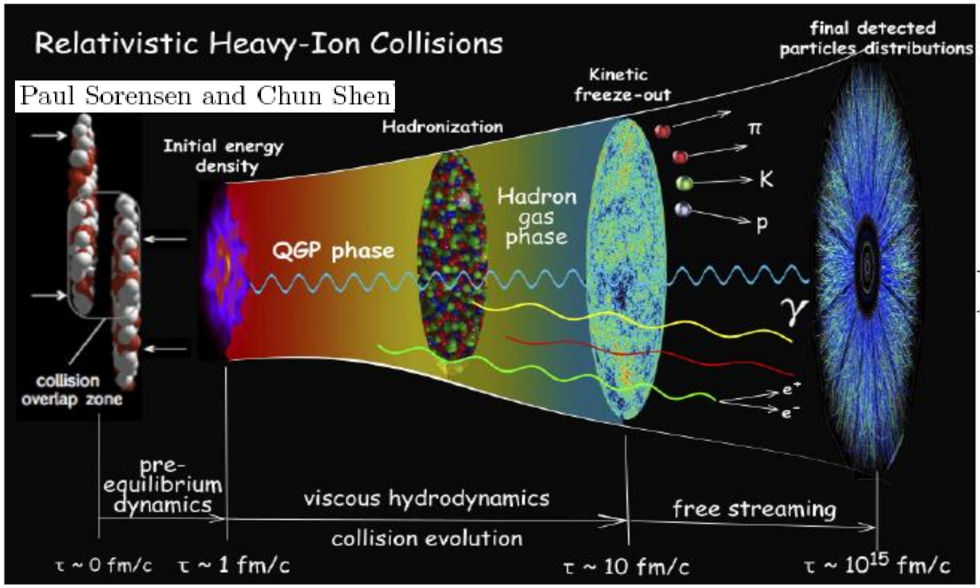
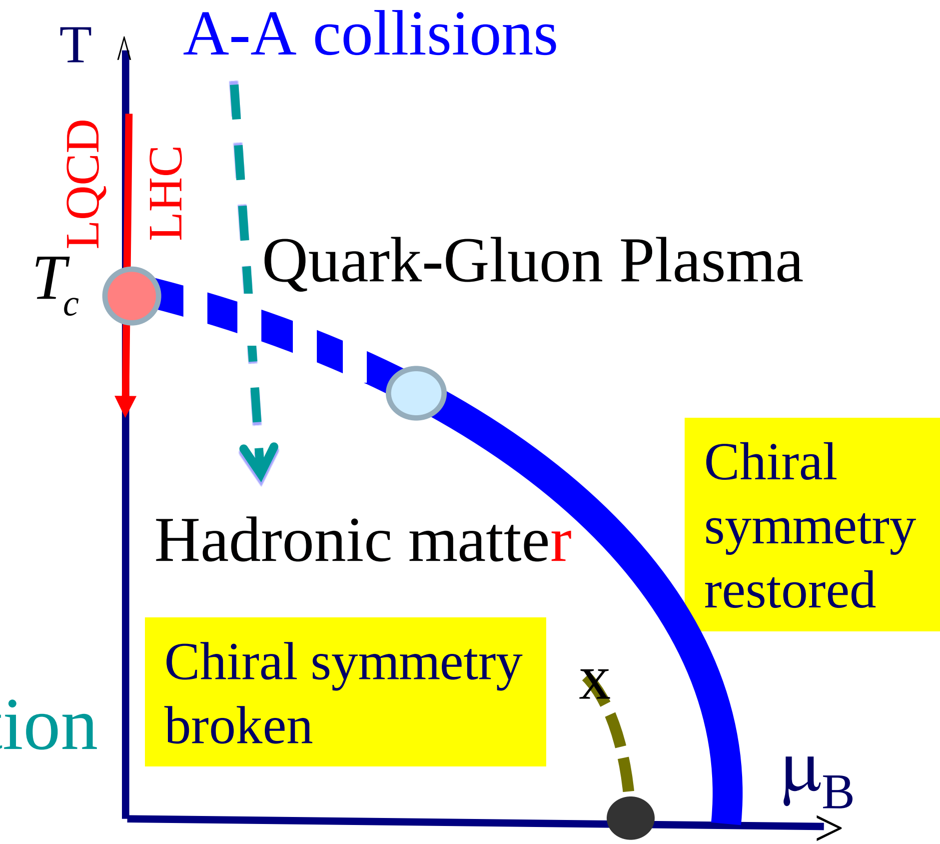
Probing QCD phase boundary in Heavy Ion Collisions

Krzysztof Redlich, University of Wroclaw

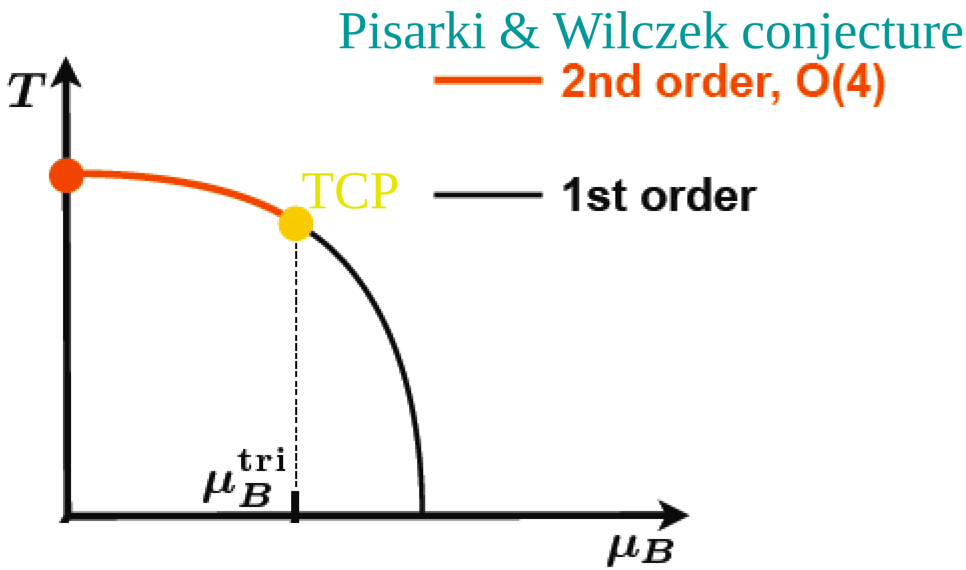




- QCD Phase Diagram from LQCD
- Thermal origin of particle production in HIC and its Equation of State
- Fluctuations of conserved charges at the QCD phase boudary

QCD phase diagram and chiral symmetry breaking

$$SU_L(2) \times SU_R(2) \rightarrow SU_V(2)$$



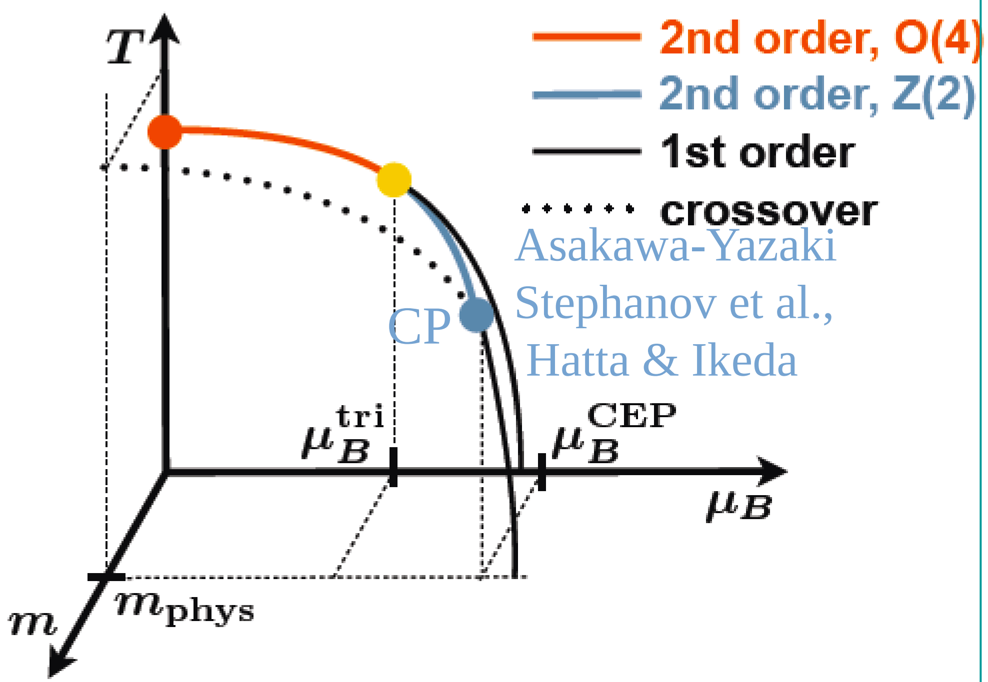
Expected phase diagram in the chiral limit, for massless u and d quarks:

TCP: Rajagopal, Shuryak, Stephanov
Y. Hatta & Y. Ikeda

- In QCD the quark masses are finite: the diagram has to be modified

The phase diagram at finite quark masses

At the CP: Divergence of Fluctuations, Correlation Length and Specific Heat

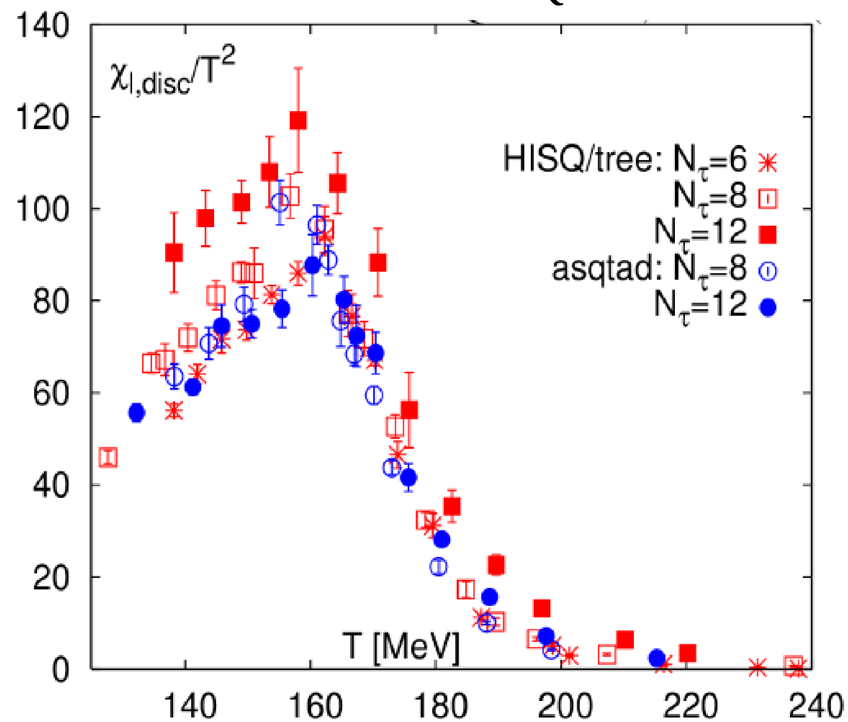


The existence of the CP in QCD has not been established yet

- To identify chiral crossover consider fluctuations of

$$<\bar{\psi}\psi>=\frac{T}{V}\frac{\partial \ln Z}{\partial m} \qquad \chi_{\bar{\psi}\psi}=\frac{T}{V}\frac{\partial^2 \ln Z}{\partial m^2}$$

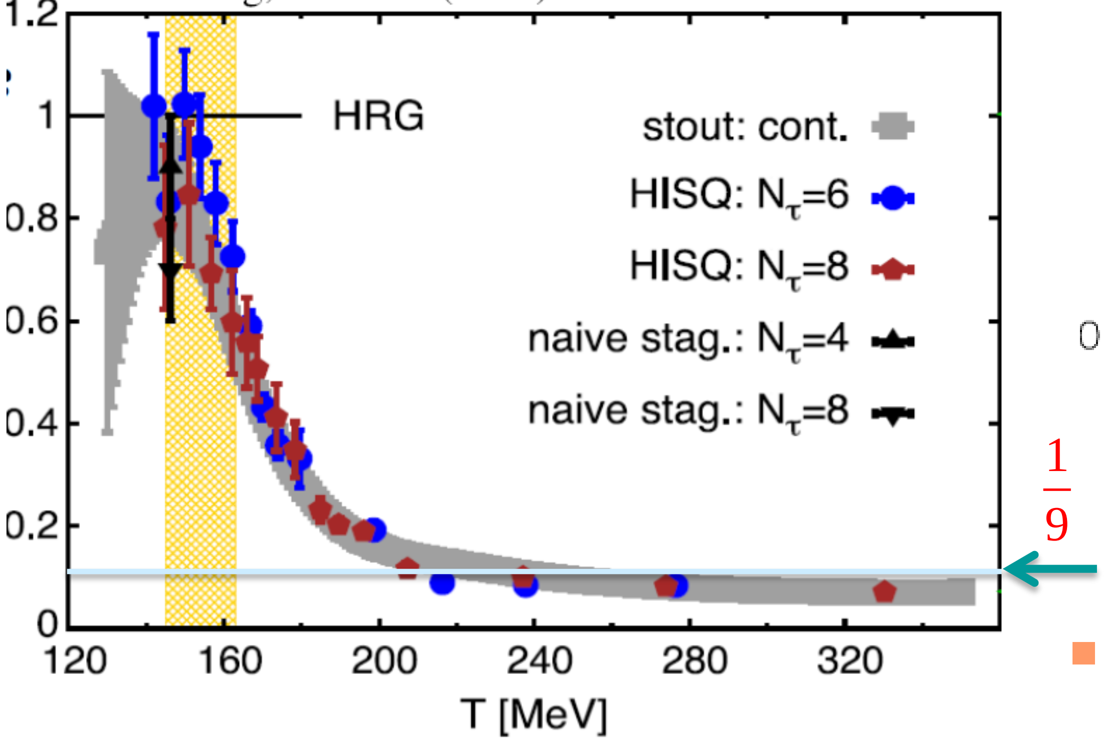
S. Borsayi et al. Wuppertal-Budapest Coll.
A. Bazavov et al. HotQCD Coll.



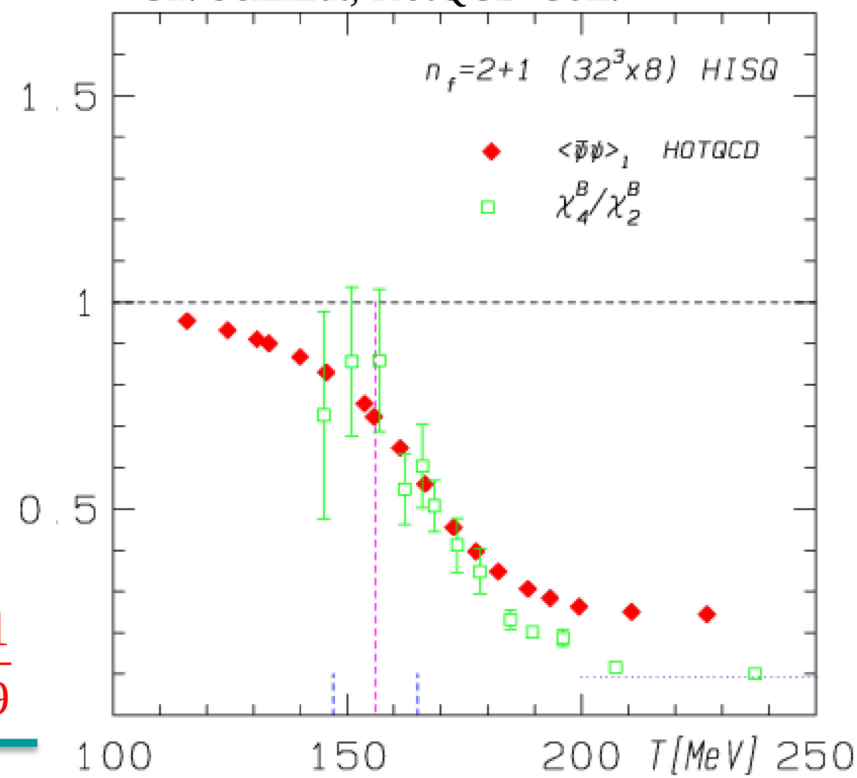
Deconfinement and the chiral crossover in LQCD

Scaled kurtosis and excellent probe for deconfinement S. Ejiri, F Karsch and K.R. (2006)

H.T.Ding, NPA931 (2014) 52



Ch. Schmidt, HotQCD Coll.

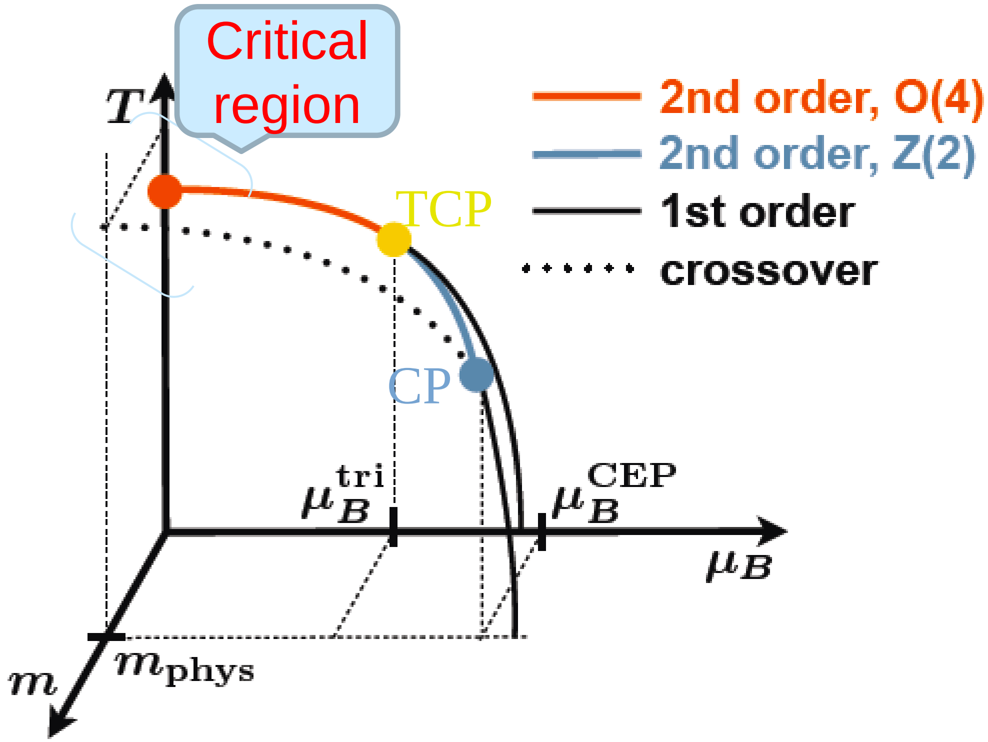


- Measure of the baryon number, where $\chi_4/\chi_2 \approx B^2$, and

$$\chi_n = \partial^n P / \partial \mu^n$$

- Similar rate of change of $<\bar\psi\psi>$ and χ_4/χ_2 with T, indicates that deconfinement and the chiral crossover appear in the same narrow T range

Remnants of the O(4) criticality in QCD ?



- The u,d quark masses are small, thus :

- can the QCD crossover line appear in the O(4) critical region?

Consider scaling properties of the magnetic eos in LQCD calculations

Hot QCD Coll. Results:

Phys. Rev. D83, 014504 (2011)

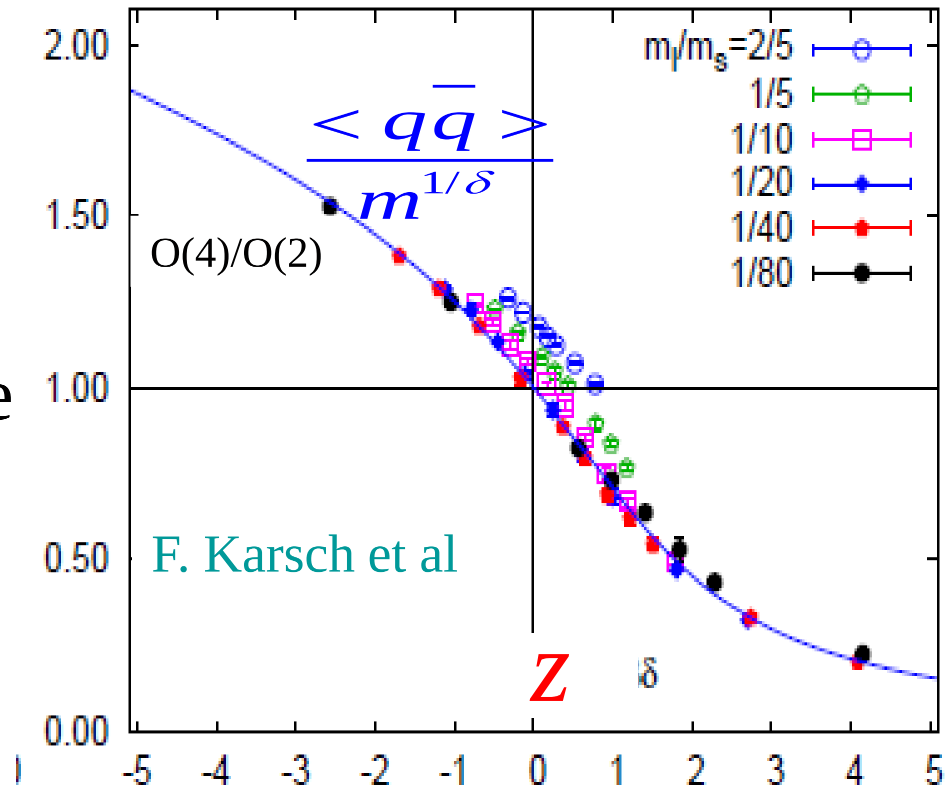
Phys. Rev. D80, 094505 (2009)

O(4) scaling and magnetic equation of state

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

QCD chiral crossover transition in the critical region of the O(4) 2nd order

- Phase transition encoded in the magnetic equation of state



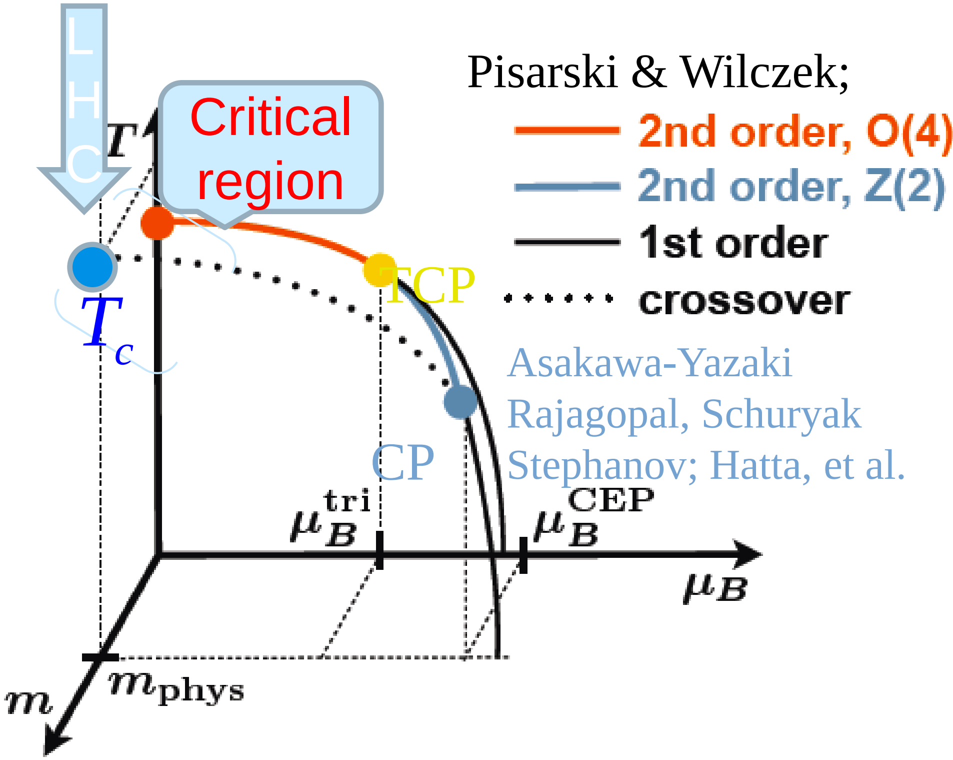
$$<q\bar{q}> = -\frac{\partial P}{\partial m} \Rightarrow \text{pseudo-critical line}$$

$$t = (T - T_c)/T_c$$

$$\boxed{\frac{<q\bar{q}>}{m^{1/\delta}} = f_s(z)\ , \quad z = t m^{-1/\beta\delta}}$$

universal scaling function common for all models belonging to the O(4) universality class: known from spin models J. Engels & F. Karsch (2012)

Deconfinement and chiral symmetry restoration in QCD



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

- 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

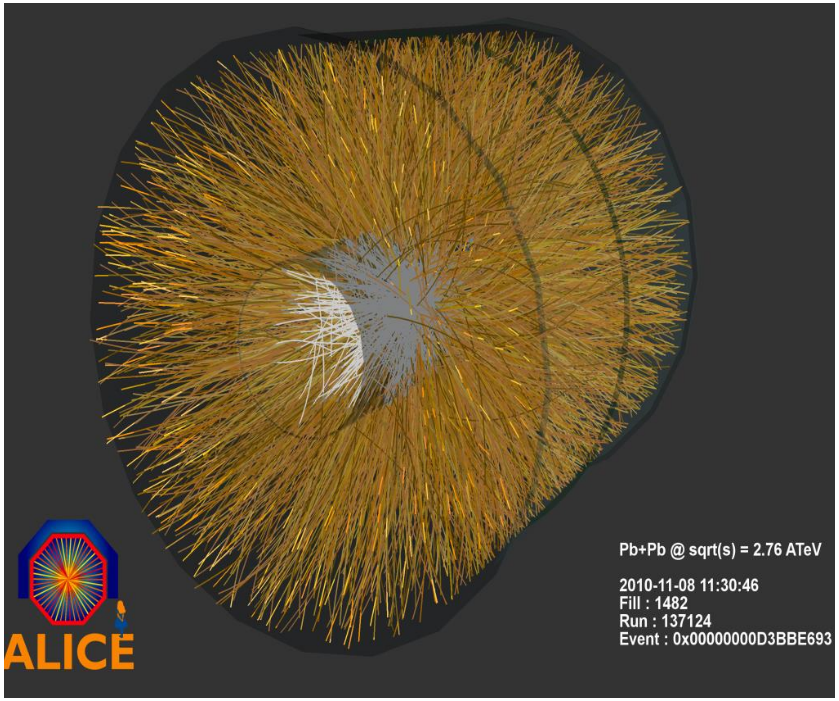
- The shift of T_c with chemical potential

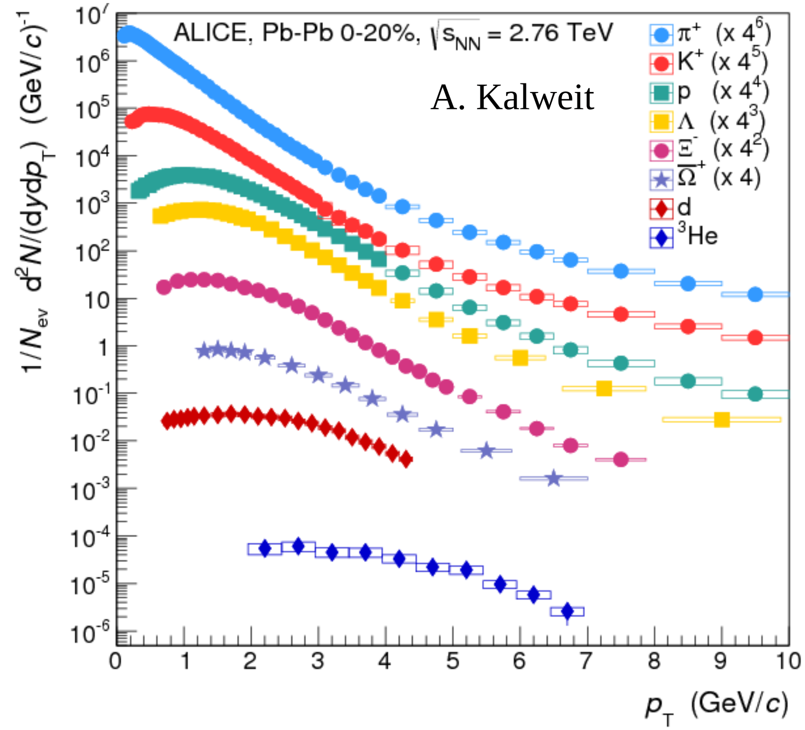
  $$\boxed{T_c(\mu_B) = T_c(0)[1 - 0.0066 \cdot (\mu_B / T_c)^2]}$$

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

Thermal particle prodution in Heavy Ion Collisions form SIS to LHC

Paolo Giubellino & Jürgen Schukraft for ALICE Collaboration





Can the thermal nature and composition of the collision fireball in HIC   be verified ?

Equlibration of 1st "moments": particle yields

- **resonance dominance: Rolf Hagedorn, Hadron Resonance Gas (HRG) partition function from S-matrix theory**

- $$\ln Z(T,\vec{\mu}) \approx \frac{VT}{2\pi^2} \sum_{i \in hadrons} d_i e^{\frac{\vec{Q}_i \vec{\mu}}{T}} \int ds\, s\, K_2\left(\frac{\sqrt{s}}{T}\right) F^{B-W}(m_i, s)$$

Breit-Wigner res.

particle yield **thermal density** **BR** **thermal density of resonances**

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

- **Only 3-parameters needed to fix all particle yields**

Thermal origin of particle yields with respect to HRG

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

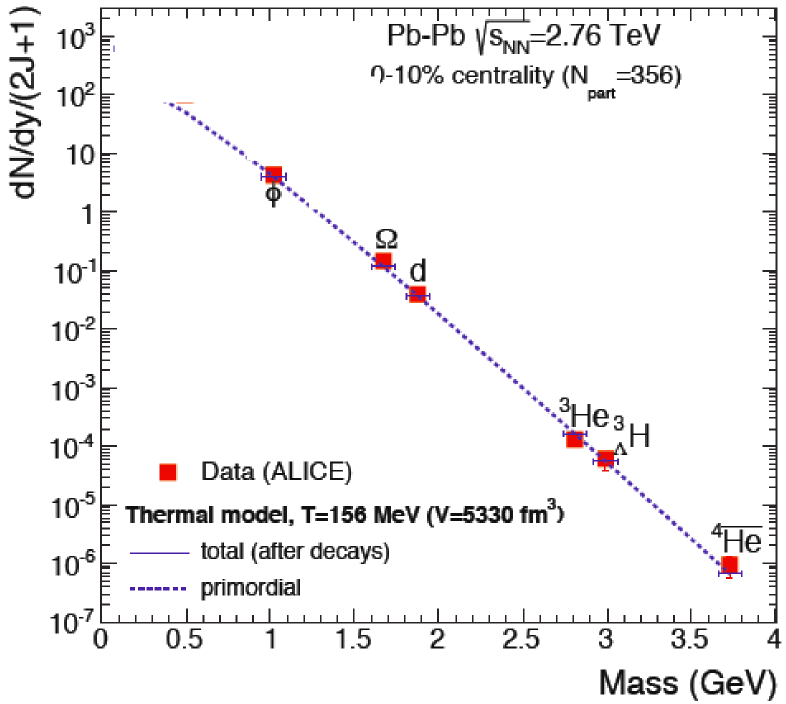
"uncorrelated" gas of hadrons and resonances

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

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

Particle yields with no resonance decay contributions:

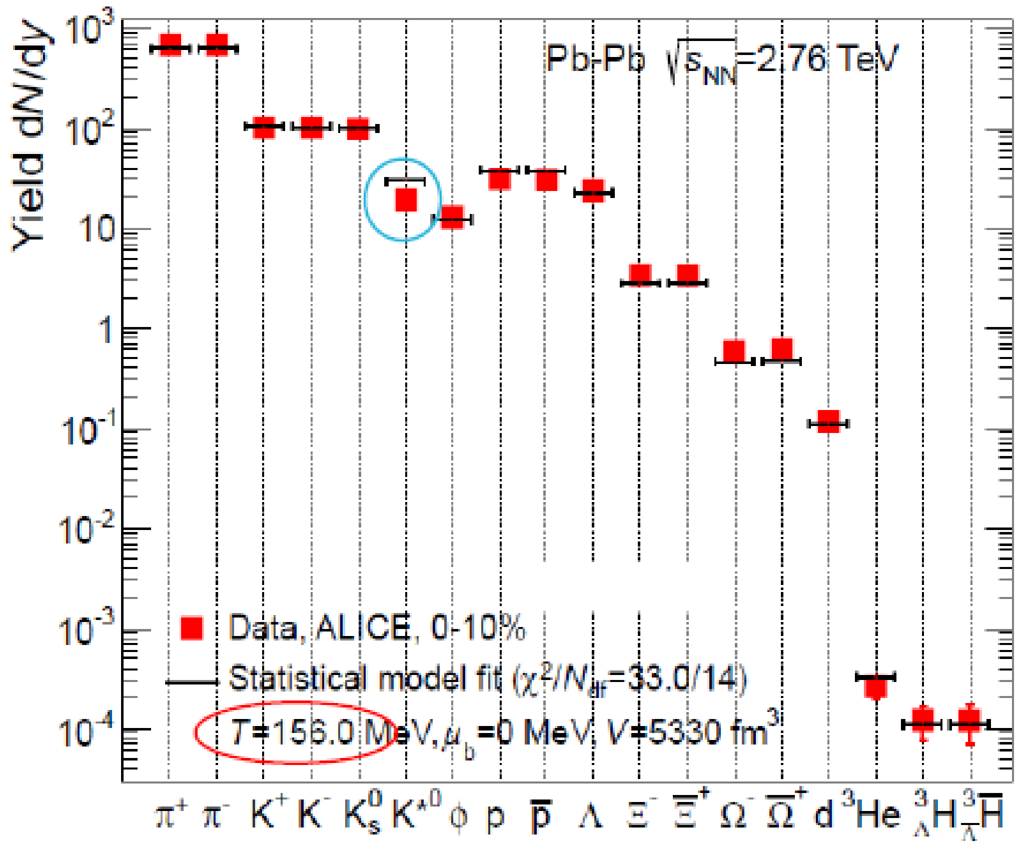
$$\frac{1}{2j+1}\frac{dN}{dy} = V(m/T)^2 K_2(m/T)$$

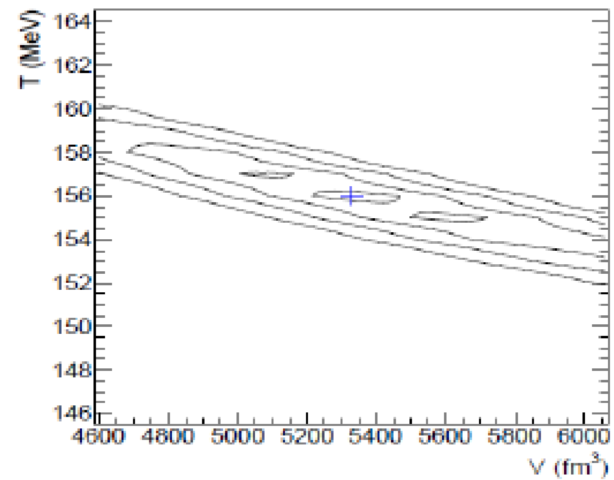


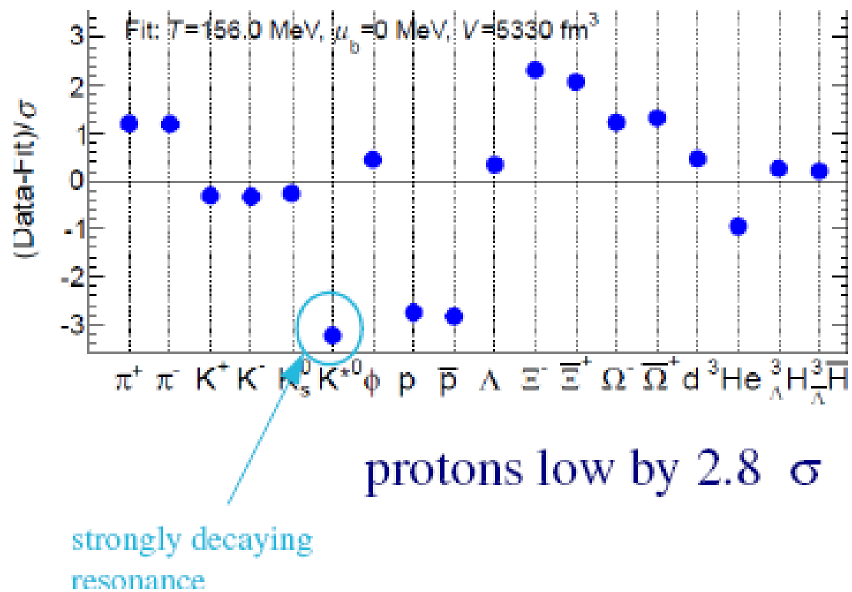
- Measured yields are reproduced with HRG at $T \approx 156$ MeV

Thermal equilibrium at the LHC

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







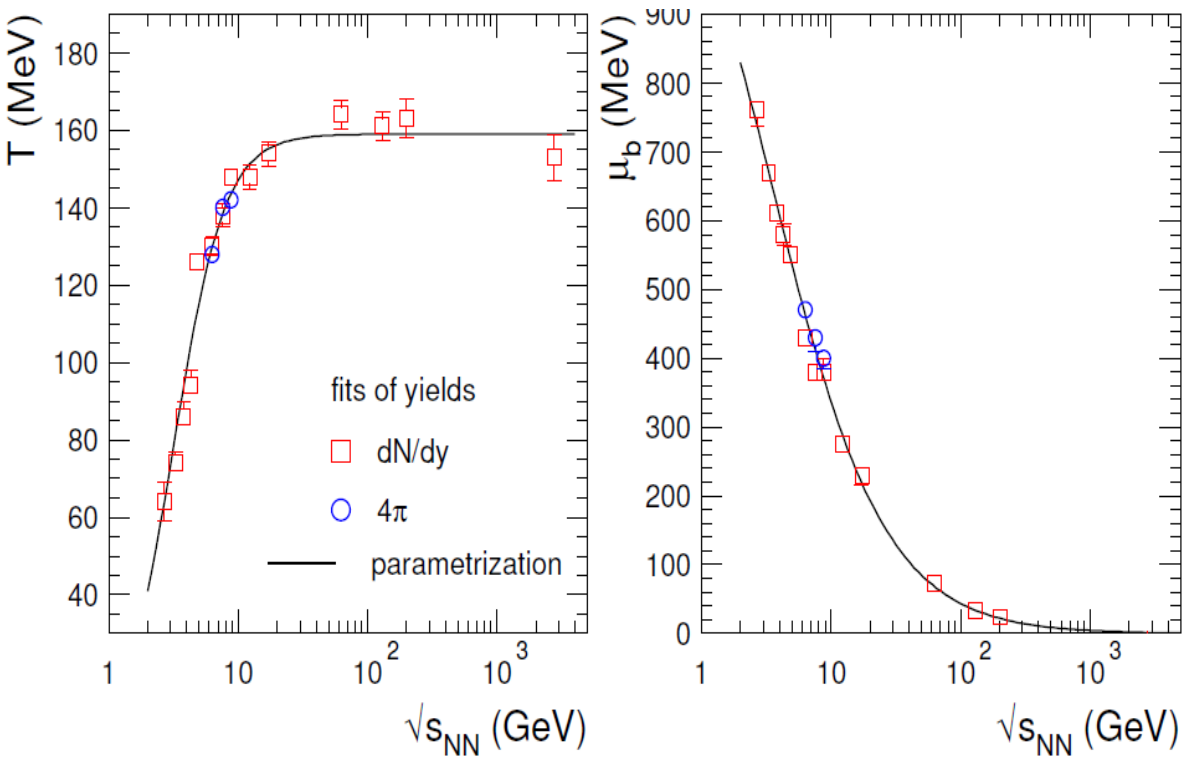
T = 156 MeV
red. χ^2 = 2.33

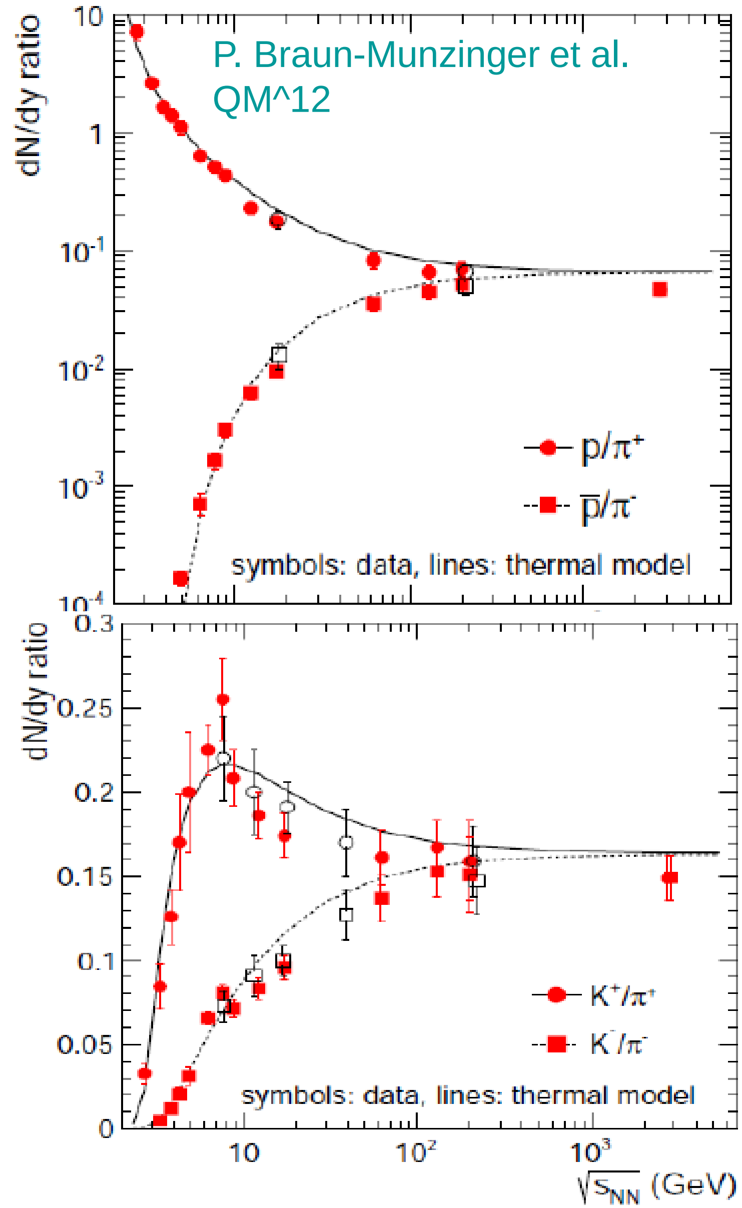
protons low by 2.8 σ

Thermal yields and parameters and their energy dependence in HIC

A. Andronic, P. Braun-Munzinger & J. Stachel, Nucl. Phys. (06)

J. Cleymans et al. Phys.Rev. C73 (2006) 034905



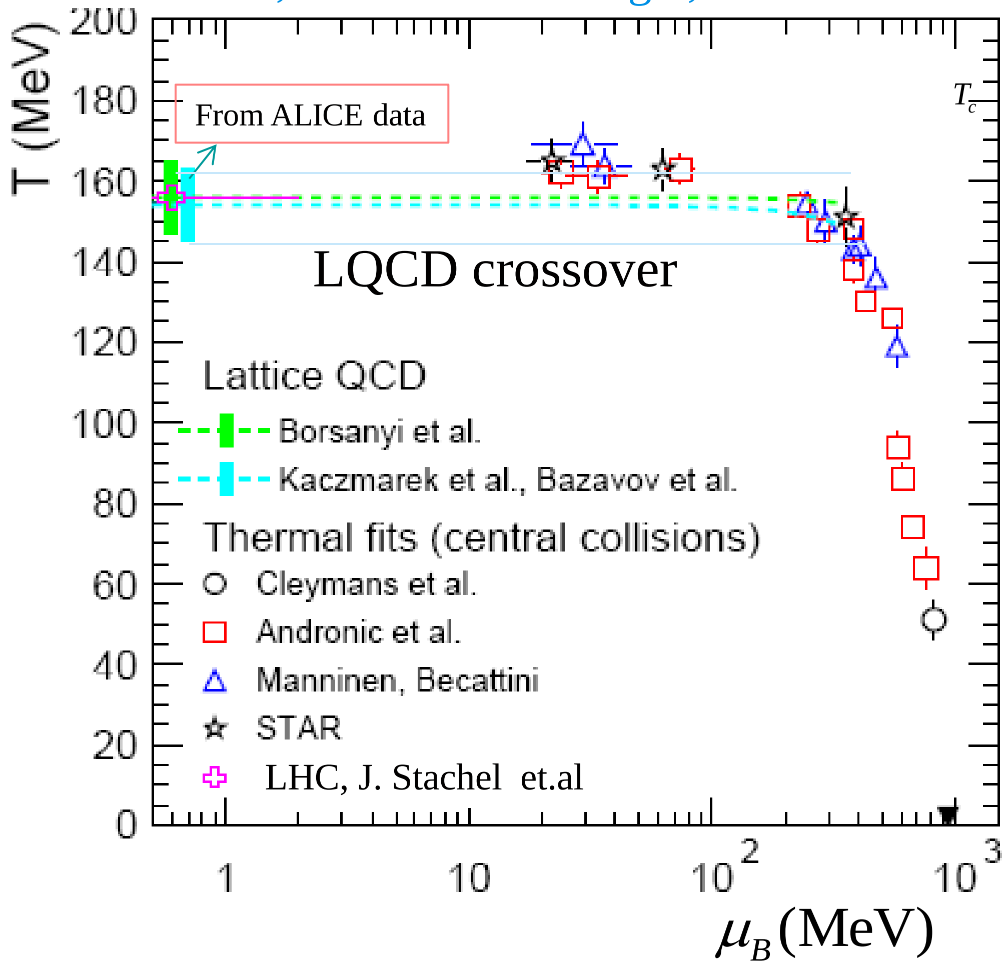


- Thermal origin of particle yields in HIC is well justified

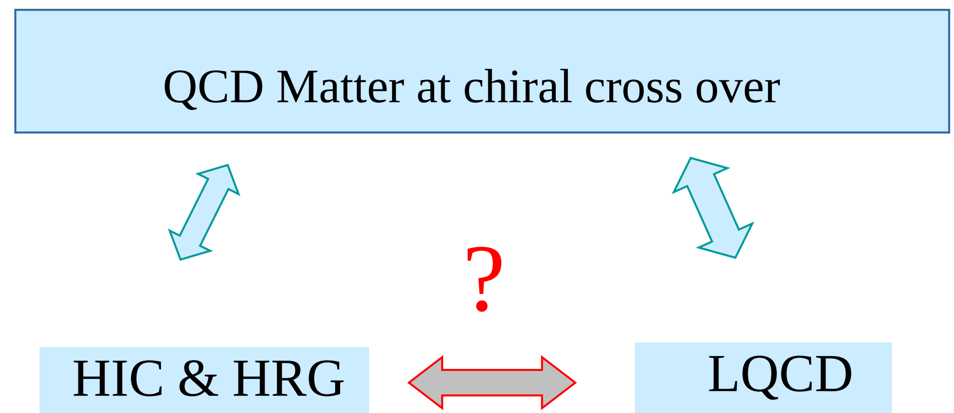
Chemical Freeze out and QCD Phase Boundary

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

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



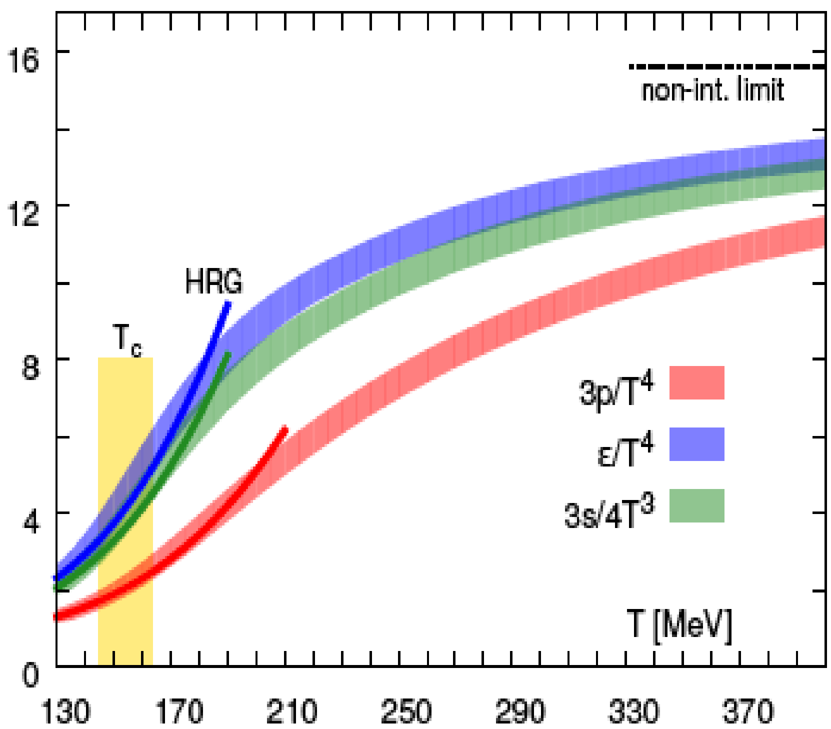
- The QCD phase boundary coincides with chemical freeze out conditions obtained from HIC data analyzed with the HRG model



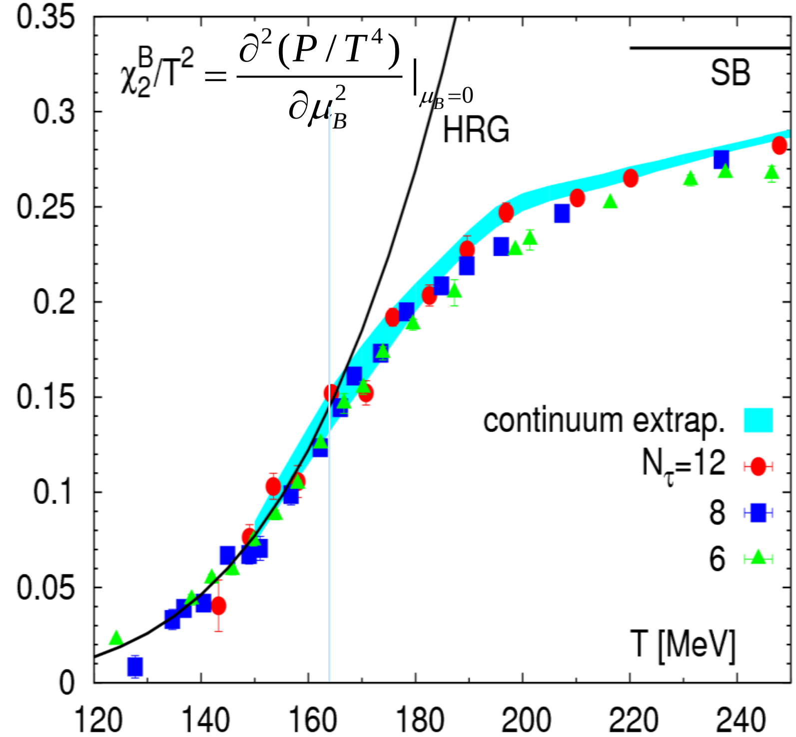
- The HRG should describe the QCD thermodynamics in the hadronic phase

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

A. Bazavov et al. HotQCD Coll. July 2014



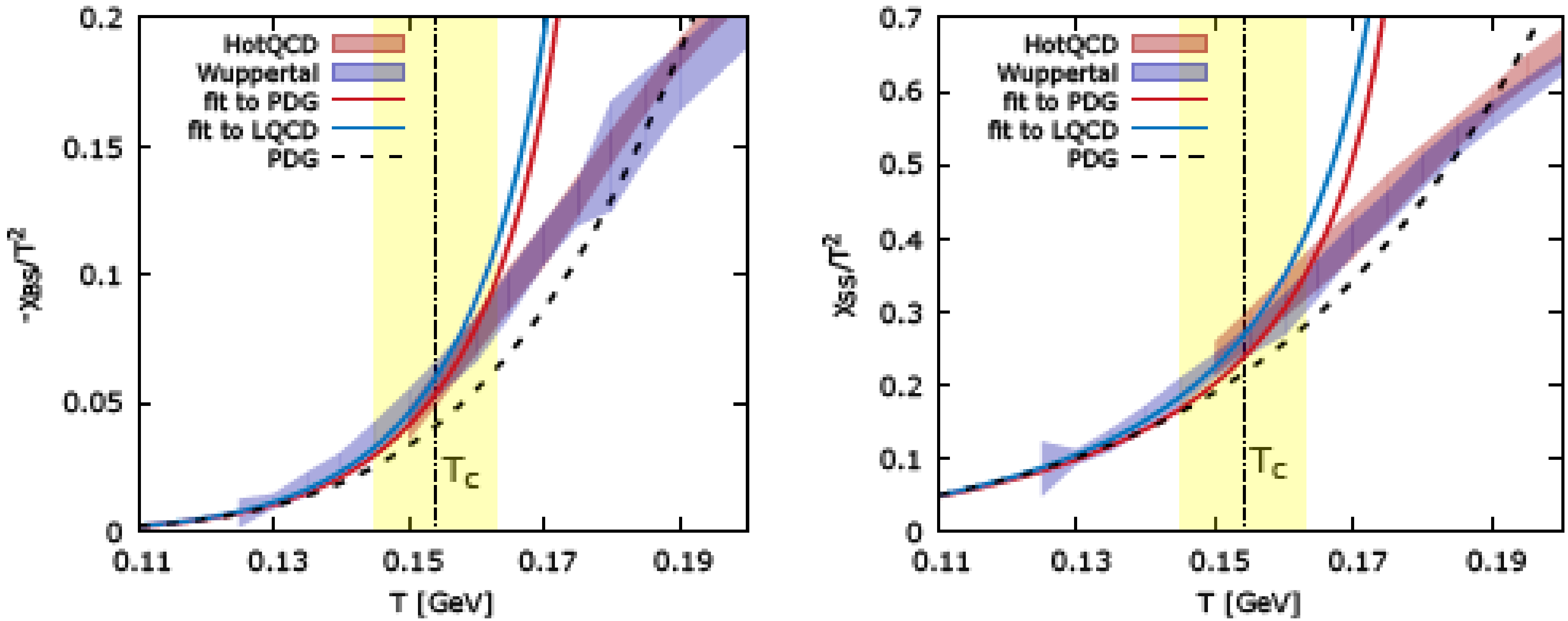
F. Karsch et al. HotQCD Coll.



- Hagedorn Gas thermodynamic potential provides an excellent description of the QCD equation of states in confined phase

- As well as, an excellent description of the net-baryon number fluctuations

Hagedorn's continuum mass spectrum contribution to strangeness fluctuations



- Missing strange baryon and meson resonances in the PDG

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

  P.M. Lo, et al. arXiv:1507.06398

- Satisfactory description of LGT with asymptotic states from Hagedorn's exponential mass spectrum $\rho^H(m) = m^a e^{m/T_H}$ fitted to PDG

Net baryon number fluctuations and the O(4) universality class

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

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

- Consider generalized susceptibilities of net-quark number

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

- Since for $T < T_{pc}$, $c_R^{(n)}$ are well described by the HRG

⇨ search for deviations (in particular for larger n) from HRG to quantify the contributions of $c_S^{(n)}$, i.e. the O(4) criticality

F. Karsch & K. R. Phys.Lett. B695 (2011) 136

B. Friman, et al. . Phys.Lett. B708 (2012) 179, Nucl.Phys. A880 (2012) 48

Quark-meson model w/ FRG approach

$$\mathcal{L}_{\mathrm{QM}} = \bar{q}[i\gamma_\mu\partial^\mu - g(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})]q + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 - U(\sigma,\vec{\pi})$$

Effective potential is obtained by solving *the exact flow equation* (Wetterich eq.) with the approximations resulting in the O(4) critical exponents

B.J. Schaefer & J. Wambach,; B. Stokic, B. Friman & K.R.

$$\partial_k\Omega_k(\sigma) = \frac{Vk^4}{12\pi^2}\left[\sum_{i=\pi,\sigma}\frac{d_i}{E_{i,k}}[1+2n_B(E_{i,k})] - \frac{2\nu_q}{E_{q,k}}[1-n_F(E^+_{q,k})-n_F(E^-_{q,k})]\right]$$

$$E_{\pi,k} = \sqrt{k^2+\Omega'_k}$$

$$E_{\sigma,k} = \sqrt{k^2+\Omega'_k+2\rho\Omega''_k}$$

$$E_{q,k} = \sqrt{k^2+2g^2\rho}$$

$$\Omega'_k \equiv \frac{\partial\Omega_k}{\partial(\sigma^2/2)}$$

Full propagators with $k < q < \Lambda$

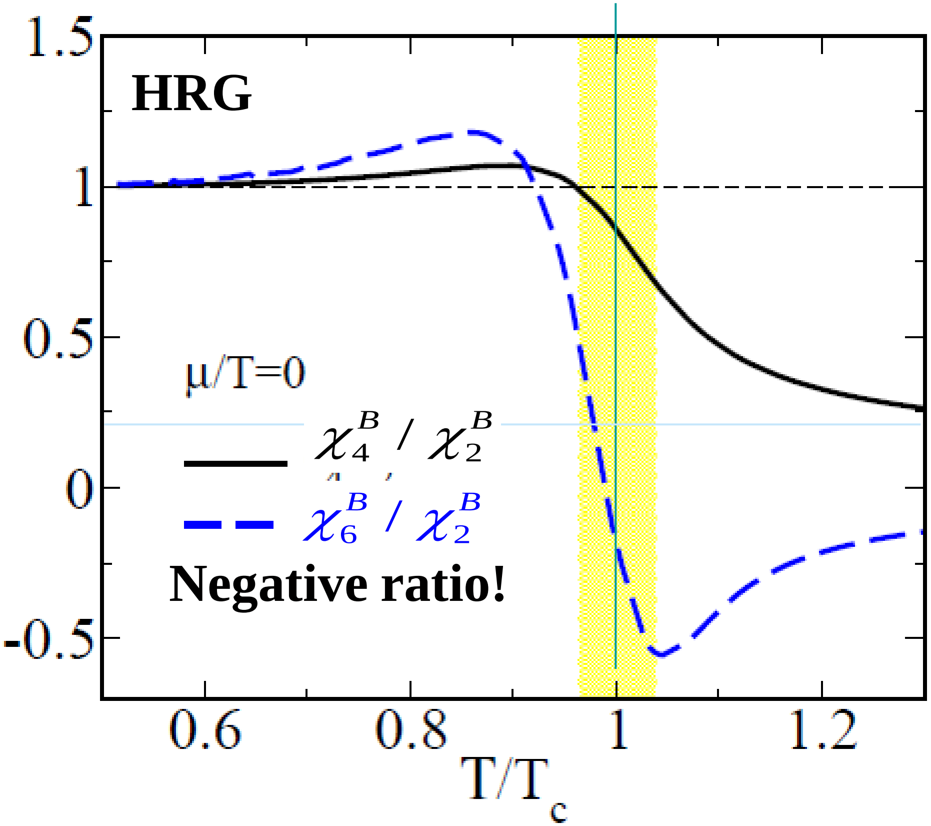
$\Gamma_\Lambda = S_{\text{classical}}$

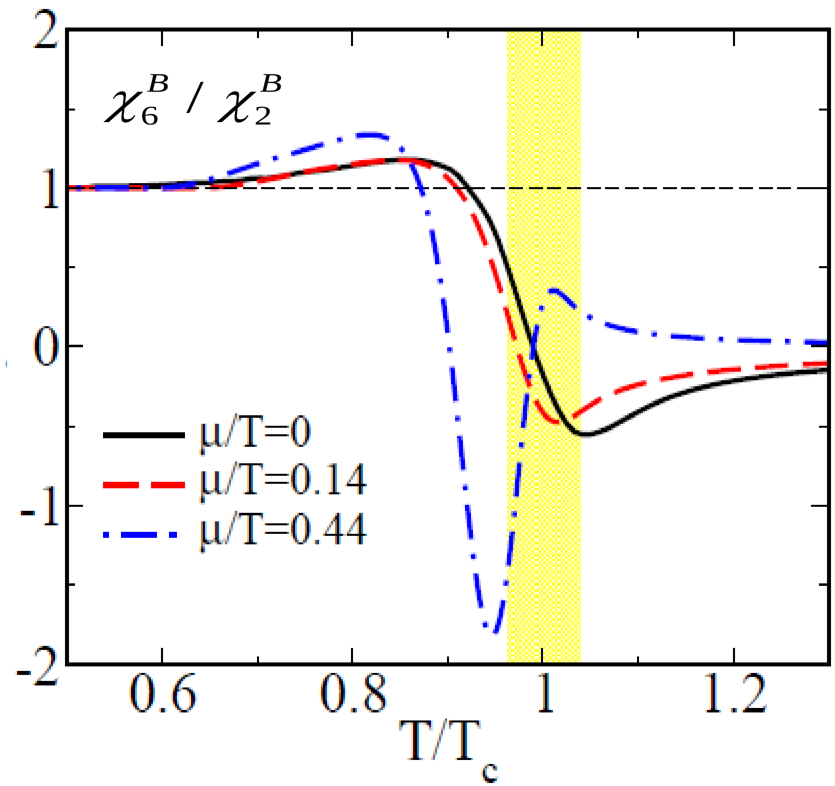
Integrating from $k=\Lambda$ to $k=0$ gives a full quantum effective potential

Put $\Omega_{k=0}(\sigma_{\min})$ into the integral formula for P(N)

Higher order cumulants in effective chiral model within FRG approach to preserve the O(4) universality class

B. Friman, V. Skokov &K.R. Phys. Rev. C83 (2011) 054904



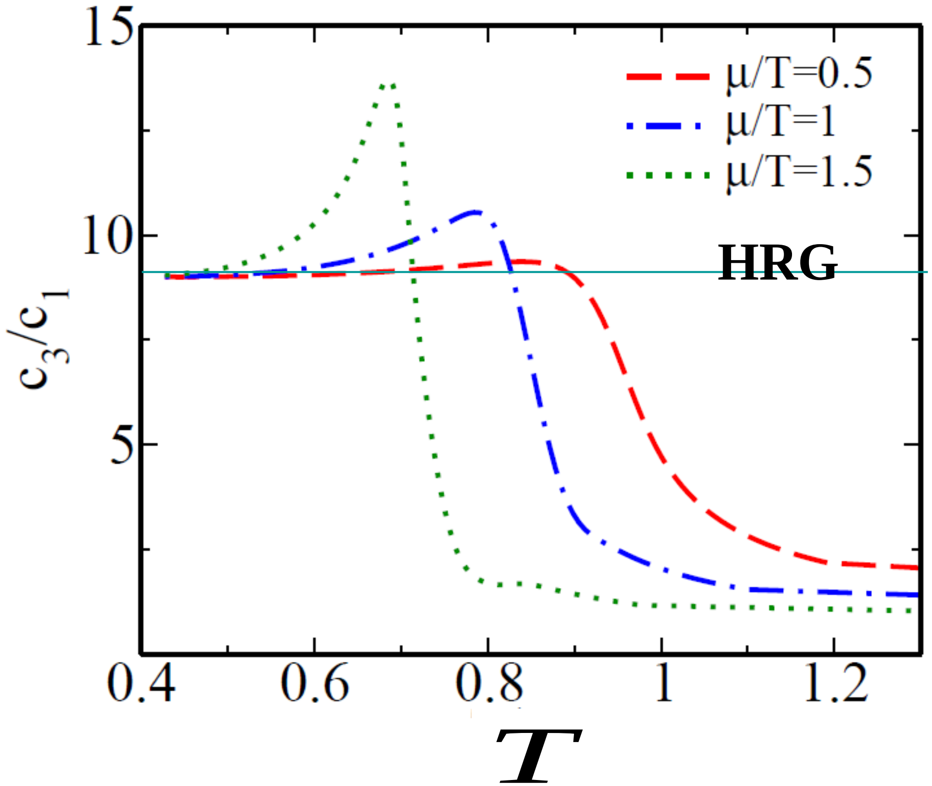


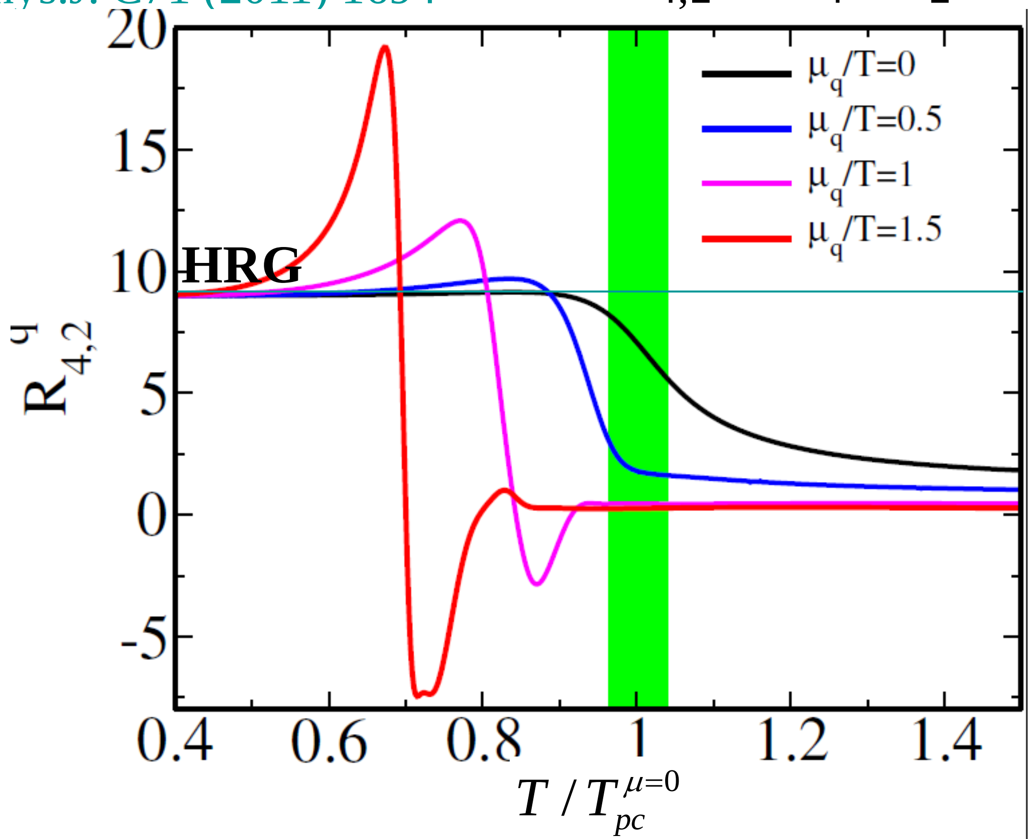
Deviations of cumulant ratios from their asymptotic, HRG values, are increasing with the order of the cumulants and can be used to identify the QCD phase boundary in HIC

Ratios of cumulants at finite density

B. Friman, F. Karsch, V. Skokov &K.R. Eur.Phys.J. C71 (2011) 1694

$R_{4,2} = c_4 / c_2$

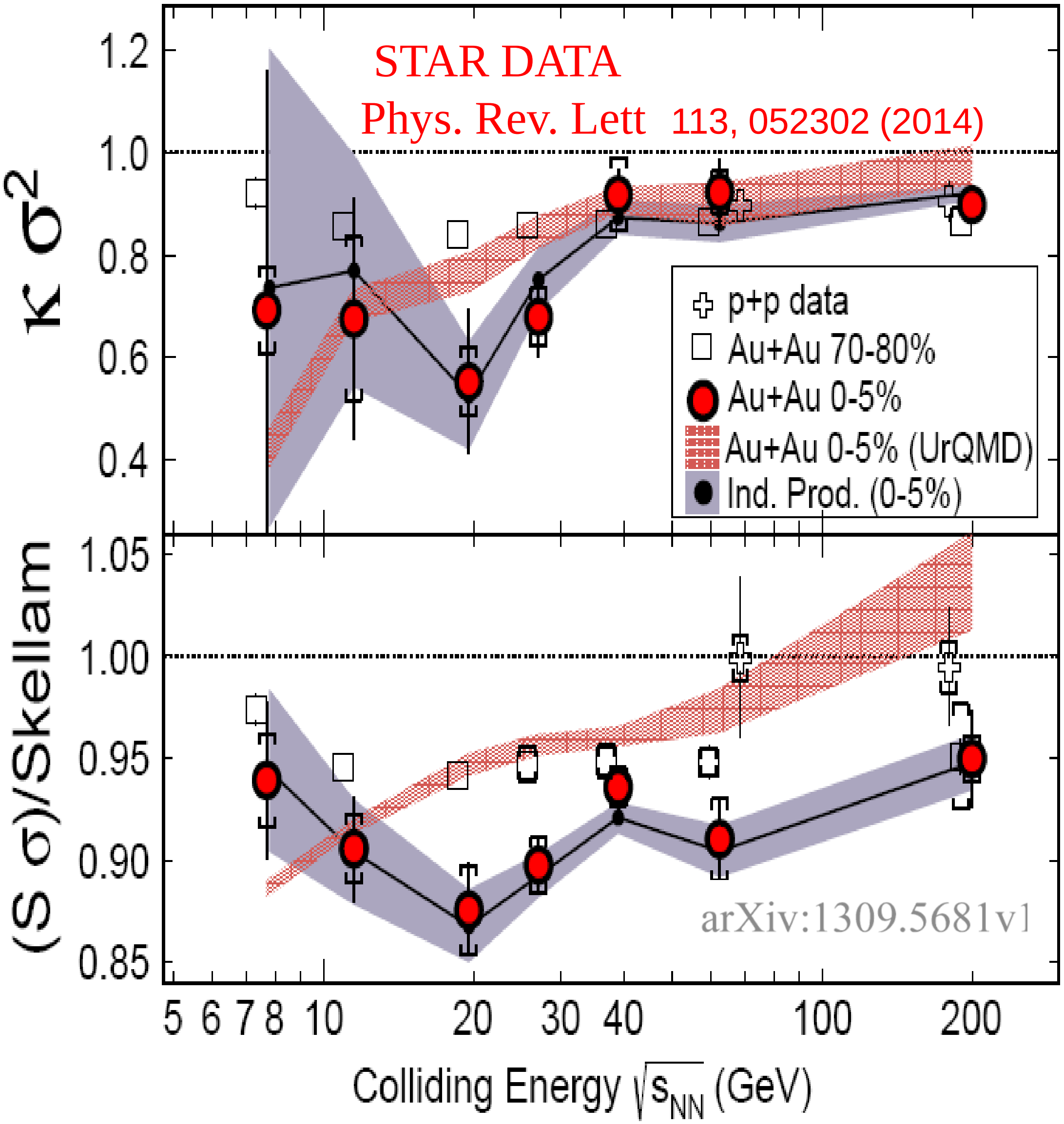




Deviations of the ratios of odd and even order cumulants from their asymptotic, low T-value: $c_4 / c_2 = c_3 / c_1 = 9$ **are increasing with** μ / T **and the cumulant order**

Properties essential in HIC to discriminate the phase change by measuring baryon number fluctuations !

STAR data on the cumulants of the net baryon number



Deviations from the HRG

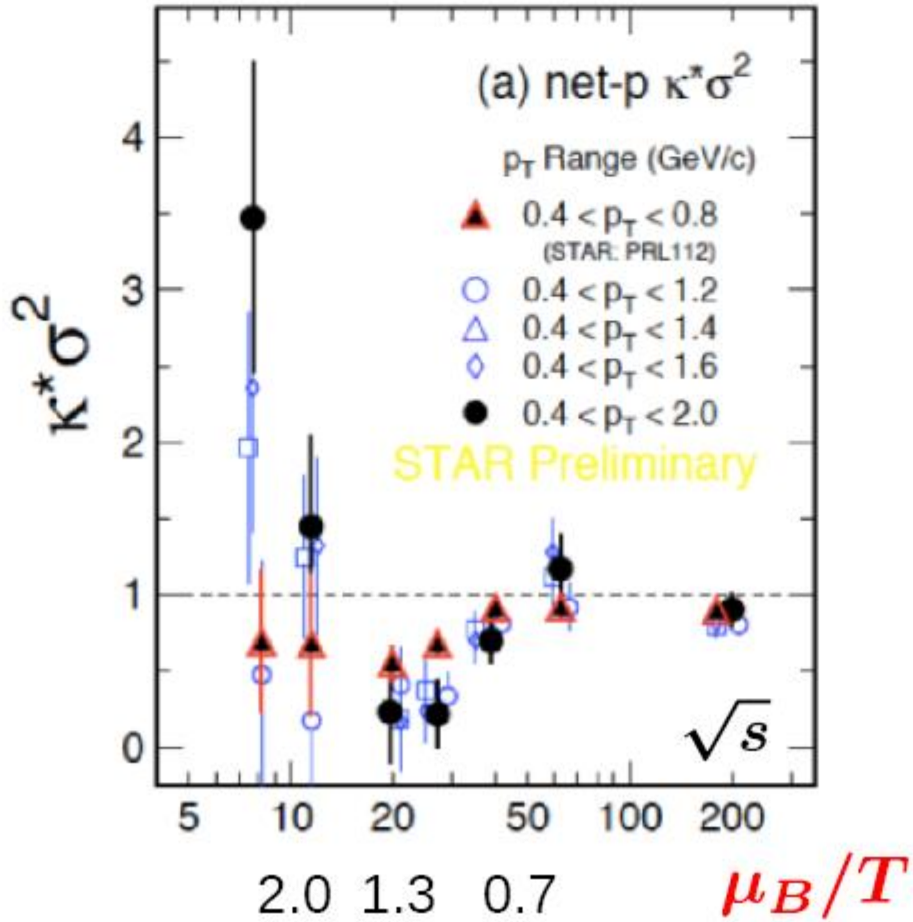
$$S\,\sigma = \frac{\chi_B^{(3)}}{\chi_B^{(2)}} \quad , \quad \kappa\,\sigma^2 = \frac{\chi_B^{(4)}}{\chi_B^{(2)}}$$

$$S\,\sigma\,|_{HRG} = \frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}} \quad , \kappa\sigma\,|_{HRG} = 1$$

Data qualitatively consistent with the change of these ratios due to the contribution of the O(4) singular part to the free energy

STAR “BES” and recent results on net-proton fluctuations

X. Luo et al. (2015), STAR Coll. Preliminary



- With increasing acceptance of the transverse momentum, large increase of net-proton fluctuations at $\sqrt{s} < 20$ GeV beyond that of a non-critical reference of a HRG
- Is the above an Indication of the CEP?
- At $\sqrt{s} > 20$ GeV data consistent with LQCD results near the chiral crossover

Direct comparisons of Heavy ion data at LHC with LQCD

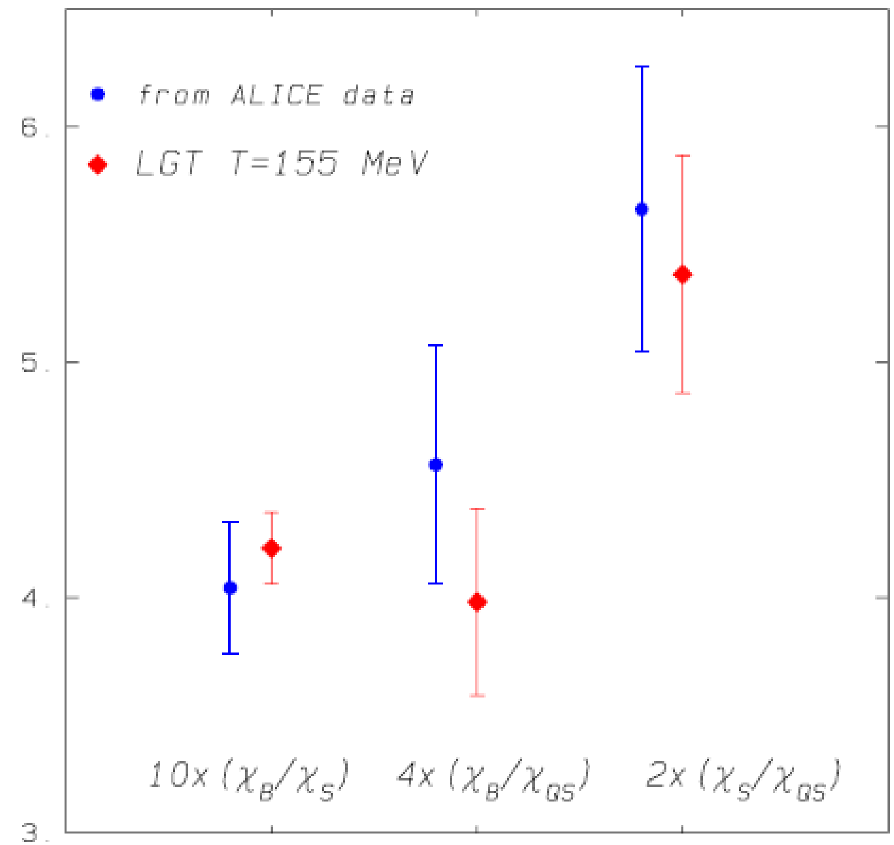
- STAR results => the 2nd order cumulants χ_2 are consistent with Skellam distribution, thus χ_N and χ_{NM} with $N,M=\{B,Q,S\}$ are expressed by particle yields. Consider LHC data

$$\frac{\chi_B}{T^2} \approx \frac{1}{VT^3}\left(2\langle p\rangle + \langle \Lambda+\Sigma_0\rangle + 2\langle \Sigma^+\rangle + 2\langle \Xi^0\rangle + \langle \Omega^-\rangle + \overline{par}\ \right) = \frac{203.7\pm 11.4}{VT^3}$$

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

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

Compare ratios with LQCD at chiral crossover



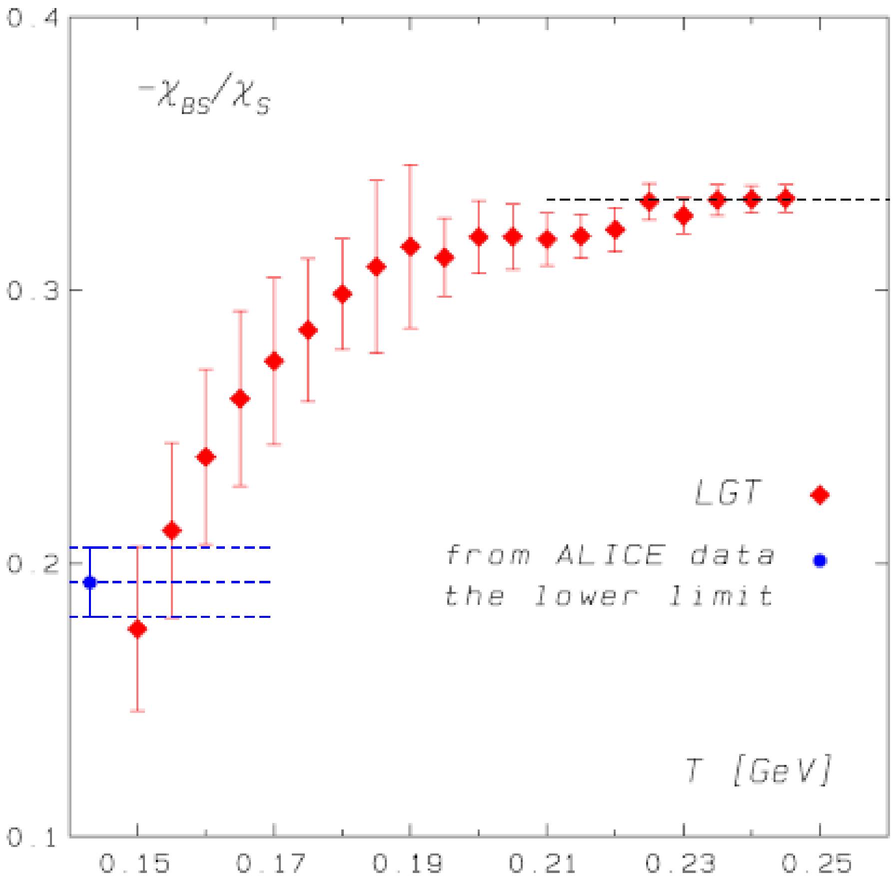
The cumulant ratios obtained from ALICE data are consistent with LQCD at the chiral crossover: Strong evidence of thermalisation at the phase boundary

P. Braun-Munzinger, A. Kalweit, K. Redlich and J. Stachel, Phys. Lett. B747, 292 (2015)

Constraining chemical freezeout temperature at the LHC

P. Braun-Munzinger, A. Kalweit, J. Stachel, & K.R. Phys. Lett. B 747, 292 (2015)

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



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

- Excellent observable to fix the temperature

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

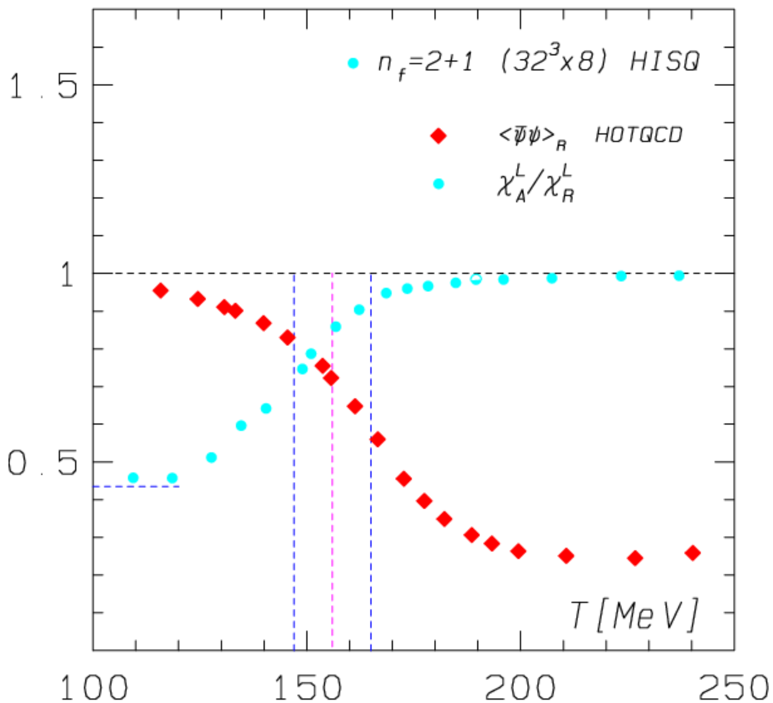
- Data compared to LQCD consistent

with $0.15 < T_f \leq 163$ MeV

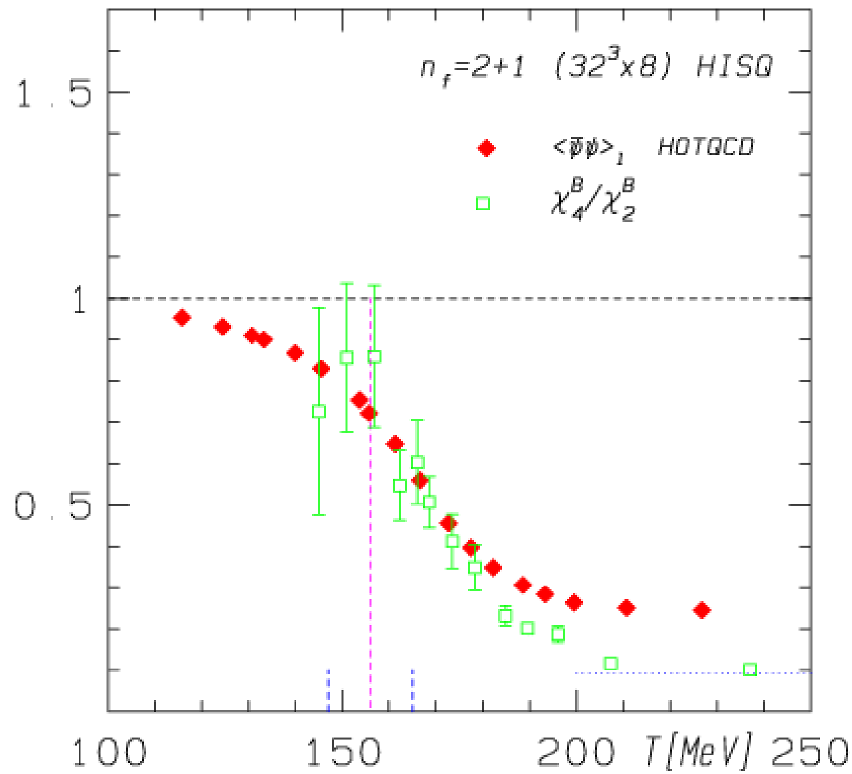
At the LHC energy the fireball created in HIC is a QCD medium at the chiral cross over temperature.

Conclusions:

- Chiral crossover in QCD is the remnant of the 2^{nd} order phase transition belonging to the O(4) universality class
- The medium created in HIC is of thermal origin and at $\sqrt{s} \geq 20$ GeV follows the properties expected in LQCD at the phase boundary
- Ratios of the net-charge cumulants are an excellent probe of the QCD phase boundary and the conjecture CP
- Systematics of the net-proton number fluctuations and their probability distributions measured by STAR Coll. in HIC at RHIC energies is qualitatively consistent with the expectation, that they are influenced by the critical chiral dynamics



n_f=2+1 (32^3x8) HISQ
$<\bar\psi\psi>_R$ HOTQCD
χ^L_A/χ^L_R
1.5
1
0.5
100
150
200
250
T [MeV]



n_f=2+1 (32^3x8) HISQ
$<\bar\psi\psi>_l$ HOTQCD
χ^B_4/χ^B_2
1.5
1
0.5
100
150
200
T[MeV]
250