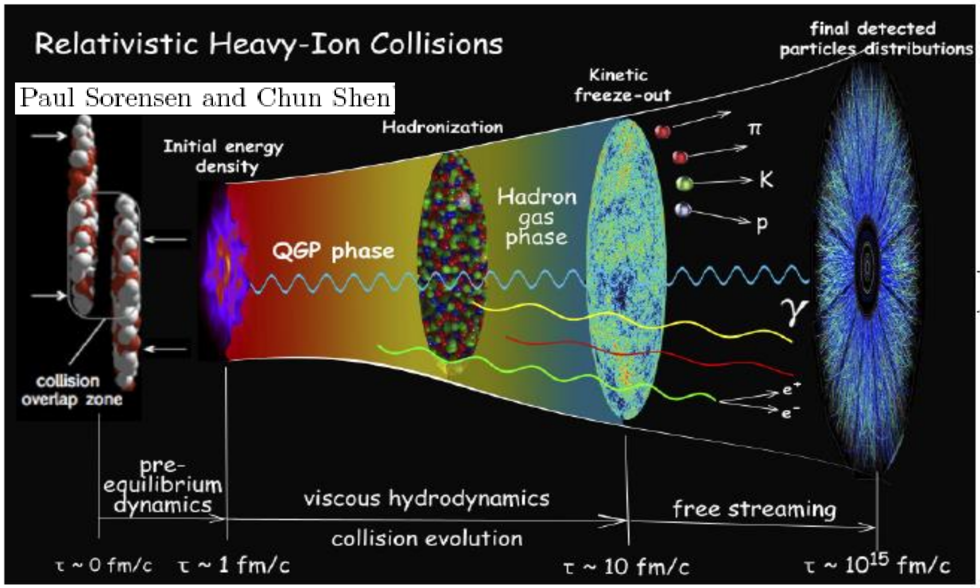
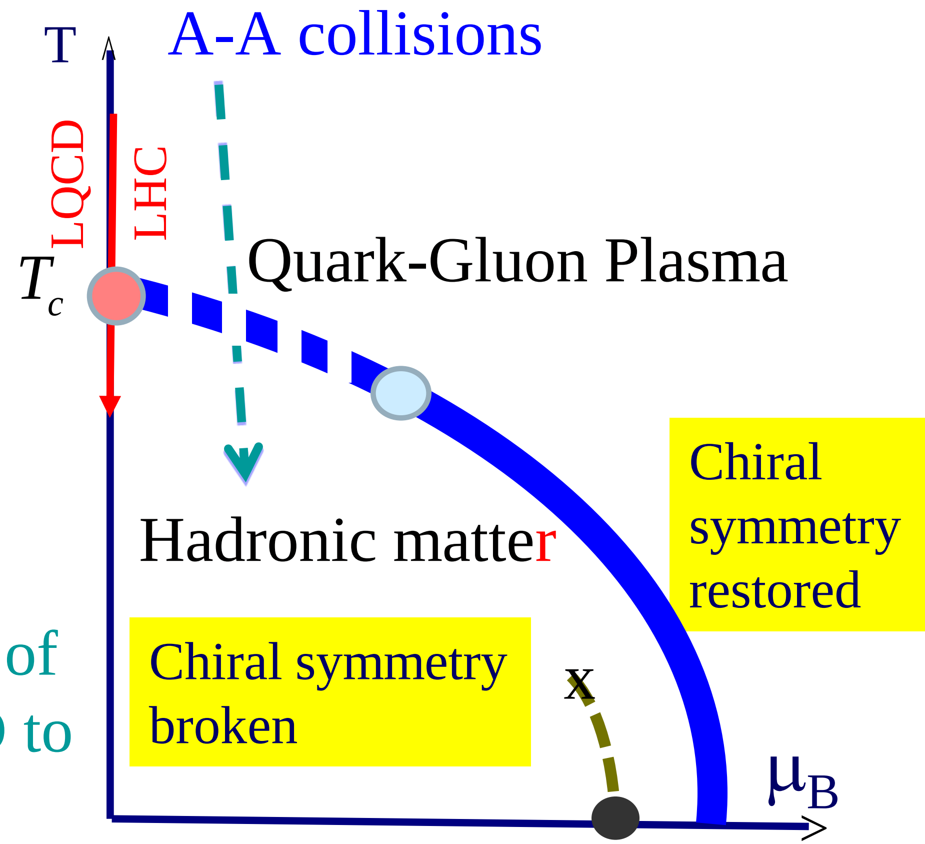
Imprints of the Quark-Gluon Plasma in Heavy Ion Collisions

Krzysztof Redlich, Uni Wroclaw



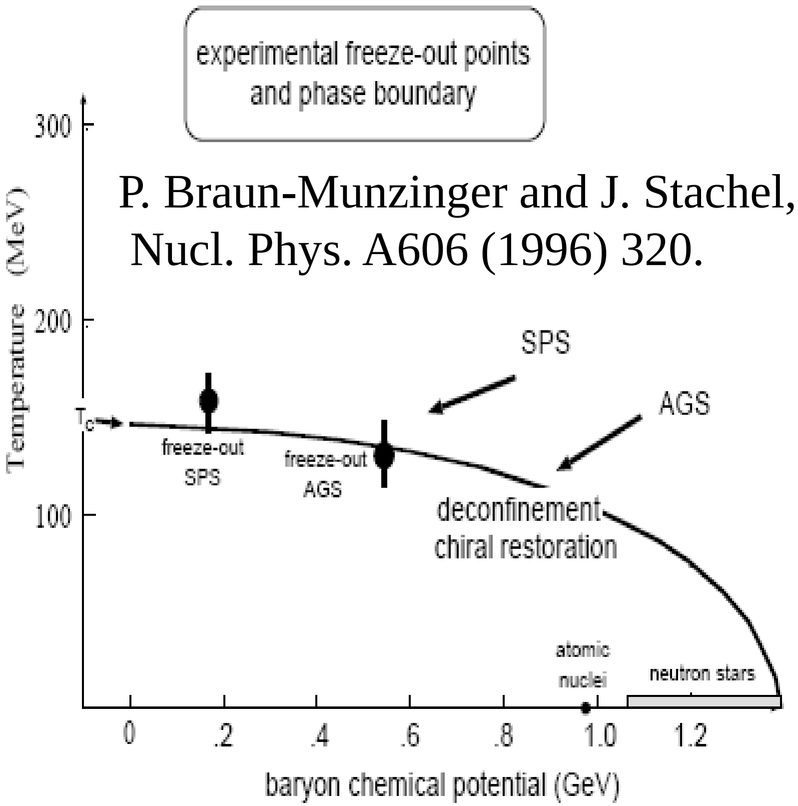


Confronting Fluctuations and correlations of conserved charges at the LHC with LQCD to identify their common properties

Work done with:

P. Braun-Munzinger, A. Kalweit & J. Stachel

Thermal and chemical equilibrium population of particles produced in HIC as imprints of the QGP formation



P. Braun-Munzinger, J. Stachel, J. P. Wessels and N. Xu, Phys.
Phys. Lett . B365, 1 (1996)
Phys. Lett. B344, 43 (1995)

Modelling the QCD thermodynamic potential as a hadron resonance gas

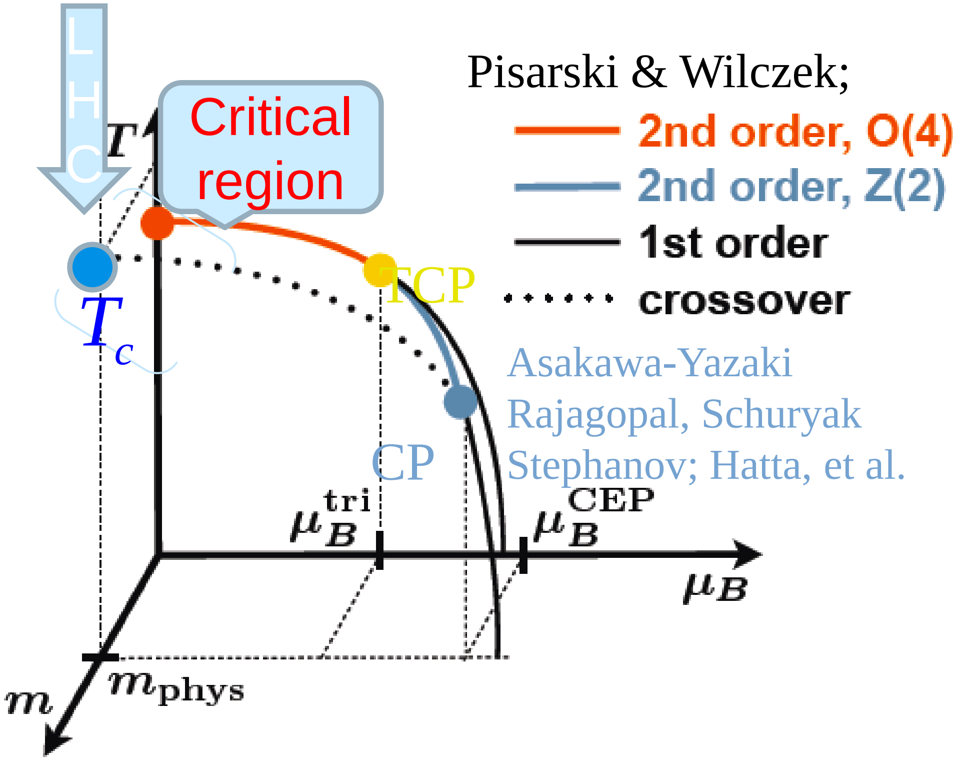
$$P \approx T^4 \sum_i F(m_i / T) \cosh(\vec{Q} \cdot \vec{\mu} / T)$$

with the PDG mass spectrum

- Excellent description of particle yields in HIC with at the AGS and SPS with a common thermal parameters (T, μ_B)

- Conjectured coincidence of chemical freezeout and the QCD phase boundary by P. Braun-Munzinger and J. Stachel ?

Deconfinement and chiral symmetry restoration in QCD



- The QCD chiral transition is crossover   Y.Aoki, et al Nature (2006)
  and appears in the O(4) critical region

  O. Kaczmarek et.al. Phys.Rev. D83, 014504 (2011)

- Chiral transition temperature

  $$T_c = 155(1)(8)\ \text{MeV}$$

  T. Bhattacharya et.al.
  Phys. Rev. Lett. 113, 082001 (2014)

- Deconfinement of quarks sets in at the chiral crossover

  A.Bazavov, Phys.Rev. D85 (2012) 054503

- The shift of T_c with chemical potential

$$T_c(\mu_B) = T_c(0)[1 - 0.0066 \cdot (\mu_B / T_c)^2]$$

Ch. Schmidt Phys.Rev. D83 (2011) 014504

See also:
Y. Aoki, S. Borsanyi, S. Durr, Z. Fodor, S. D. Katz, *et al.*
JHEP, 0906 (2009)

The thermal nature and composition of the collision fireball in HIC can be verified

- with respect to the QCD partition function

  by comparing

  LQCD results at finite temperature

  with

  LHC data taken in central

  Pb-Pb collisions at $\sqrt{s} = 2.75\ \text{TeV}$

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 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

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

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

- 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:

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

$$< N_q > \equiv \bar{N}_q \quad =>$$

- Charge and anti-charge uncorrelated and Poisson distributed, then
- $P(N)$ the Skellam distribution

$$P(N) = \left(\frac{\bar{N}_q}{\bar{N}_{-q}} \right)^{N/2} I_N(2\sqrt{\bar{N}_{-q}\bar{N}_q}) \exp[-(\bar{N}_{-q} + \bar{N}_q)]$$

- Then the susceptibility

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

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

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

- The probability distribution

$$< S_{-q} > \equiv \bar{S}_{-q}$$

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

$$P(S) = \left(\frac{\bar{S}_1}{\bar{S}_{\bar{1}}}\right)^{\frac{S}{2}} \exp\left[\sum_{n=1}^{3}(\bar{S}_n + \bar{S}_{\bar{n}})\right] \sum_{i=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \left(\frac{\bar{S}_3}{\bar{S}_{\bar{3}}}\right)^{k/2} I_k(2\sqrt{\bar{S}_3 \bar{S}_{\bar{3}}}) \left(\frac{\bar{S}_2}{\bar{S}_{\bar{2}}}\right)^{i/2} I_i(2\sqrt{\bar{S}_2 \bar{S}_{\bar{2}}}) \left(\frac{\bar{S}_1}{\bar{S}_{\bar{1}}}\right)^{-i-3k/2} I_{2i+3k-S}(2\sqrt{\bar{S}_1 \bar{S}_{\bar{1}}})$$

Fluctuations

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

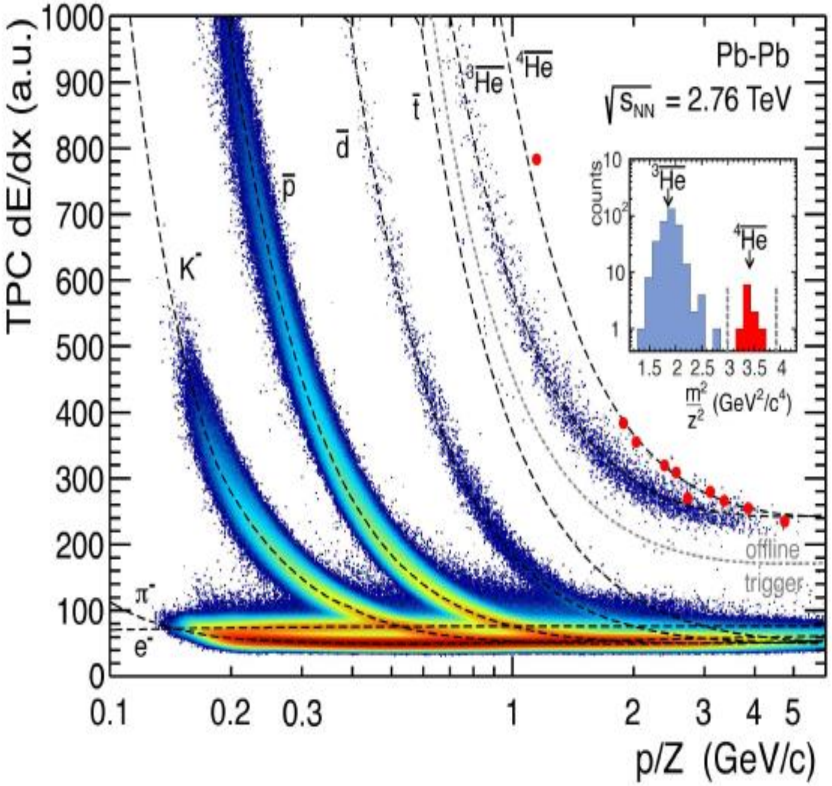
Correlations

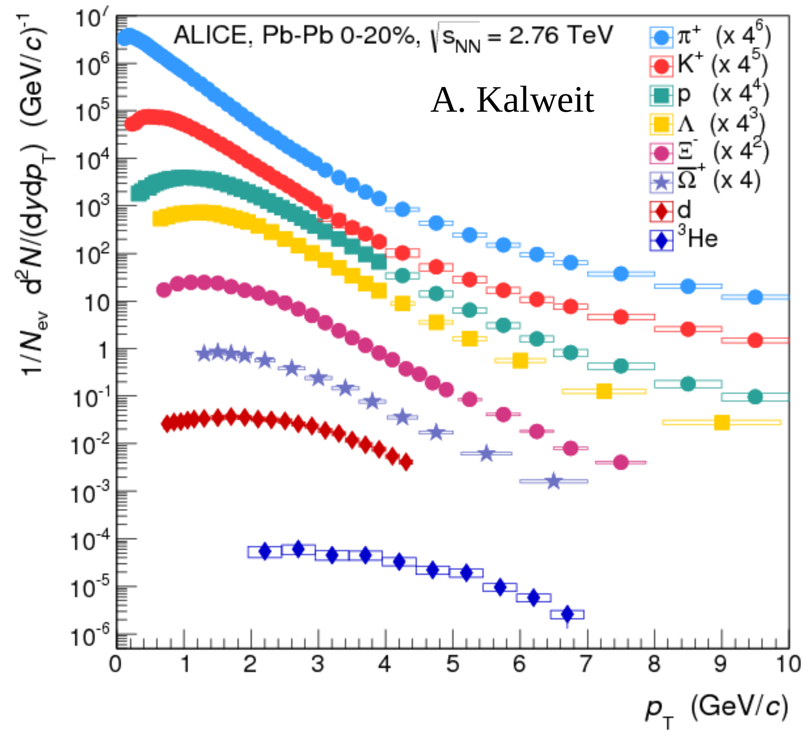
$$\frac{\chi_{NM}}{T^2} = \frac{1}{VT^3} \sum_{n=-q_N}^{q_N} \sum_{m=-q_M}^{q_M} nm \langle N_{n,m} \rangle$$

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

Excellent performance of ALICE detectors for particles identification

Paolo Giubellino & Jürgen Schukraft for ALICE Collaboration

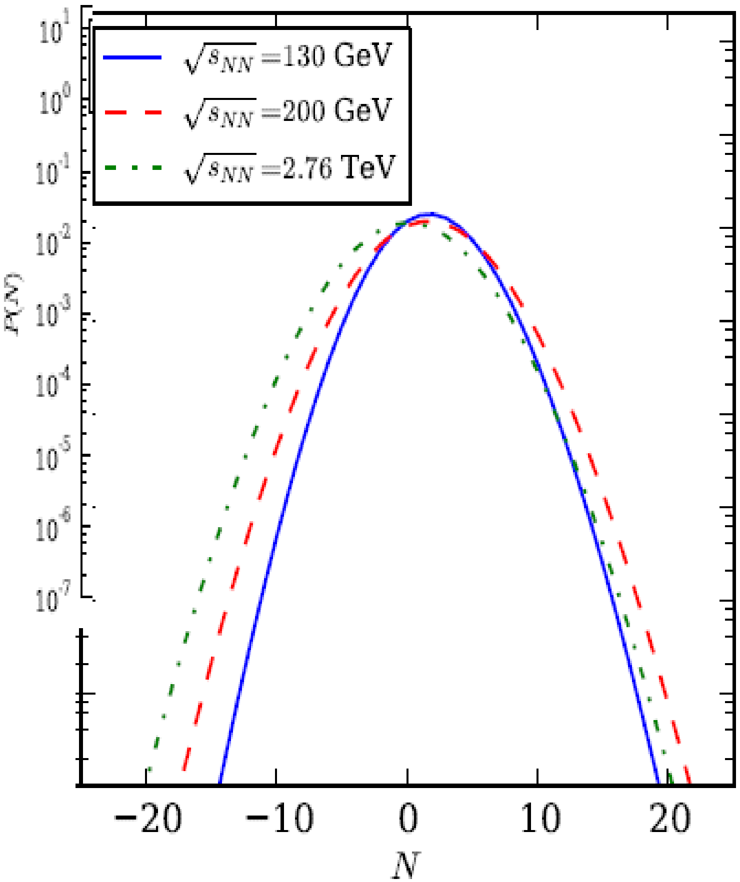




ALICE Time Projection Chamber (TPC), Time of Flight Detector (TOF), High Momentum Particle Identification Detector (HMPID) together with the Transition Radiation Detector (TRD) and the Inner Tracking System (ITS) provide information on the flavour composition of the collision fireball, vector meson resonances, as well as charm and beauty production through the measurement of leptonic observables.

Variance at 200 GeV AA central coll. at RHIC

P. Braun-Munzinger, et al.
Nucl. Phys. A880 (2012) 48)



STAR Collaboration data in central coll. 200 GeV

- Consistent with Skellam distribution

$$\chi_{2N} \propto \langle p \rangle + \langle \bar{p} \rangle$$

$$\chi_{2N+1} \propto \langle p \rangle - \langle \bar{p} \rangle$$

$$\frac{\chi_{2N+1}}{\chi_{2M+1}} = 1$$

$$\frac{\langle p \rangle + \langle \bar{p} \rangle}{\sigma^2} = 1.022 \pm 0.016$$

$$\frac{\chi_1}{\chi_3} = 1.076 \pm 0.035$$

- Consider ratio of cumulants in in the whole momentum range:

$$\frac{\sigma^2}{p - \bar{p}} = 6.18 \pm 0.14 \; in \; 0.4 < p_t < 0.8 GeV$$

$$\frac{p + \bar{p}}{p - \bar{p}} = 7.67 \pm 1.86 \; in \; 0.0 < p_t < \infty \; GeV$$

Probing O(4) chiral criticality with charge fluctuations

- Due to expected O(4) scaling in QCD the free energy:

$$P = P_R(T, \mu_q, \mu_I) + b^{-1} P_S(b^{(2-\alpha)^{-1}} t(\mu), b^{\beta\delta/\nu} h)$$

- Generalized susceptibilities of net baryon number

$$c_B^{(n)} = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n} = c_R^{(n)} + c_S^{(n)} \quad \text{with} \quad \begin{aligned} c_s^{(n)}\big|_{\mu=0} &= d\ h^{(2-\alpha-n/2)/\beta\delta}\ f_\pm^{(n)}(z) \\ c_s^{(n)}\big|_{\mu\neq 0} &= d\ h^{(2-\alpha-n)/\beta\delta}\ f_\pm^{(n)}(z) \end{aligned}$$

- At $\mu = 0$ only $c_B^{(n)}$ with $n \geq 6$ receive contribution from $c_S^{(n)}$
- At $\mu \neq 0$ only $c_B^{(n)}$ with $n \geq 3$ receive contribution from $c_S^{(n)}$

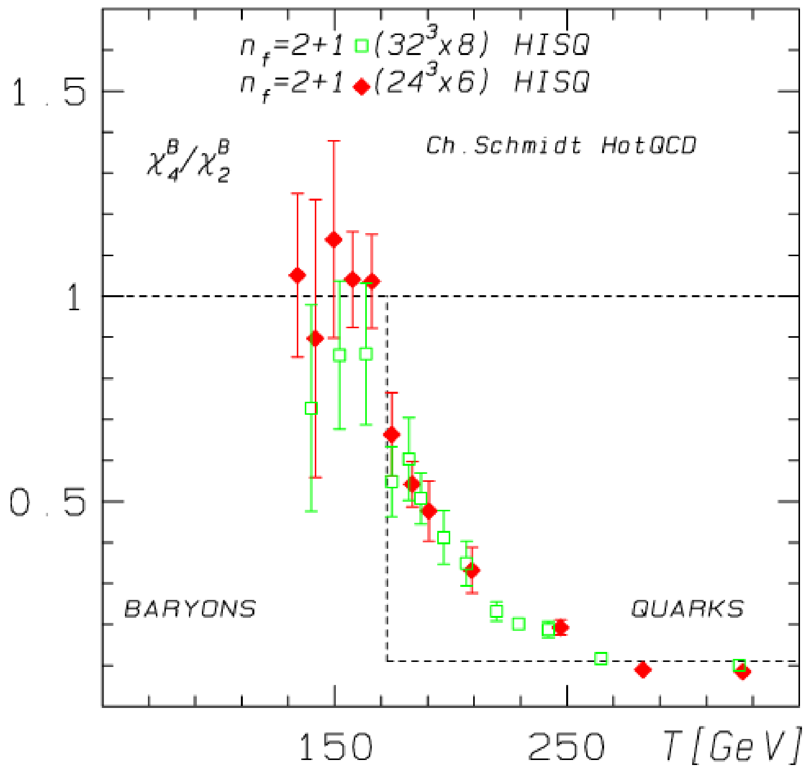
- $c_B^{n=2} = \chi_B / T^2$ Generalized susceptibilities of the net baryon number is non- critical with respect to O(4)

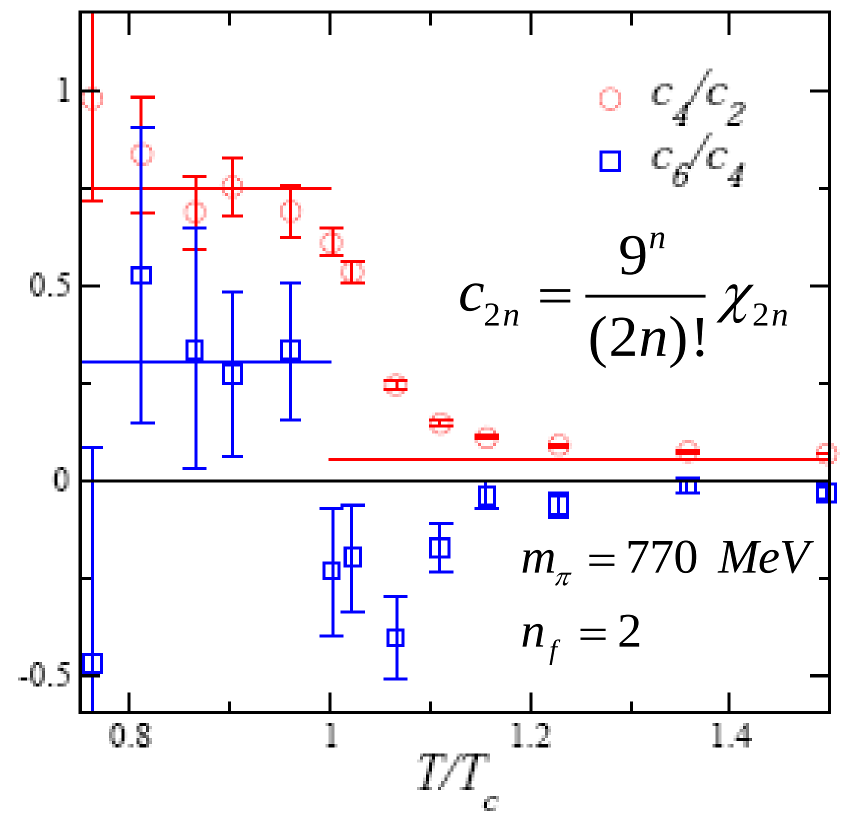
LQCD and Skelam distribution of the net baryon number

P(N) Skellam then: $\frac{\chi_{2n+2}}{\chi_{2n}} = 1$

$m_\pi = 140 \; MeV$

S. Eijri, F. Karsch et al. (2006)





LQCD follow the properties of the net baryon number cumulant ratios expected for the Skellam probability distribution

Constructing net charge fluctuations and correlation from ALICE data

- Net baryon number susceptibility

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

- Net strangeness

$$\frac{\chi_S}{T^2} \approx \frac{1}{VT^3}\left(\langle K^+\rangle + \langle K_S^0\rangle + \langle \Lambda + \Sigma_0\rangle + \langle \Sigma^+\rangle + \langle \Sigma^-\rangle + 4\langle \Xi^-\rangle + 4\langle \Xi^0\rangle + 9\langle \Omega^-\rangle + \overline{par}\right.$$
$$\left. -(\Gamma_{\varphi\to K^+} + \Gamma_{\varphi\to K^-} + \Gamma_{\varphi\to K_S^0} + \Gamma_{\varphi\to K_L^0})\langle \varphi\rangle\ \right)$$

- Charge-strangeness correlation

$$\frac{\chi_{QS}}{T^2} \approx \frac{1}{VT^3}\left(\langle K^+\rangle + 2\langle \Xi^-\rangle + 3\langle \Omega^-\rangle + \overline{par}\right.$$
$$\left. -(\Gamma_{\varphi\to K^+} + \Gamma_{\varphi\to K^-})\langle \varphi\rangle - (\Gamma_{K_0^*\to K^+} + \Gamma_{K_0^*\to K^-})\langle K_0^*\rangle\ \right)$$

$\chi_B, \chi_S, \chi_{QS}$ constructed from ALICE particle yields

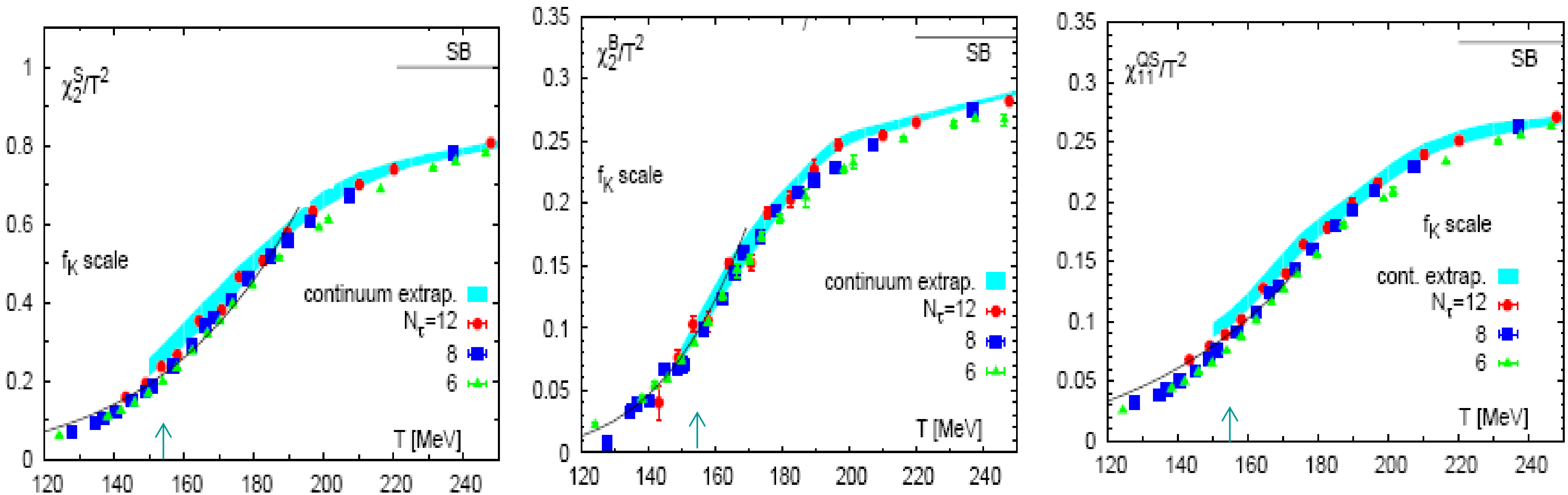
- use also $\Sigma^0/\Lambda = 0.278$ from pBe at $\sqrt{s} = 25\ GeV$
- Net baryon fluctuations $\frac{\chi_B}{T^2} \approx \frac{1}{VT^3}(203.7 \pm 11.4)$
- Net strangeness fluctuations $\frac{\chi_S}{T^2} \approx \frac{1}{VT^3}(504.2 \pm 24)$
- Charge-Strangeness corr. $\frac{\chi_{QS}}{T^2} \approx \frac{1}{VT^3}(178 \pm 17)$
- Ratios is volume independent

$$\frac{\chi_B}{\chi_S} = 0.404 \pm 0.028 \quad \text{and} \quad \frac{\chi_B}{\chi_{QS}} = 1.14 \pm 0.13$$

Compare the ratio with LQCD data:

A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, Y. Maezawa and S. Mukherjee

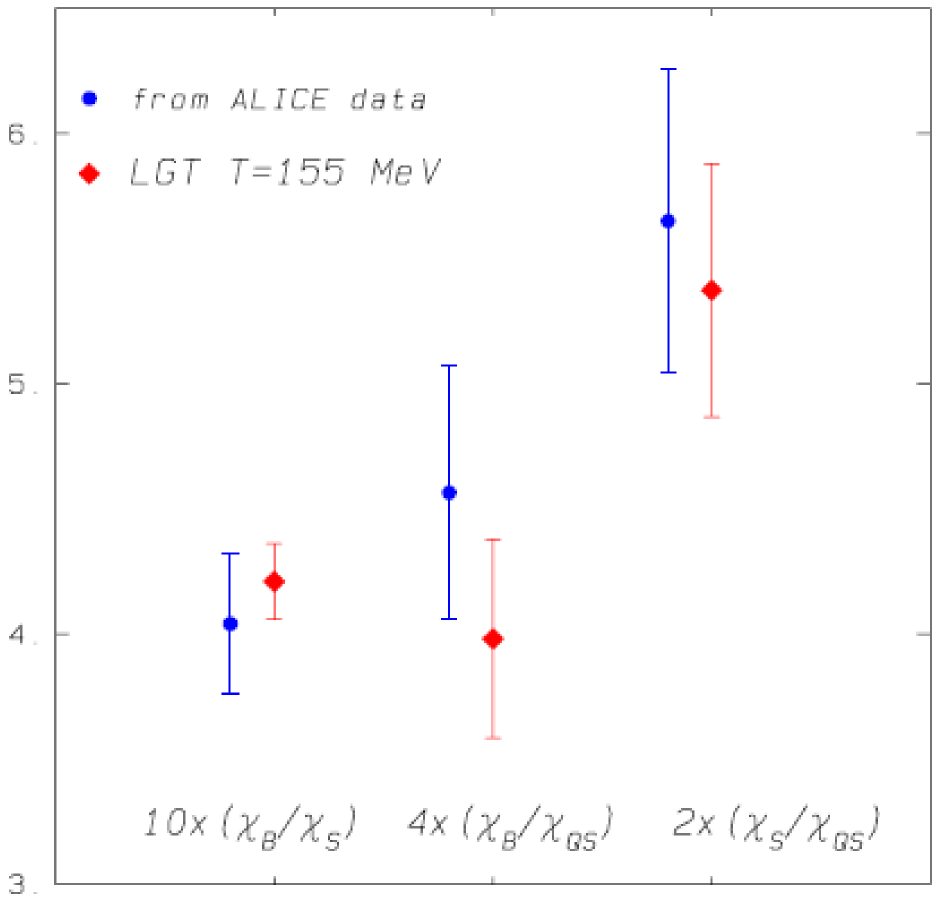
Phys.Rev.Lett. 113 (2014) and HotQCD Coll. A. Bazavov et al. Phys.Rev. D86 (2012) 034509



- Is there a temperature where calculated ratios from ALICE data agree with LQCD?

Baryon number, strangeness and Q-S correlations

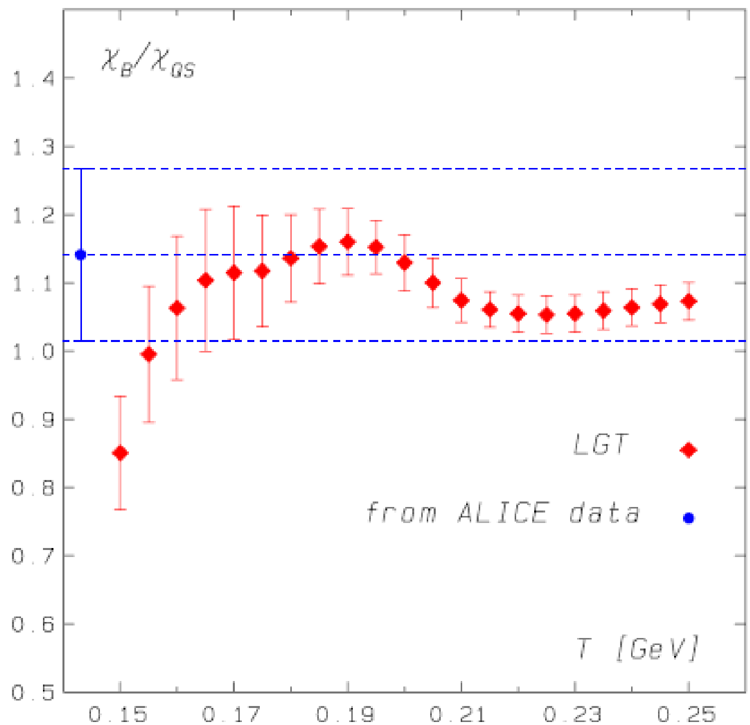
Compare ratios at the chiral crossover

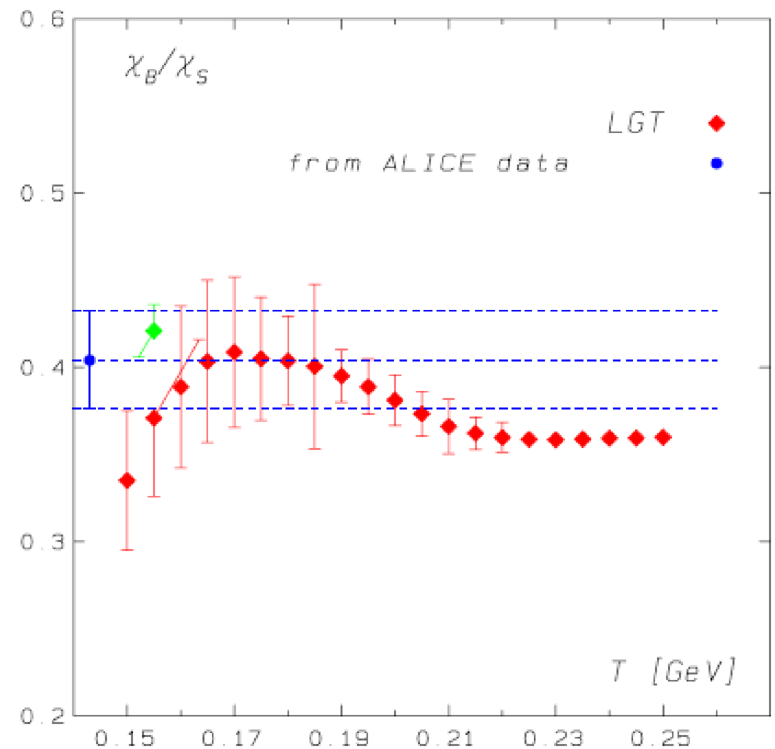


- There is a very good agreement, within systematic uncertainties, between extracted susceptibilities from ALICE data and LQCD at the chiral crossover

- How unique is the determination of the temperature at which such agreement holds?

Consider T-dependent LQCD ratios and compare with ALICE data





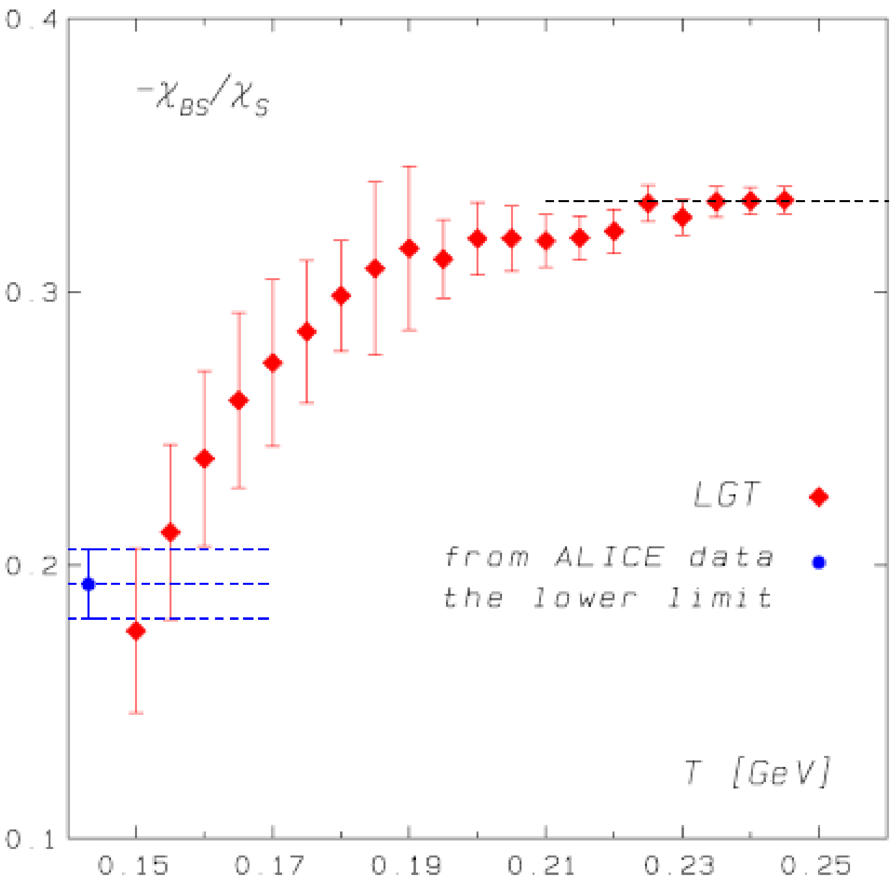
- The LQCD susceptibilities ratios are weakly T-dependent for $T \geq T_c$
- We can reject $T \leq 0.15\ GeV$ for saturation of χ_B, χ_S *and* χ_{QS} at the LHC, and can fix T to be in the range $0.15 < T \leq 0.21\ GeV$, however
- LQCD => for $T > 0.163\ GeV$ thermodynamics cannot be anymore described by the hadronic degrees of freedom

Baryon-Strangeness Correlations

Consider

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

V. Koch 05

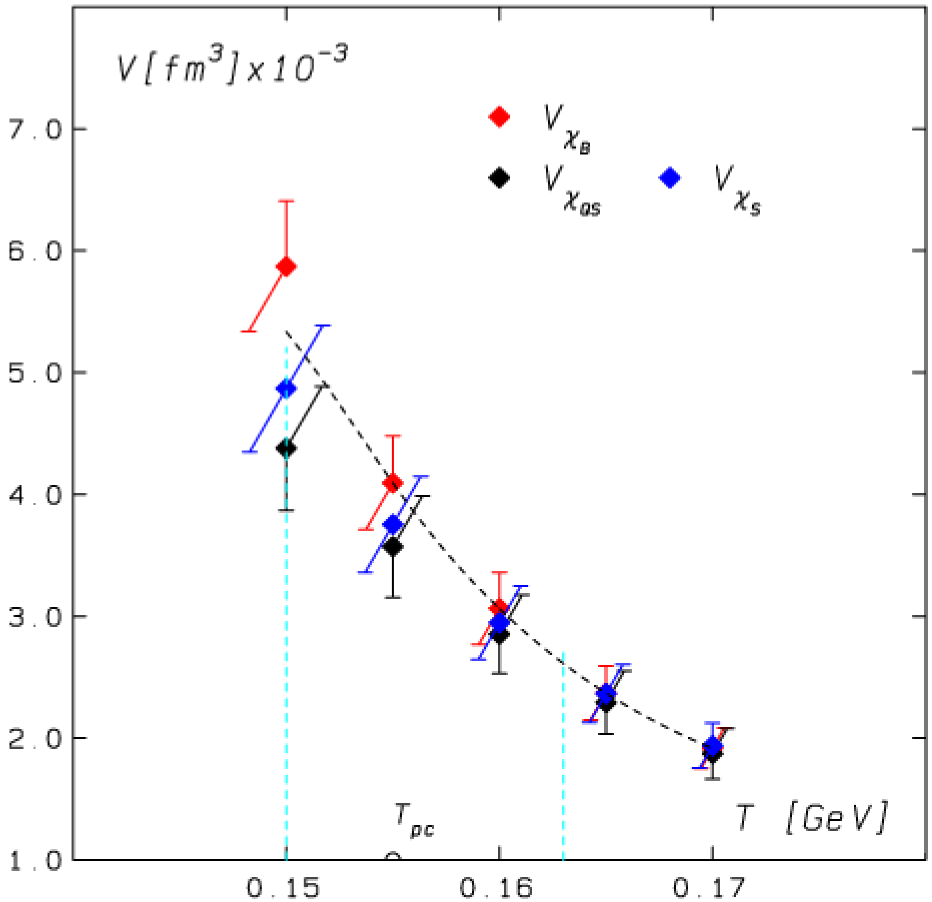


- Excellent observable to fix temperature

$$-\frac{\chi_{BS}}{T^2} > \frac{1}{VT^3}[2\langle\Lambda+\Sigma^0\rangle + 4\langle\Sigma^+\rangle + 8\langle\Xi\rangle + 6\langle\Omega^-\rangle] = 97.4 \pm 5.8.$$

- Data fix only the lower limit since e.g. $\Sigma^* \to N\bar{K}$ not included

Extract the volume by comparing data with LQCD



- Since

$$(\chi_N / T^2)_{LQCD} = \frac{(<N^2> - <N>^2)_{LHC}}{V_N T^3}$$

thus

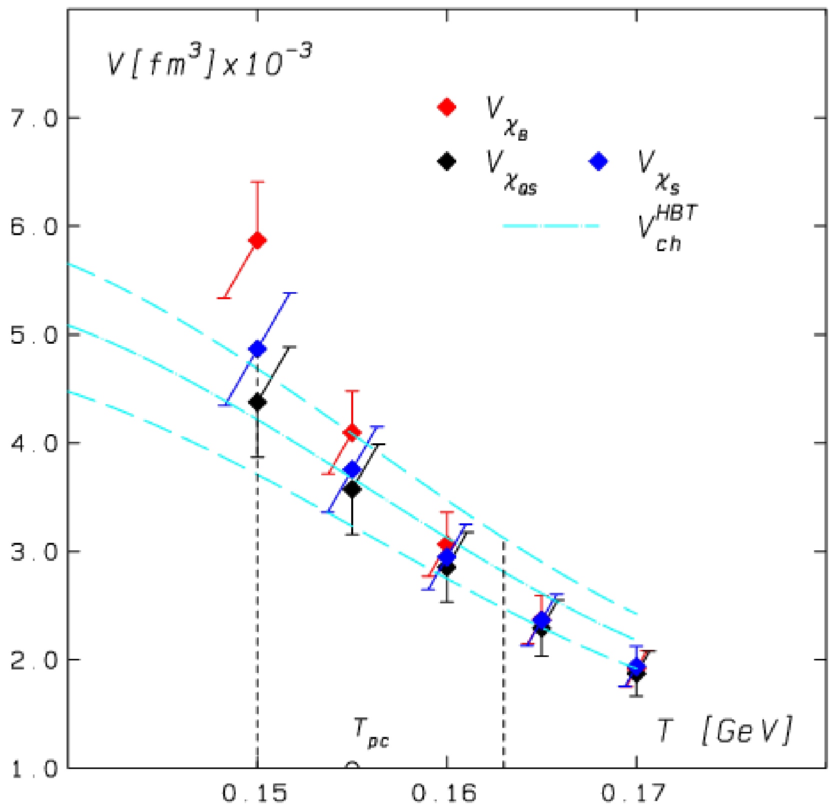
$$V_{\chi_B}(T) = \frac{203.7 \pm 11.4}{T^3(\chi_B / T^2)_{LQCD}} \qquad V_{\chi_S}(T) = \frac{504.2 \pm 24.2}{T^3(\chi_B / T^2)_{LQCD}}$$

$$V_{\chi_{QS}}(T) = \frac{178 \pm 17}{T^3(\chi_B / T^2)_{LQCD}}$$

- All volumes, should be equal at a given temperature if originating from the same source, thus

$$T > 150\ MeV$$

Constraining the volume from HBT and percolation theory



D. Adamova, et al (CERES) Phys Rev. Lett 90, 022301 (2003).

S.V. Akkelin, P. Braun-Munzinger & Y. Sinyukov Nucl. Phys. A710 (2002).

- Some limitation on volume from Hanbury-Brown–Twiss: HBT

$$V_{HBT} = (2\pi)^{3/2} R_l R_o R_s.$$

Take ALICE data from pion interferometry $V_{HBT} = 4800 \pm 640\ fm^{-3}$

Use 3D hydro to transfer

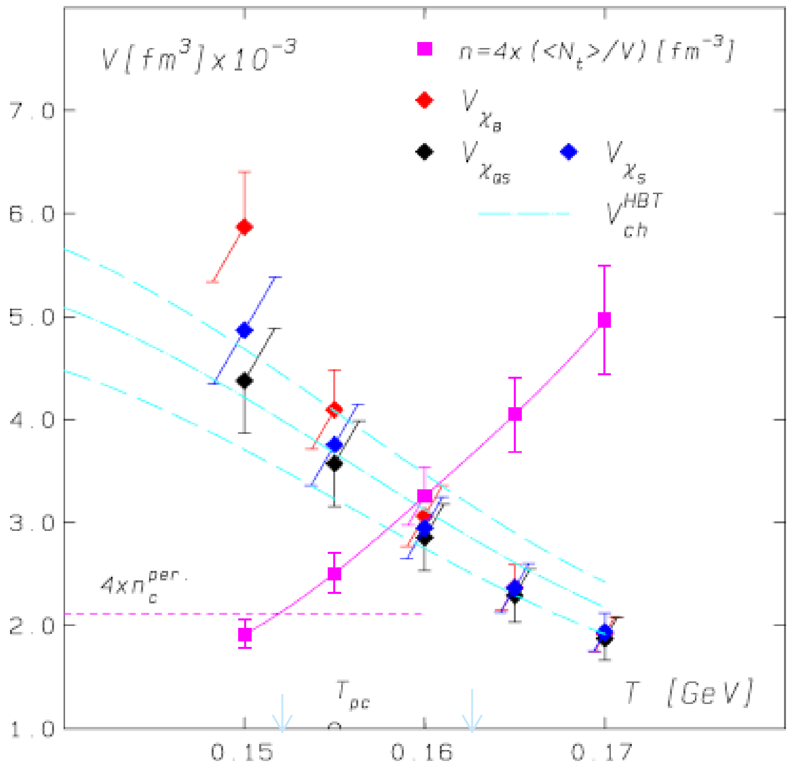
V_{HBT} : the volume of the homogeneity at the last interaction

$V_{th}(T_{th})$:the volume at the thermal freezeout $T_{th} \approx 100\ MeV$

$V_{ch}(T)$: the volume at temperature

$T_{ch} > T_{th}$

Particle density and percolation theory



- Density of particles at a given volume $n(T) = \dfrac{N_{total}^{\exp}}{V(T)}$

- Total number of particles in HIC at LHC, ALICE

$$\langle N_t \rangle = 3\langle \pi \rangle + 4\langle p \rangle + 4\langle K \rangle + (2 + 4 \times 0.2175)\langle \Lambda_\Sigma \rangle + 4\langle \bar{\Xi} \rangle + 2\langle \bar{\Omega} \rangle,$$

$$\boxed{\langle N_t \rangle = 2486 \pm 146}$$

- Percolation theory: 3-dim system of objects of volume $V_0 = 4/3\pi R_0^3$

$$n_c = \frac{1.22}{V_0} \quad \text{take} \quad R_0 \approx 0.82\, fm \Rightarrow n_c \approx 0.52\ [fm^{-3}] \Rightarrow T_c^p \approx 152\ [MeV]$$

P. Castorina, H. Satz &K.R. Eur.Phys.J. C59 (2009)

Thermal origin of particle yields with respect to HRG

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

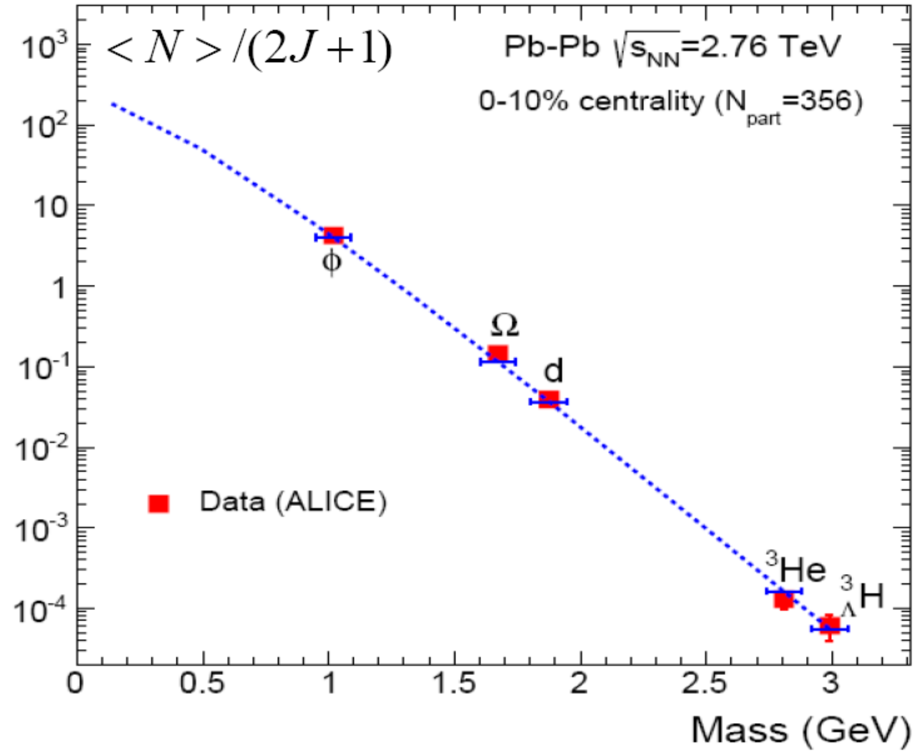
"uncorrelated" gas of hadrons and resonances

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

A. Andronic, Peter Braun-Munzinger, & Johanna Stachel, et al.

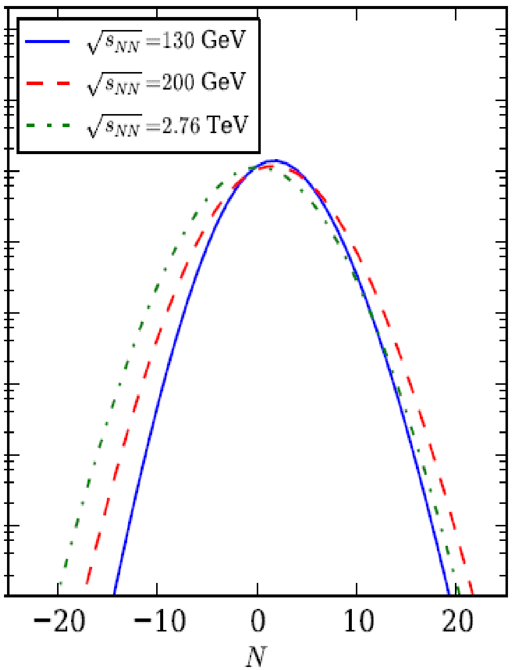
Particle yields with no resonance decay contributions:

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



- Measured yields are reproduced at $T \approx 156$ MeV

What is the influence of O(4) criticality on P(N)?



- For the net baryon number use the Skellam distribution (HRG baseline)

$$P(N) = \left(\frac{B}{\bar{B}}\right)^{N/2} I_N(2\sqrt{B\bar{B}})\exp[-(B+\bar{B})]$$

as the reference for the non-critical behavior

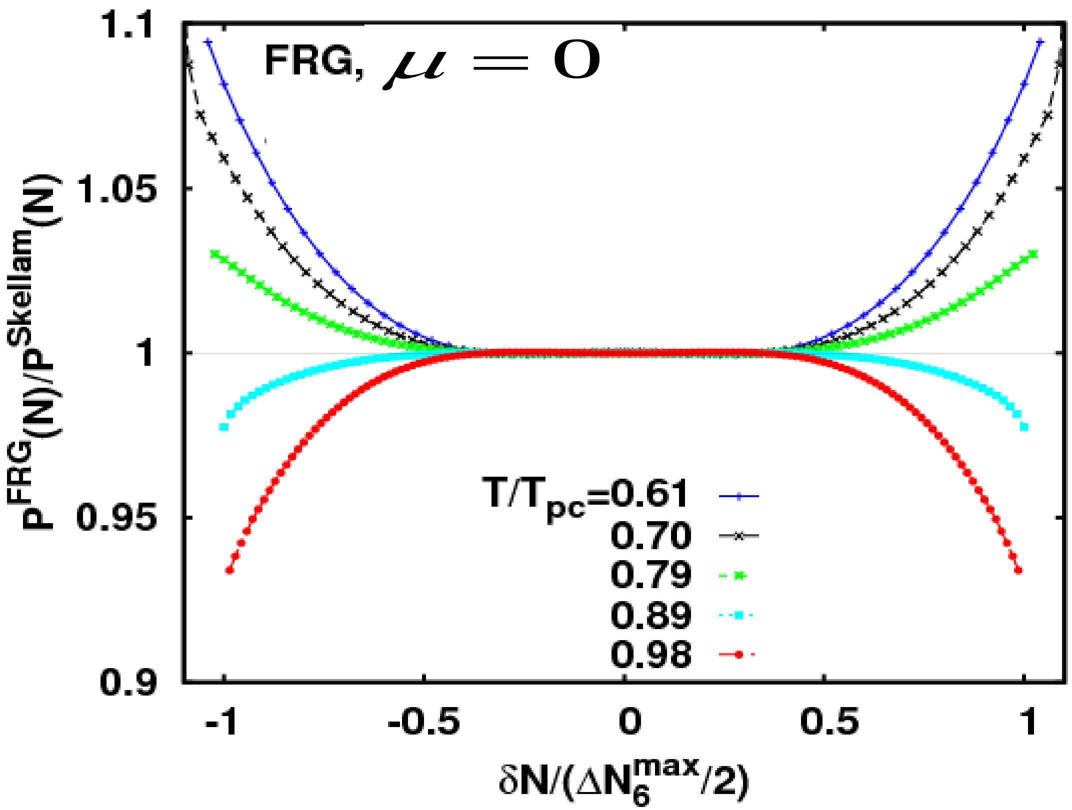
- Calculate P(N) in an effective chiral model which exhibits O(4) scaling and compare to the Skellam distribtuion

$$P(N) = \frac{Z_C(N)}{Z_{GC}} e^{\frac{\mu N}{T}}$$

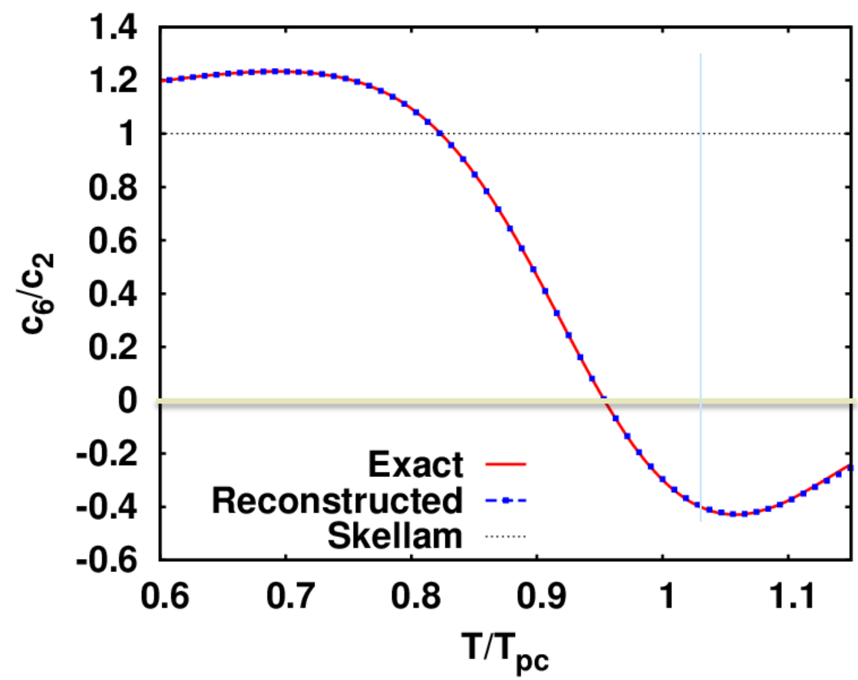
The influence of O(4) criticality on P(N) for $\mu = 0$

- Take the ratio of $P^{FRG}(N)$ which contains O(4) dynamics to Skellam distribution with the same Mean and Variance at different T/T_{pc}

K. Morita, B. Friman &K.R. (QM model within renormalization group FRG)

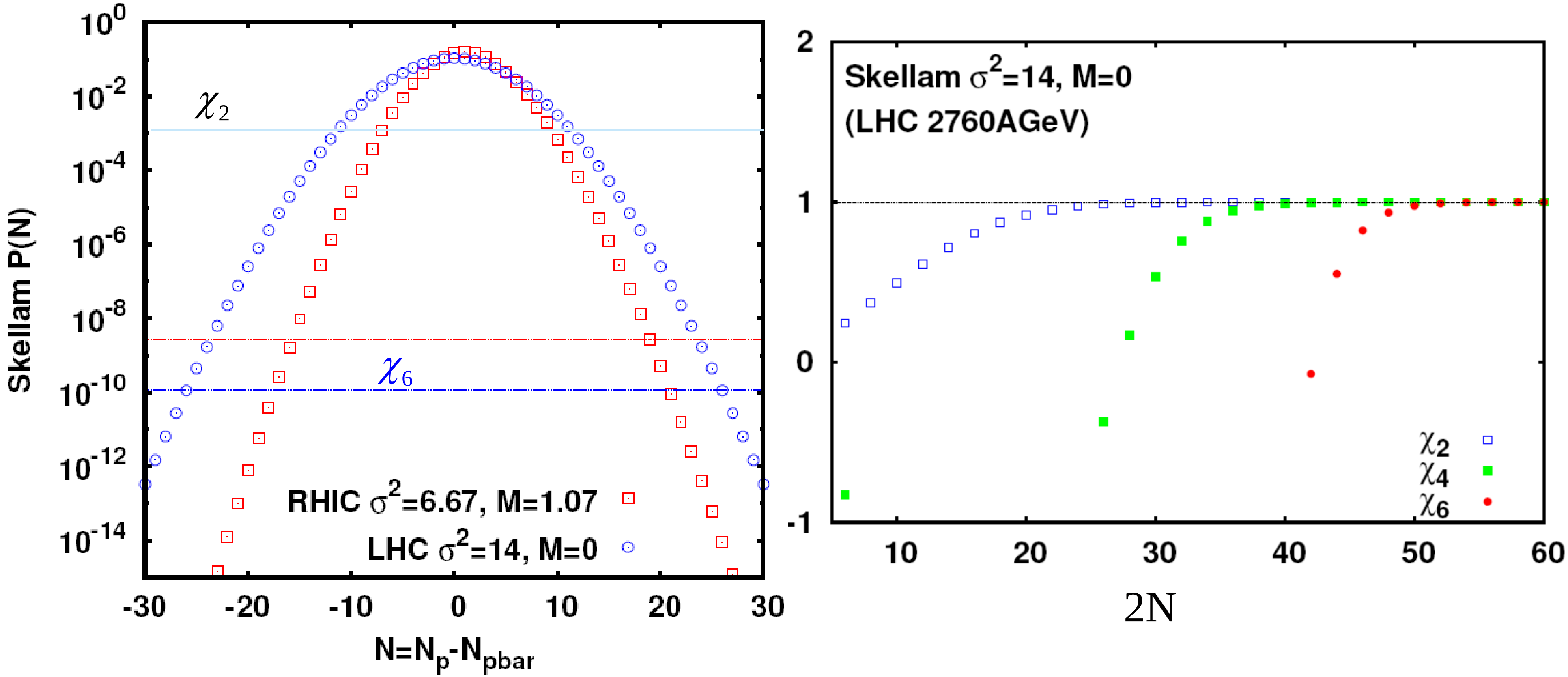


Ratio < 1 at larger |N| if $c_6/c_2 < 1$



Too see criticality at the LHC in cumulants of the net proton number

- A value of N and corresponding P(N) to be sensitive to remnant of the O(4) chiral criticality



Too see negative value of χ_6 at the LHC one needs N>23

Conclusions:

From a direct comparison of fluctuations constructed from ALICE data, and LQCD results one concludes that:

- there is thermalization in heavy ion collisions at the LHC and the 2nd order charge fluctuations and correlations are saturated at the chiral crossover temperature

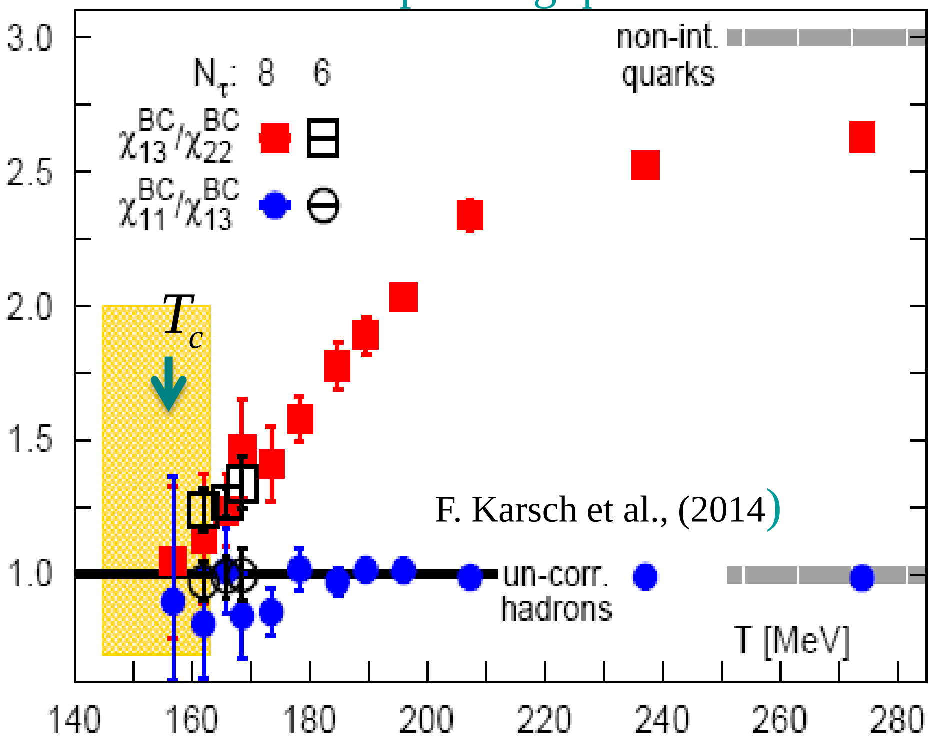
Skellam distribution, and its generalization, is a good approximation of the net charge probability distribution P(N) for small $N<10$. The chiral criticality sets in at larger $N>20$ and implies shrinking of the Skellam distribution.

Charm deconfinement in LQCD

Ratios of cumulants

$$\chi_{n,m}^{B,C} = \frac{1}{T^4} \frac{\partial^{(n+m)} P(\mu_B, \mu_C)}{\partial \mu_B^n \partial \mu_C^m} |_{\mu=0}$$

are sensitive to the degrees of freedom that are carriers of the corresponding quantum numbers



Factorized pressure in the HRG and sQGP

$$P(T,\vec{\mu}) = F(m/T)\cdot\cosh(B\mu_B + C\mu_C)$$

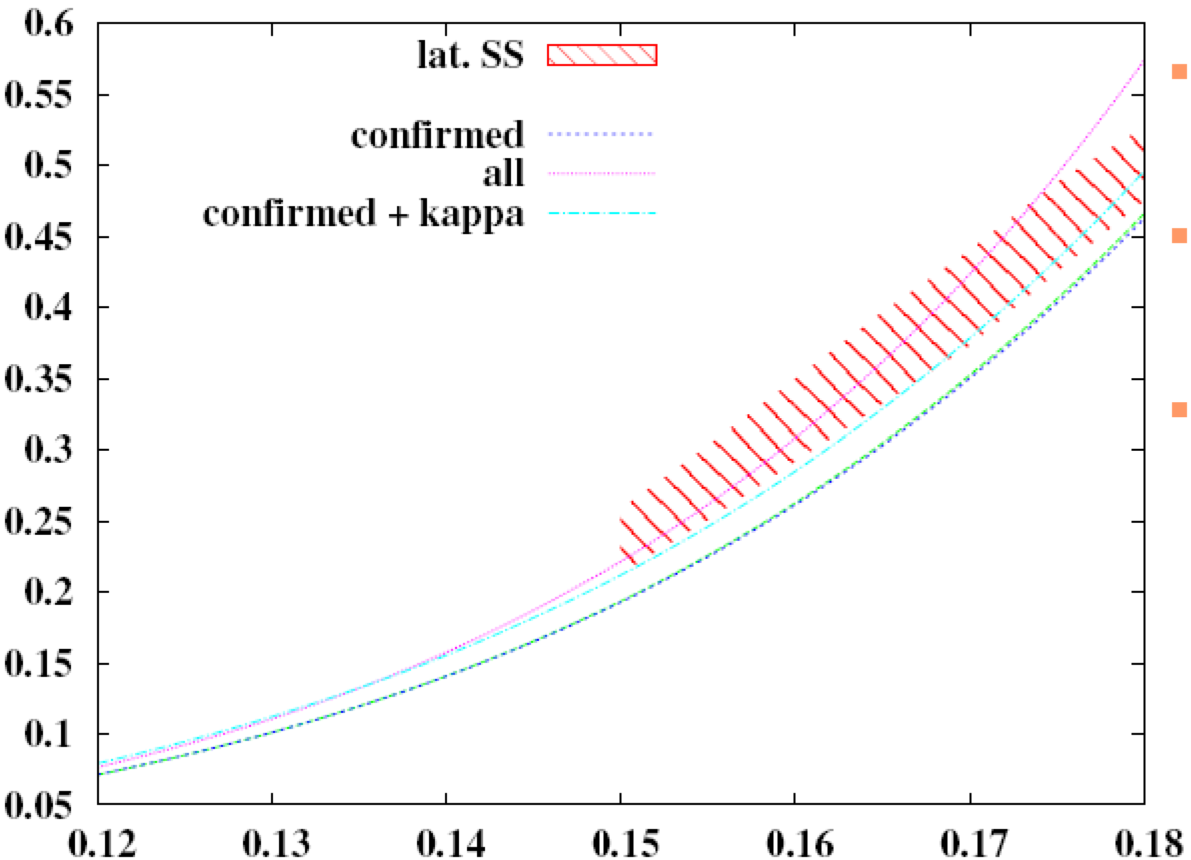
$$\frac{\chi_{1,3}^{B,C}}{\chi_{2,2}^{B,C}} \approx \frac{C}{B} = \begin{cases} 1 & T < T_c \\ 3 & T \gg T_c \end{cases}$$

$$\frac{\chi_{1,1}^{B,C}}{\chi_{1,3}^{B,C}} \approx \frac{1}{C^2} = \begin{cases} 1 & T < T_c \\ 1 & T \gg T_c \end{cases}$$

- For $T > T_c$, charmed degrees of freedom can no longer be described by hadronic states.
- The dissociation of open charm hadrons and the emergence of deconfined charm sets in just near the chiral crossover transition.

Missing resonances in strangeness fluctuations

Pok Man Lo, M. Marczenko et al.



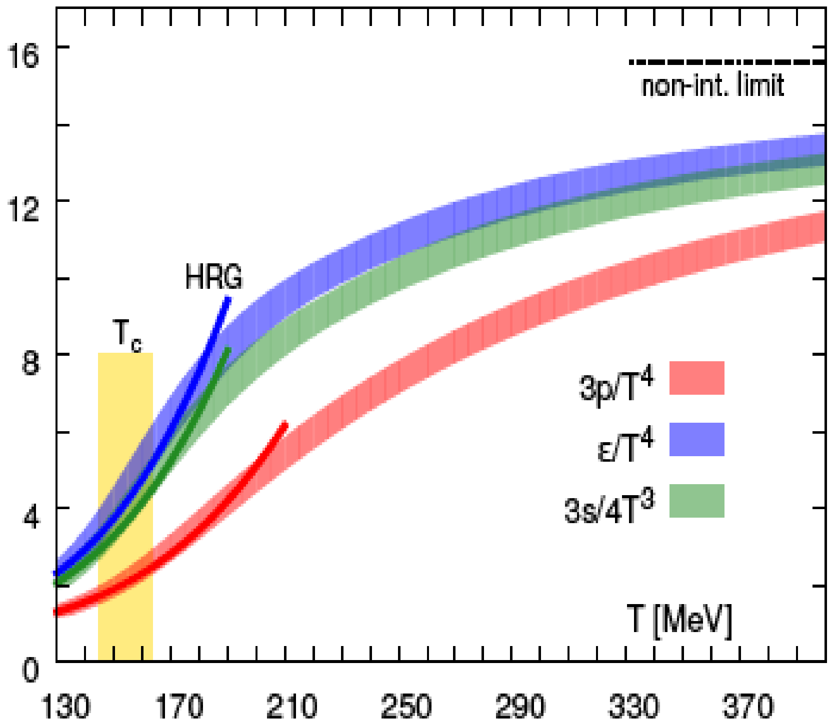
- Known strange hadrons underestimate LGT strangeness fluctuations
- One needs to include states expected in the Quark Model , particularly the low lying strange-hadrons
- The main contribution is due to expected "kappa" K*(800) strange 0^- meson in addition to already known 1^- state

K*0(800) MASS 682±29 MeV

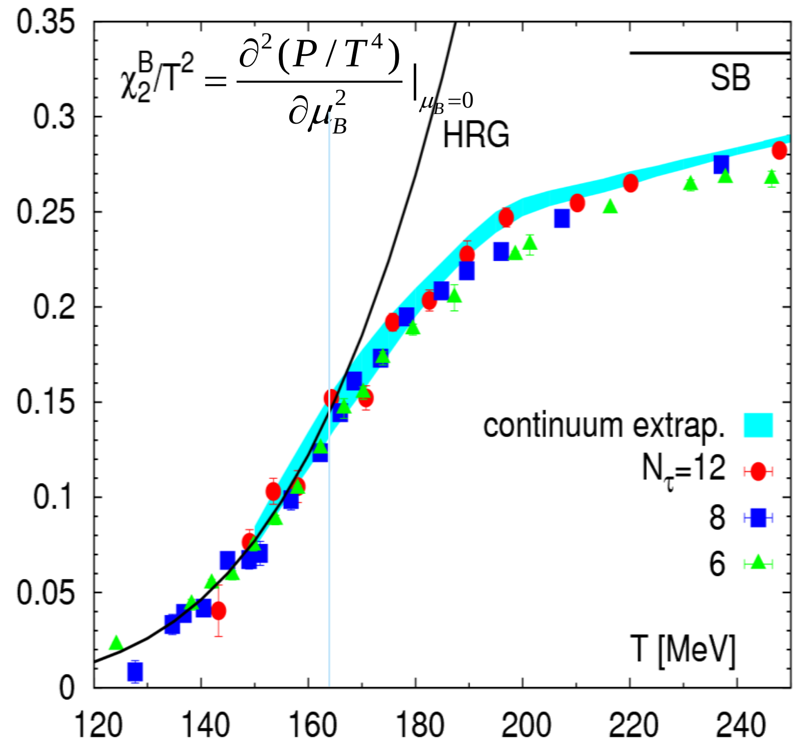
K*0(800) WIDTH 547±24 MeV

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

A. Bazavov et al. HotQCD Coll. July 2014



F. Karsch et al. HotQCD Coll.



- "Uncorrelated" Hadron Gas provides an excellent description of the QCD equation of states in confined phase

- "Uncorrelated" Hadron Gas provides also an excellent description of net baryon number fluctuations