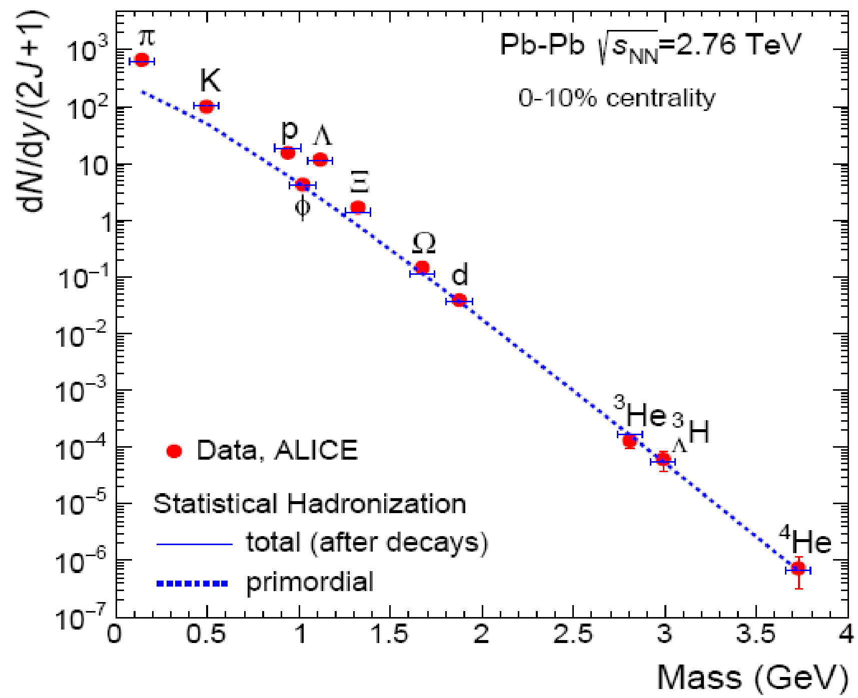
$$< N_i >= V\,[n_i^{th}(T,\vec{\mu}) + \sum_K \Gamma_{K\to i}\, n_i^{th-\mathrm{Res.}}(T,\vec{\mu})]$$

A. Andronic, Peter Braun-Munzinger, Johanna Stachel & K.R.

Particle yields with no resonance decay contributions:

$$\frac{1}{2j+1}\frac{dN}{dy} = V(m/T)^2 K_2(m/T)$$

$$m^{3/2} e^{-m/T}$$



- Measured yields are well reproduced within HRG with $T = 156 \pm 1.5\ MeV$ that coincides with the chiral crossover

Helmut Oeschler ⇨ Correlated strangeness production

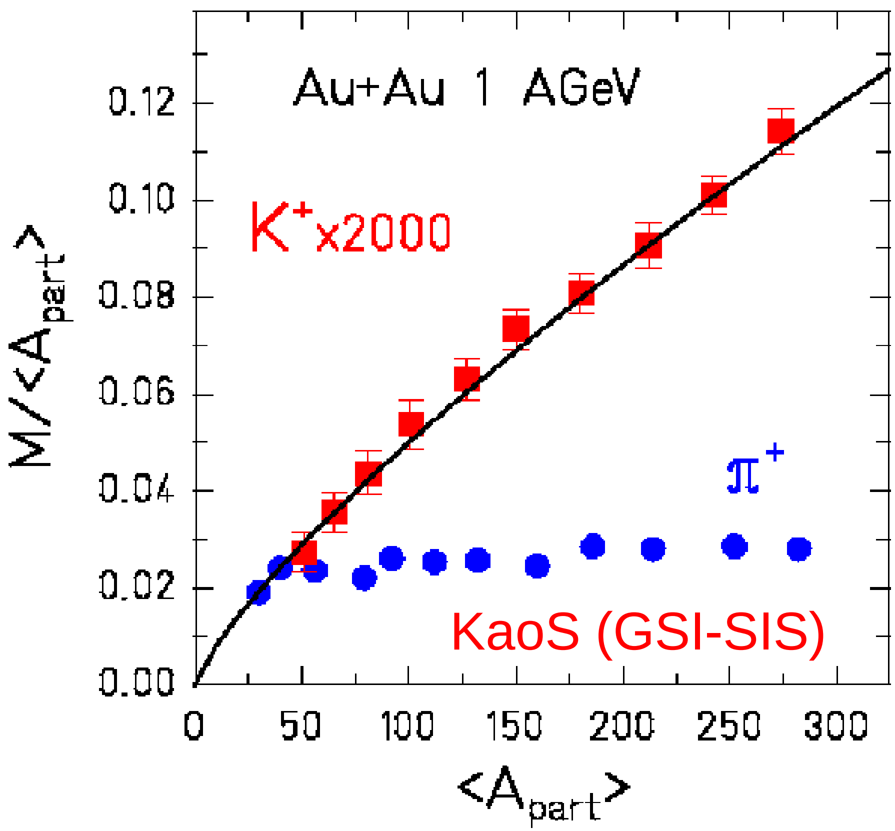
$$N + N \rightleftarrows K^+ + Y + N$$

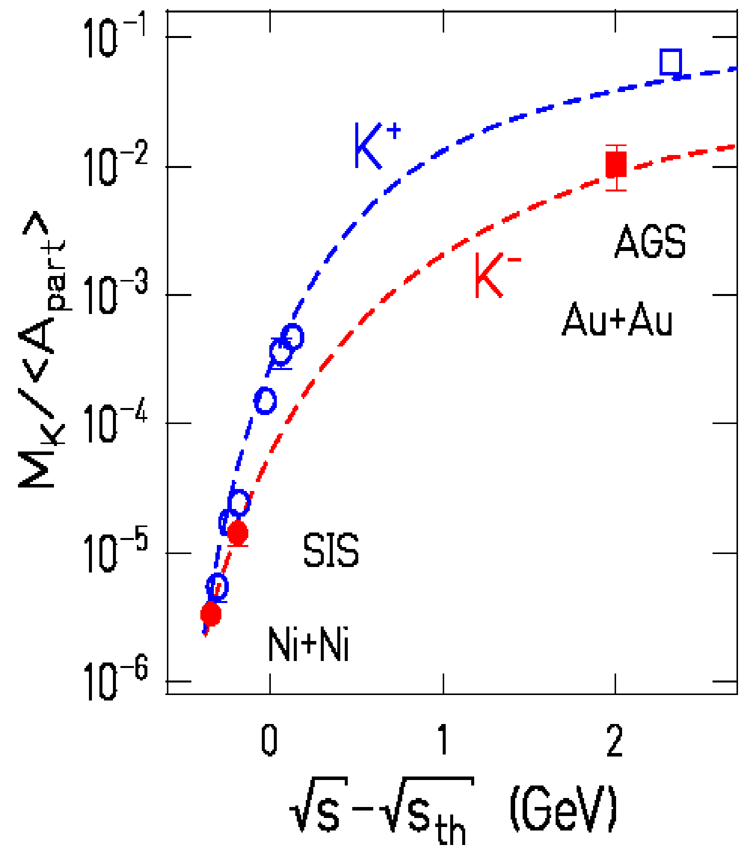
$$< \pi^+ > \sim A_{part} e^{-(m_\Delta - \mu_B)/T}$$

⇨

$$< K^+ >^C \sim A_{part}^2 e^{-m_k/T} e^{-(m_Y - \mu_B)/T}$$

$$\pi + Y \rightleftarrows K^- + N$$

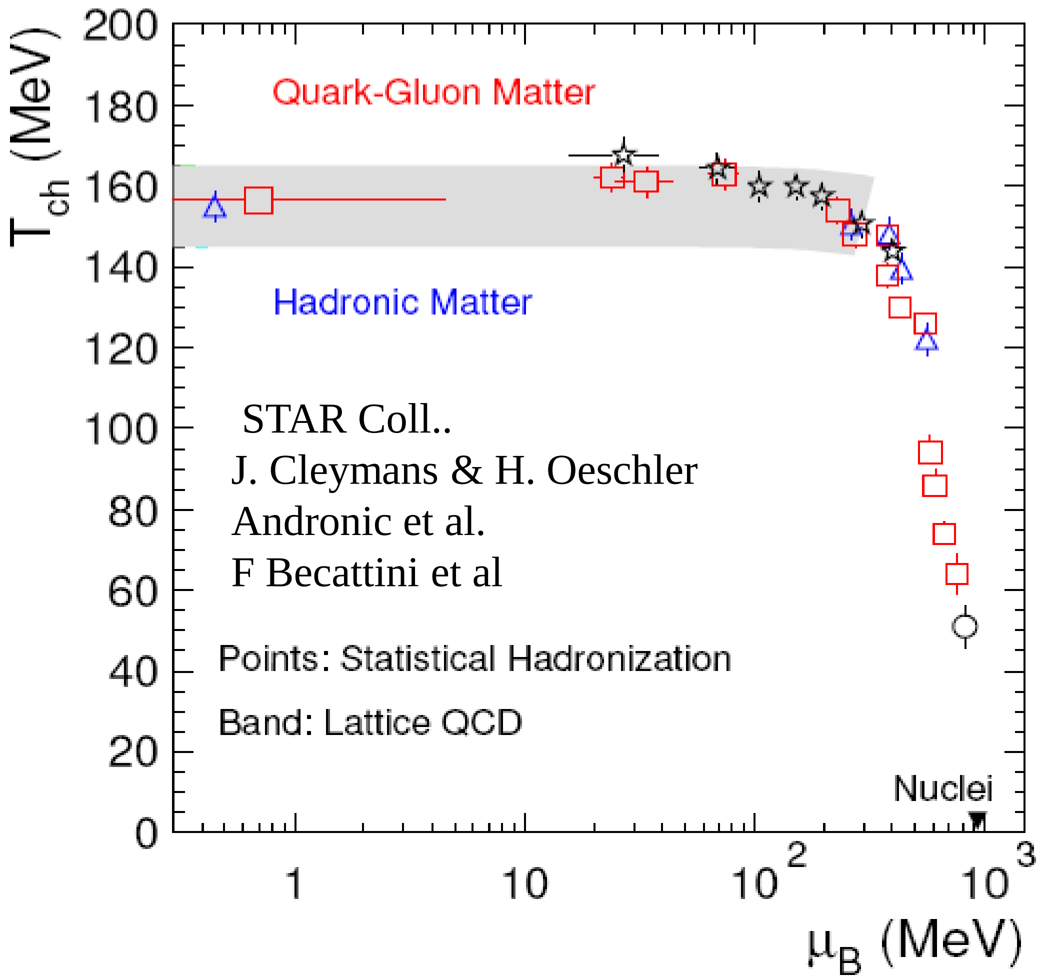




Chemical Freeze out and QCD Phase Boundary

Chemical freeze out defines a lower bound for the QCD phase boundary

A. Andronic, P. Braun-Munzinger, K.R. & J. Stachel



- The QCD phase boundary coincides with chemical freeze out conditions obtained from HIC data analyzed with the HRG model
  - J Stachel and P. Braun-Munzinger
  - J. Cleymans, H. Oeschler & K.R.

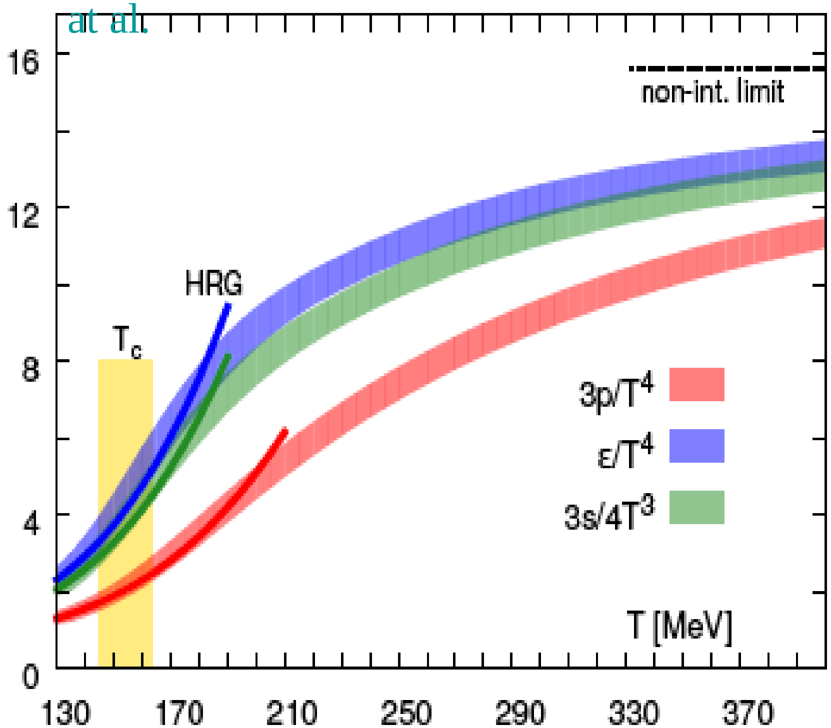
QCD Matter at chiral cross over

- HIC & HRG ⟷ LQCD

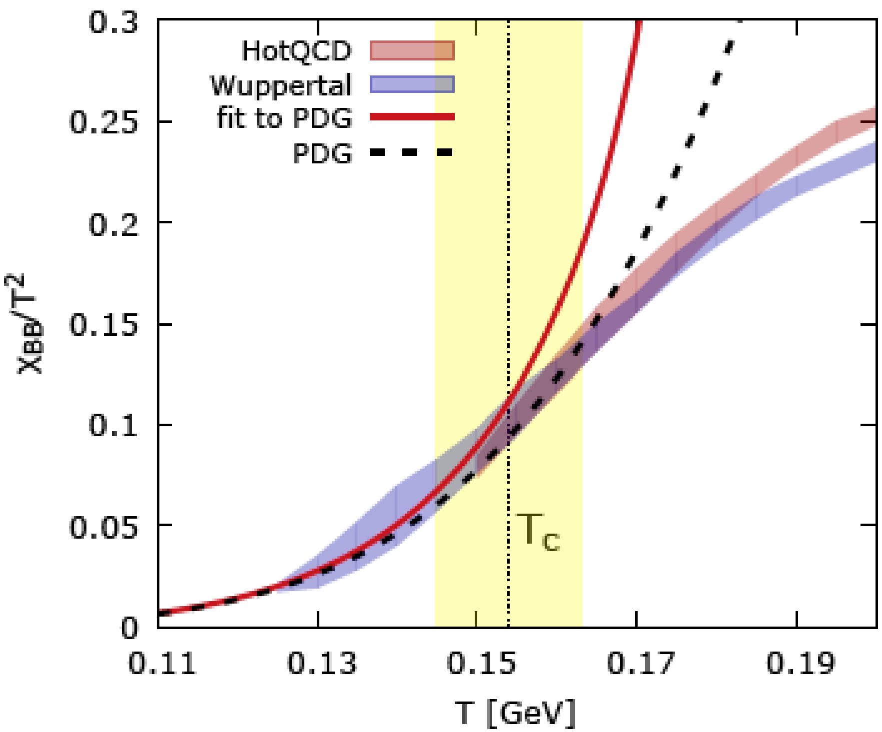
- The HRG describes the QCD thermodynamics in the hadronic phase

Good description of the QCD Equation of States by Hadron Resonance Gas

A. Bazavov et al. HotQCD Coll. July 2014 at al.



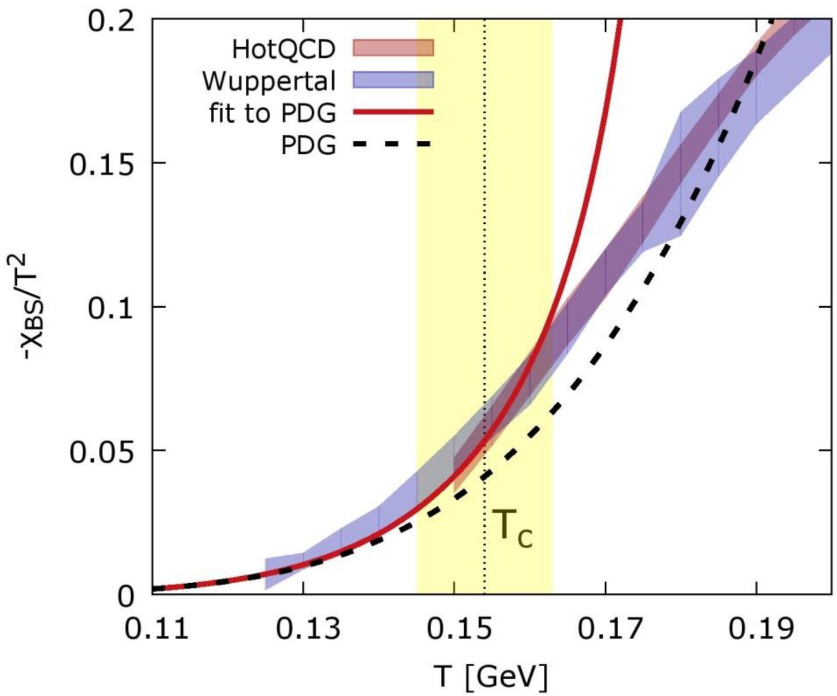
P.M. Lo, M Marczenko et al. Eur. Phys.J. A52 (2016)

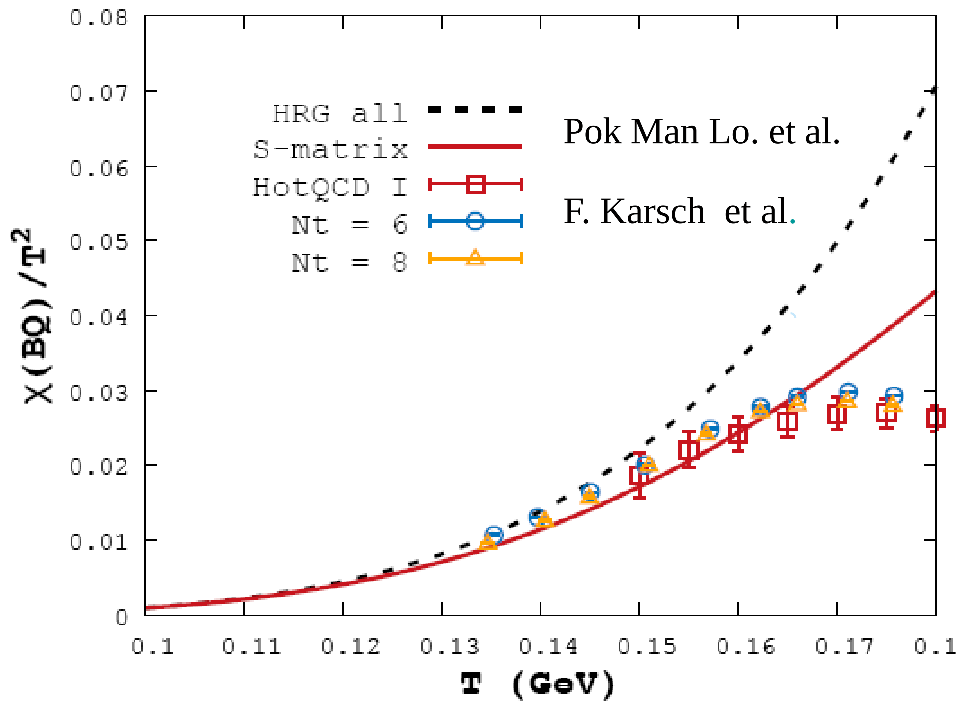


- Hadron Gas thermodynamic potential provides an excellent approximation of the QCD equation of states in confined phase

- As well as, good description of the net-baryon number fluctuations which can be improved by adding baryonic resonances expected in the Hagedorn exponential mass spectrum

Deviation of Hadron Resonace Gas from LQCD





- Missing strange baryon and meson resonances in the PDG

  F. Karsch, et al., Phys. Rev. Lett. 113, no. 7, 072001 (2014)

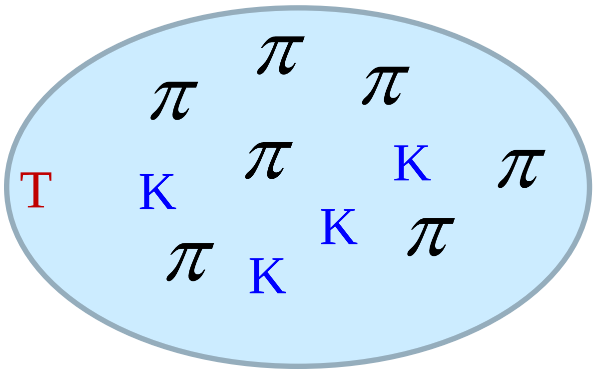
  P.M. Lo, M. Marczenko, et al. Eur. Phys.J. A52 (2016)

- Large deviation of HRG from LQCD results due to missing strange baryon resonances and incorrect treatment of dynamical width of non-strange resonaces

HRG model and S-MATRIX APPROACH

R. Dashen, S. K. Ma and H. J. Bernstein,
Phys. Rev. 187, 345 (1969)
W. Weinhold, & B. Friman
Phys. Lett. B 433, 236 (1998).

$$\boxed{\pi + K \leftrightarrow \pi + K}$$



- Consider interacting pions and kaons gas in thermal equilibrium at temperature T
- Due to $K\pi$ scattering resonances are formed

  I =1/2, s -wave : κ(800), K0*(1430) [*JP* = 0+]

  I =1/2, p -wave : *K**(892), *K**(1410), *K**(1680) [*JP* =1−]
- In the S-matrix approach the thermodynamic pressure in the low density approximation

$$\boxed{P(T) \approx P_{\pi}^{id} + P_{K}^{id} + P_{\pi K}^{\text{int}}}$$

$$P^{\text{int}}{}_{\pi K} = \int_{m_{th}}^{\infty} \frac{dM}{2\pi} B(M) P_T(M)$$

linked to empirical scattering phase shift

$$B(M) = 2\frac{d}{dM}\delta(M)$$

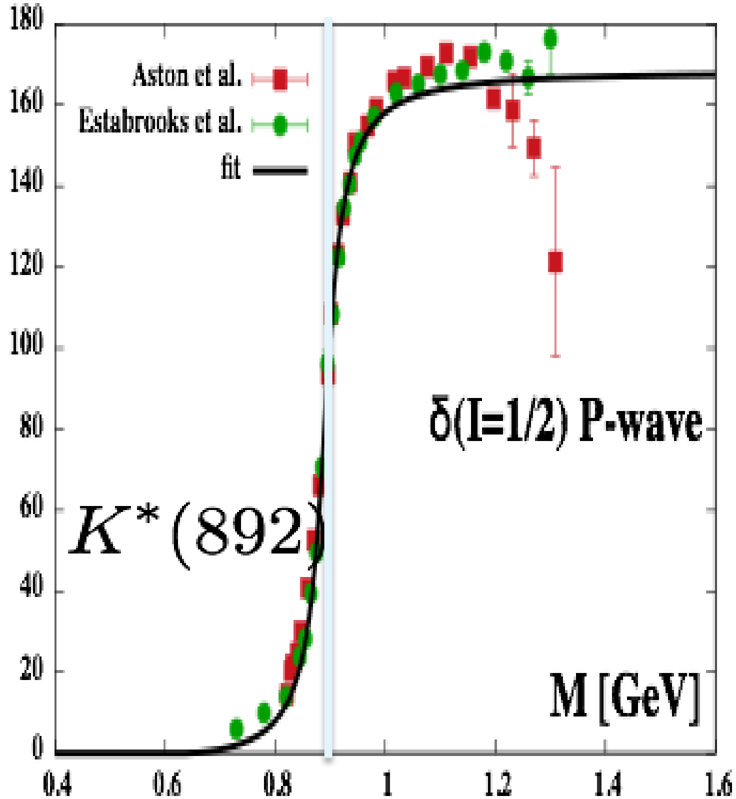
Only for narrow resonance

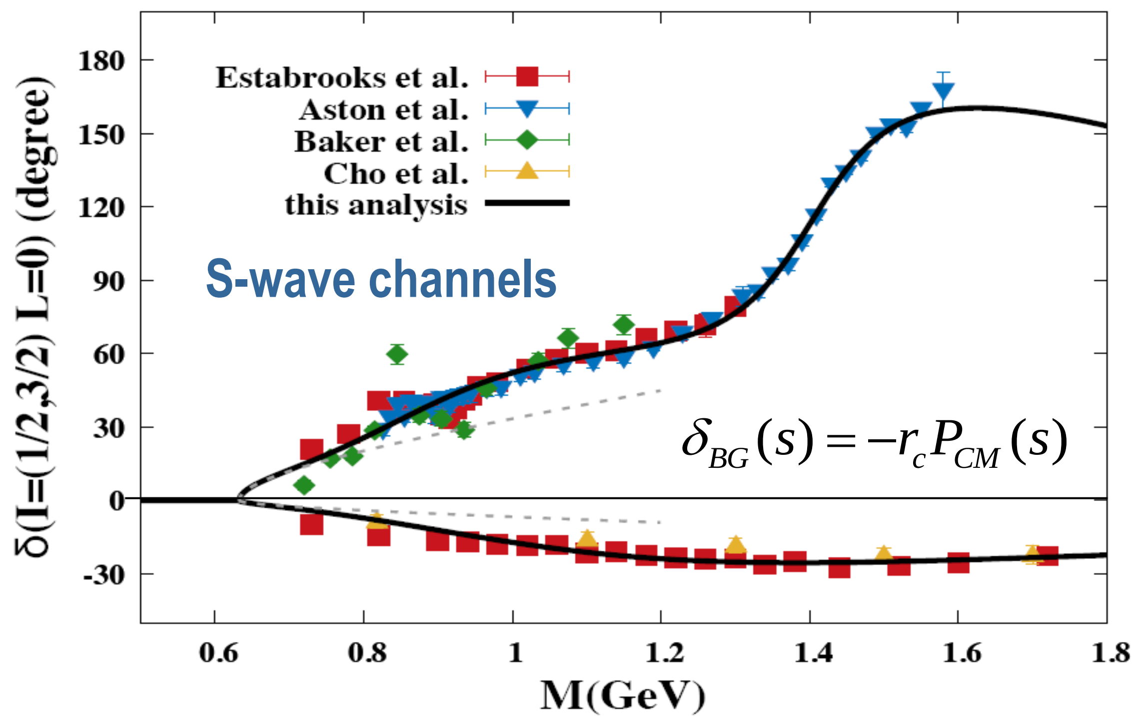
$$B(M) = \delta(M^2 - M_0^2)$$

$$P_{K\pi}^{\text{int}}(T) \approx P_R^{id}(T)$$ as HRG

Experimental phase shifts in πK scattering

Pok Man Lo et al., Phys.Rev. C96 (2017)
Phys.Rev. D92 (2015)





Narrow resonance:

$$\boxed{\delta_0(M) \approx \theta(M - M_R)}$$

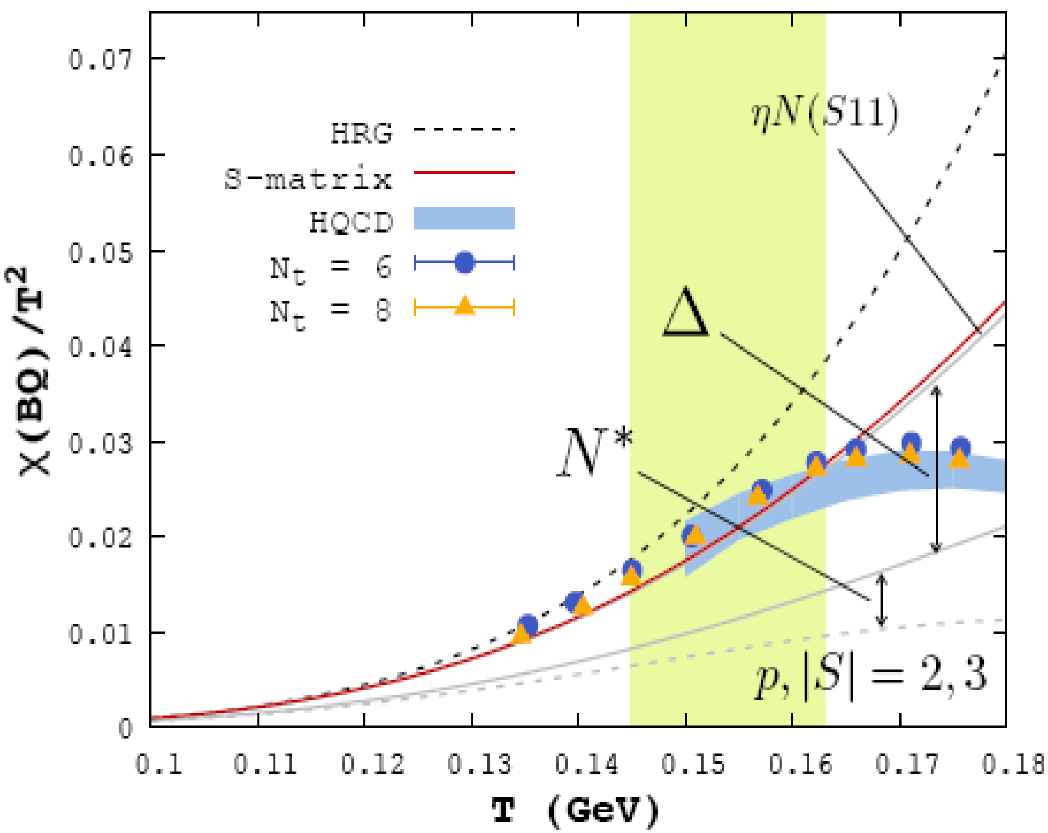
$$B(M) = \delta(M^2 - M_R^2)$$

$$\boxed{\delta_0(M) = \delta_{\kappa(800)} + \delta_{K_0^*(1430)} + \delta_{BG}}$$

$$B(M) = 2\frac{d}{dM}\delta_0(M)$$

Probing non-strange baryon sector

Pok Man Lo, B. Friman, C. Sasaki & K.R.



- Due to isospin symmetry

$$\chi_{BQ} = \frac{1}{2}(\chi_{BB} - |\chi_{BS}|)$$

where all $S = \pm 1$ baryon resonances are canceled out. The $S = \pm 2, \pm 3$ contribution is small, thus χ_{BQ} is governed mainly by the contribution of nucleons and $S = 0$ baryonic resonances N^*, Δ^*

- Considering contributions of all N^*, Δ^* resonances to χ_{BQ} with correctly implemented dynamical widths within S-matrix approach imply the reduction of the HRG contribution towards the LQCD data in the region of chiral crossover

Conclusions:

The medium created in HIC at the LHC is of thermal origin and follows properties expected in LQCD near the phase boundary at

$$148 \le T < 156 \;\; MeV$$

- The Hadron Resonance Gas is confirmed to be a very good approximation of QCD thermodynamics and provides also quantitative description of particle yields in HIC from SIS to LHC
- systematics of LQCD results on 2nd order fluctuations and correlations idicate that there are missing baryonic resonances in the $S = \pm 1$ strangeness sector
- To properly quantify fluctuation observables within HRG model the dynamical widths of broad resonances must be correctly included. e.g. by using the phase shift data within S-matrix approach