# Flavor hierarchy in the QCD deconfinement transition

Claudia Ratti

*Università degli Studi di Torino and*

*INFN, Sezione di Torino*

# Motivation

- We live in a very exciting era to understand the fundamental constituents of matter and the evolution of the Universe

- We can create the deconfined phase of QCD in the laboratory

- Lattice QCD simulations have reached unprecedented levels of accuracy

  - physical quark masses

  - several lattice spacings $\longrightarrow$ continuum limit

- The joint information between theory and experiment can help us to shed light on QCD

# Quark number susceptibilities

- The deconfined phase of QCD can be reached in the laboratory
- Need for unambiguous observables to identify the phase transition
  - susceptibilities of conserved charges (baryon number, electric charge, strangeness)

    S. Jeon and V. Koch (2000), M. Asakawa, U. Heinz, B. Müller (2000)
- A rapid change of these observables in the vicinity of $T_c$ provides an unambiguous signal for deconfinement
- These observables are sensitive to the microscopic structure of the matter
  - ➟ non-diagonal correlators give information about presence of bound states in the QGP
- They can be measured on the lattice as combinations of quark number susceptibilities

# The observables under study

- The chemical potentials are related:

$$\begin{aligned} \mu_u &= \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q; \\ \mu_d &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q; \\ \mu_s &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S. \end{aligned}$$

- susceptibilities are defined as follows:

$$\chi_{lmn}^{BSQ} = \frac{\partial^{\,l+m+n} p/T^4}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}.$$

- Here we concentrate on the quadratic susceptibilities

$$\chi_2^X = \frac{1}{VT^3}\langle N_X^2 \rangle$$

- and on the correlators between different charges

$$\chi_{11}^{XY} = \frac{1}{VT^3}\langle N_X N_Y \rangle.$$

# Physical meaning

- Diagonal susceptibilities measure the response of quark densities to an infinitesimal change in the chemical potential

$$\chi_2^X = \frac{\partial^2 p/T^4}{\partial(\mu_X/T)^2} = \frac{\partial}{\partial(\mu_X/T)}\left(n_X/T^3\right)$$

  - A rapid increase of these observables in a certain temperature range signals a phase transition

- Non-diagonal susceptibilities measure the correlation between different quark flavors

$$\chi_{11}^{XY} = \frac{\partial^2 p/T^4}{\partial(\mu_X/T)\partial(\mu_Y/T)} = \frac{\partial}{\partial(\mu_Y/T)}\left(n_X/T^3\right)$$

  - They can provide information about bound-state survival above the phase transition susceptibilities of conserved charges

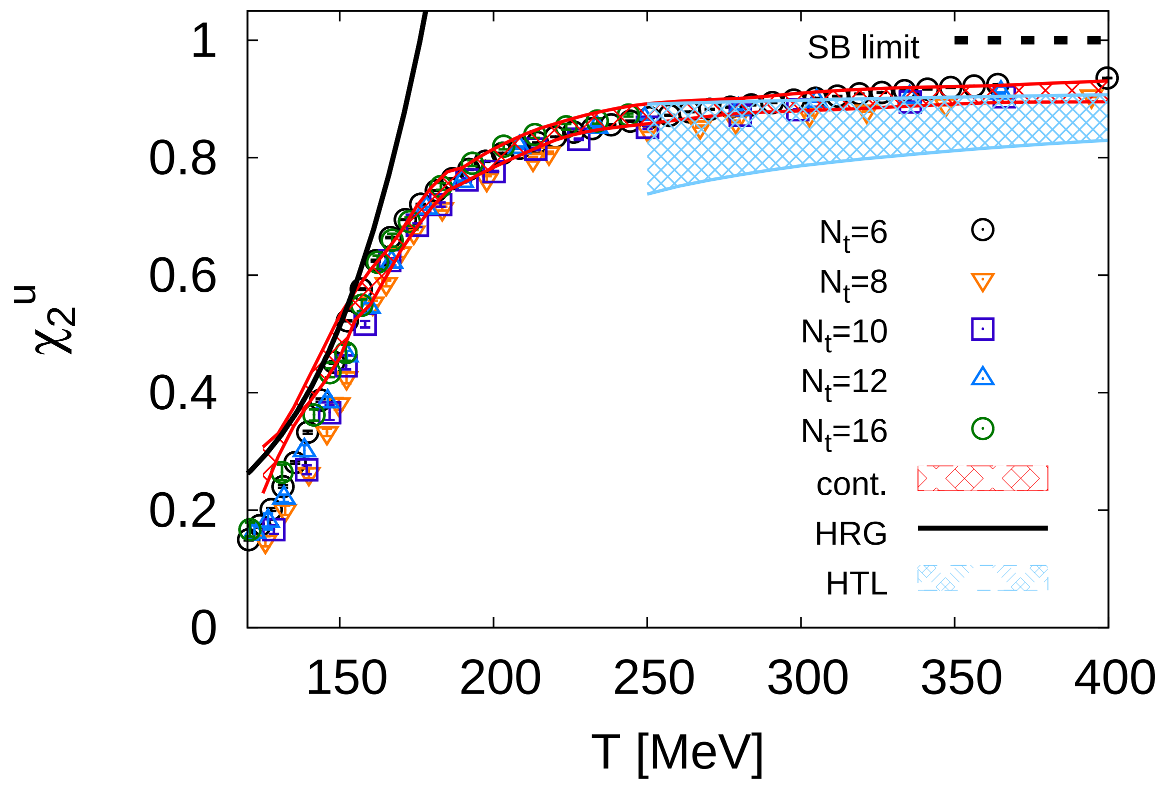
$N_f = 2 + 1$ dynamical quark flavors

$$m_s/m_{u,d} \simeq 28$$

WB collaboration, JHEP 2012

# Results: light quark susceptibilities

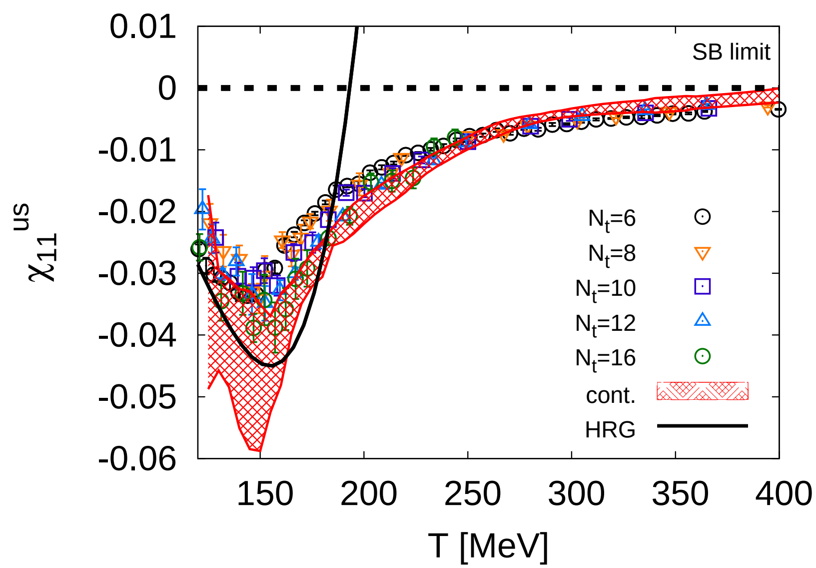
$$\chi_2^u = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial \mu_u \partial \mu_u}\bigg|_{\mu_i=0}$$




- quark number susceptibilities exhibit a rapid rise close to $T_c$
- at large $T$ they reach $\sim 90\%$ of the ideal gas limit

# Results: nondiagonal susceptibilities

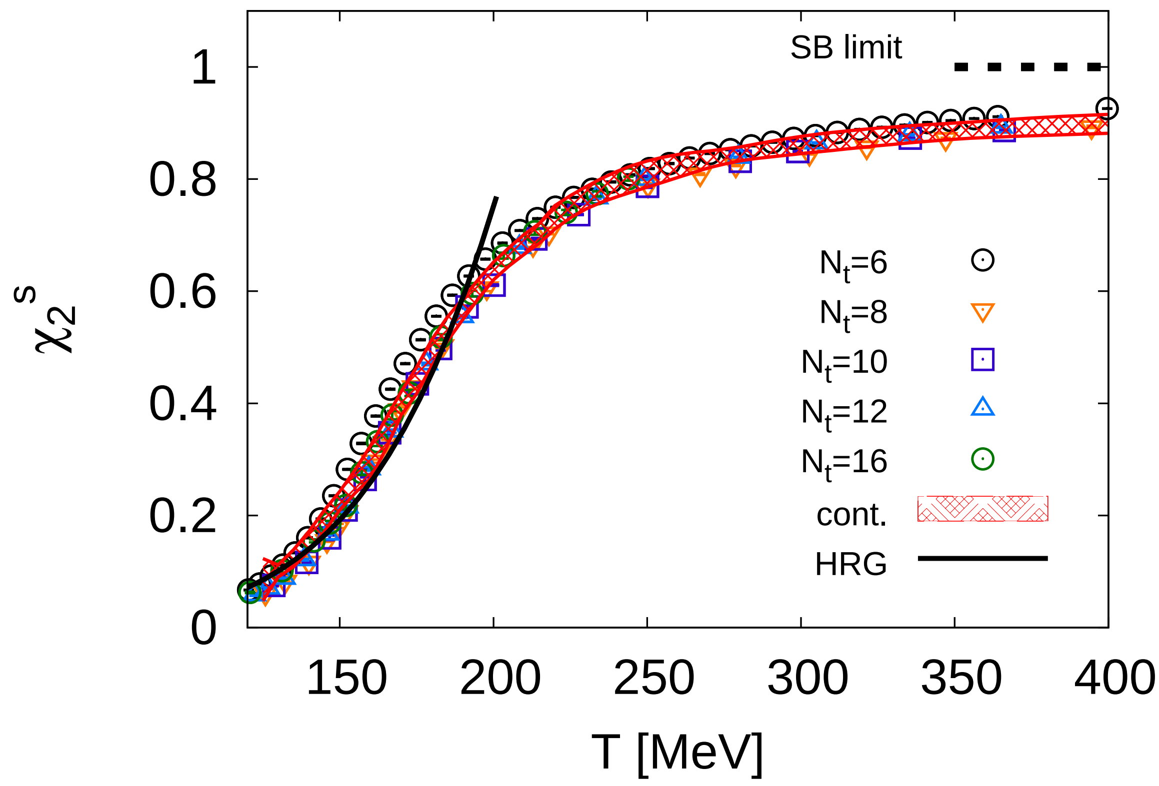
$$\chi_{11}^{us} = \chi_{11}^{ds} = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial \mu_u \partial \mu_s}\bigg|_{\mu_i = 0}$$




- non-diagonal susceptibilities look at the linkage between different flavors
- they exhibit a strong dip in the vicinity of $T_c$
- they vanish in the QGP phase at large temperatures

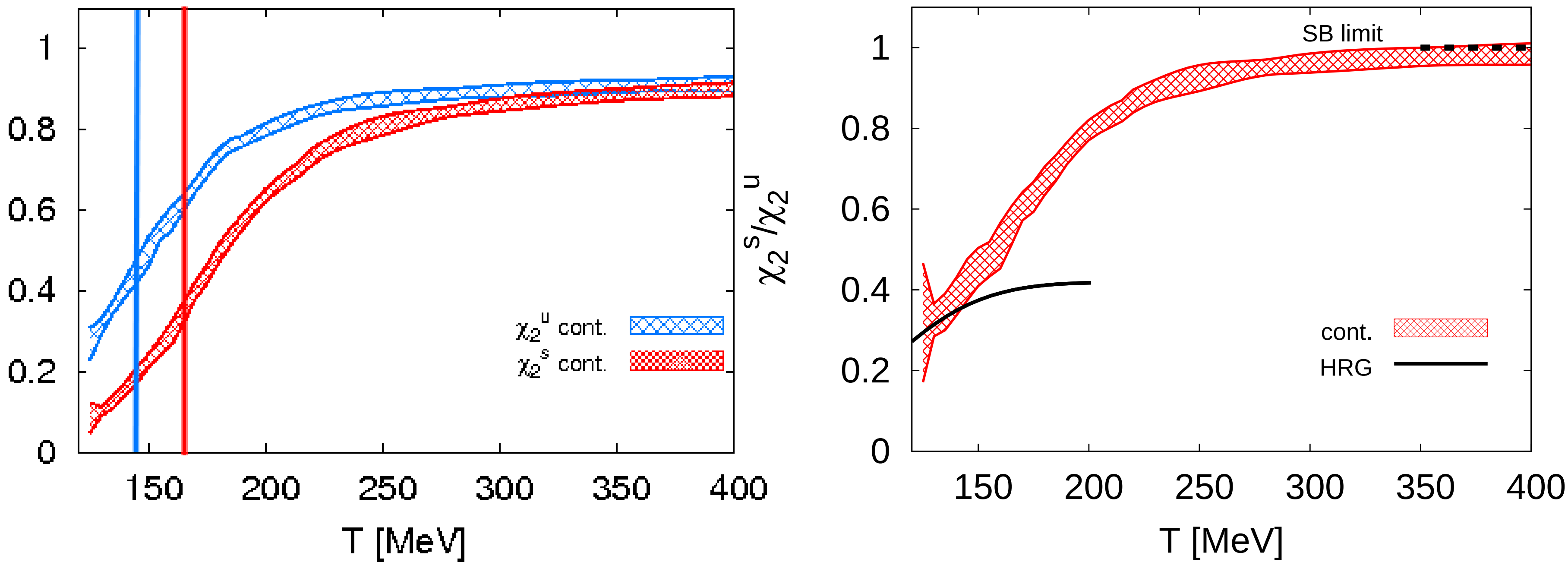
# Results: strange quark susceptibilities

$$\chi_2^s = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial \mu_s^2}\bigg|_{\mu_i=0}$$




- quark number susceptibilities exhibit a rapid rise close to $T_c$
- at large $T$ they reach $\sim 90\%$ of the ideal gas limit

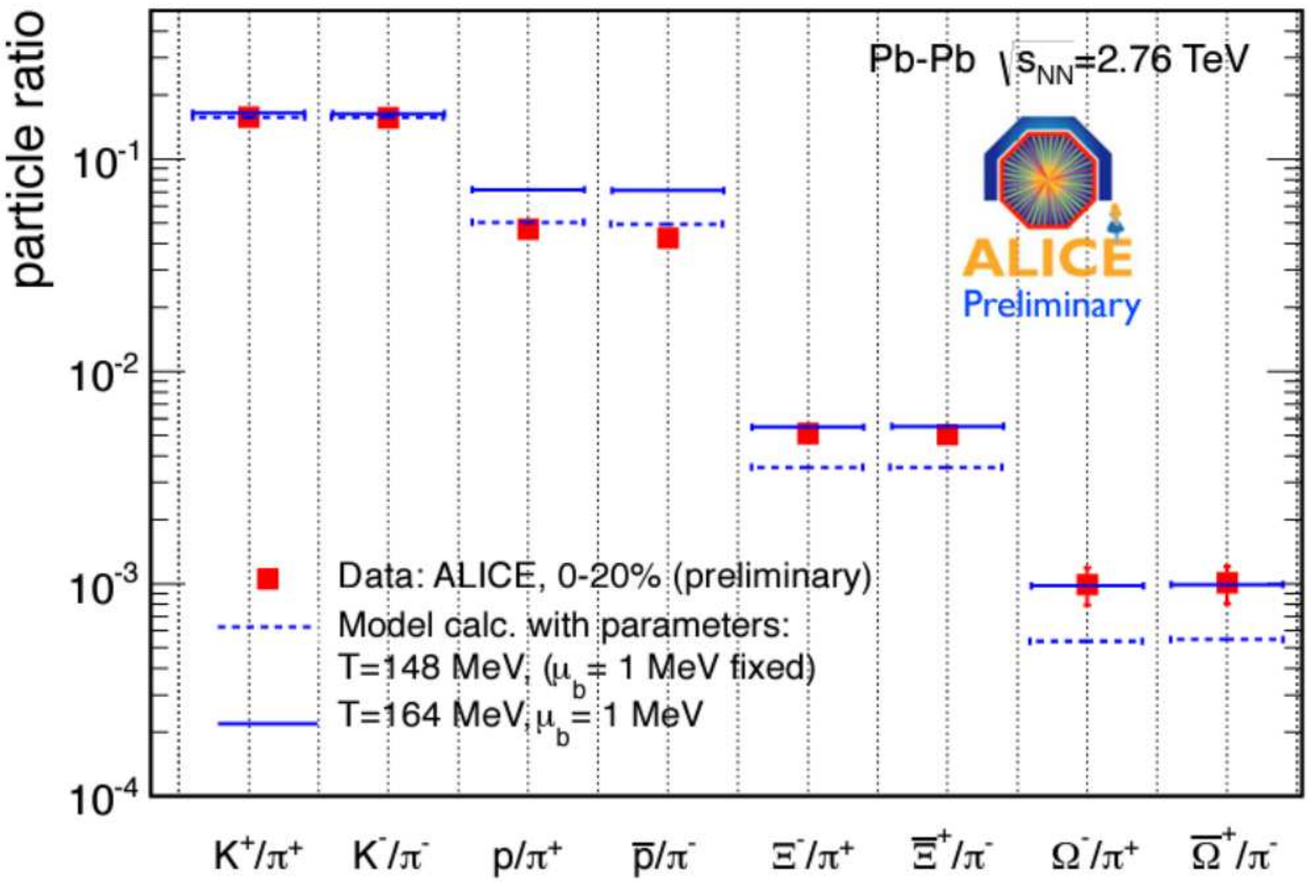
# Comparison between light and strange quark susceptibilities




- strange quark susceptibilities have their rapid rise at larger temperatures compared to the light quark ones
- they rise more slowly as a function of $T$
- There is a difference of $\sim 15 - 20$ MeV between the inflection points of the two curves

# Simple experimental verification

- Yields of strange particles should be enhanced relative to yields of non-strange particles
- yields of strange particles should result in a higher temperature than yields of non-strange particles when fitted with a statistical hadronization model (SHM)




R. Preghenella
for ALICE
SQM 2012
arXiv:1111.7080
Acta Phys. Pol.

# Caveats

- Lattice results for susceptibilities are first-principle calculations
  - However, $T_c$ cannot be univocally defined
- The experimental results are fitted by means of the Statistical Hadronization Model
- It would be nice to have a direct comparison between first-principle calculations and experimental results

# Higher order susceptibilities and ratios

- susceptibilities are defined as follows:

$$\chi_{lmn}^{BSQ} = \frac{\partial^{\,l+m+n} p/T^4}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}.$$

- we are now interested in fourth order susceptibilities ($\chi_4$) and in particular in ratios $\chi_4/\chi_2$

  - Ratios have a very peculiar shape which allows to unambiguously spot the transition

  - They can be directly related to an experimental measurement: no need for model interpretation!

# Relating lattice results to experimental measurement

- the first four cumulants are:

$$\chi_1 = \langle(\delta x)\rangle \qquad \chi_2 = \langle(\delta x)^2\rangle$$

$$\chi_3 = \langle(\delta x)^3\rangle \qquad \chi_4 = \langle(\delta x)^4\rangle - 3\langle(\delta x)^4\rangle^2$$

- we can relate them to higher moments of multiplicity distributions:

$$\text{variance}: \ \sigma^2 = \chi_2 \qquad \text{standard deviation}: \ \sigma = \sqrt{\chi_2}$$

$$\text{skewness}: \ S = \chi_3/\chi_2^{3/2} \qquad \text{kurtosis}: \ \kappa = \chi_4/\chi_2^2$$

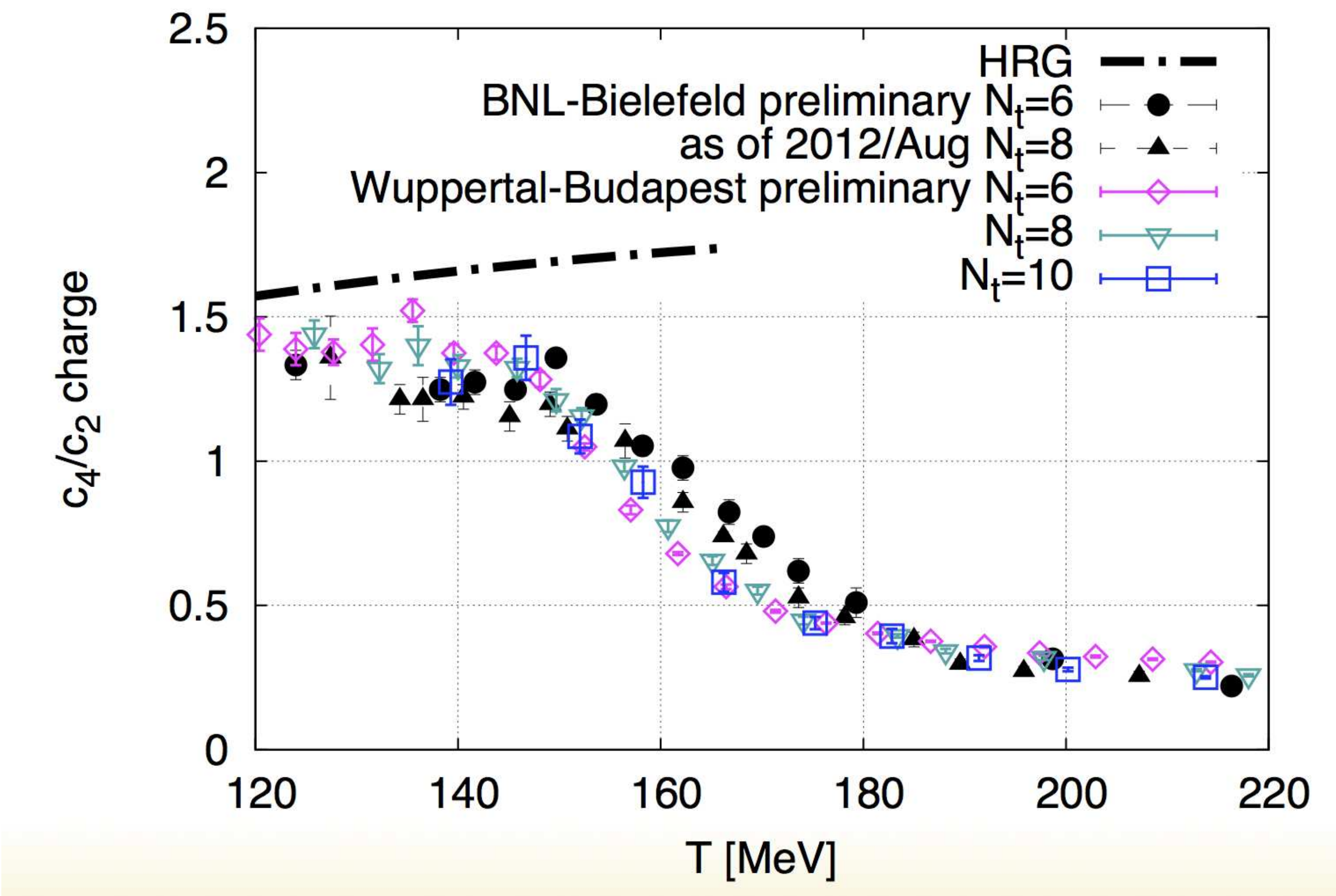
$$S\sigma = \chi_3/\chi_2 \qquad \kappa\sigma^2 = \chi_4/\chi_2$$

- and therefore:

$$\kappa_B\sigma_B^2 \equiv \frac{\chi_{4,\mu}^B}{\chi_{2,\mu}^B} = \frac{\chi_4^B(T)}{\chi_2^B(T)}\left[\frac{1+\frac{1}{2}\frac{\chi_6^B(T)}{\chi_4^B(T)}(\mu_B/T)^2+\ldots}{1+\frac{1}{2}\frac{\chi_4^B(T)}{\chi_2^B(T)}(\mu_B/T)^2+\ldots}\right]$$

F. Karsch (2012)

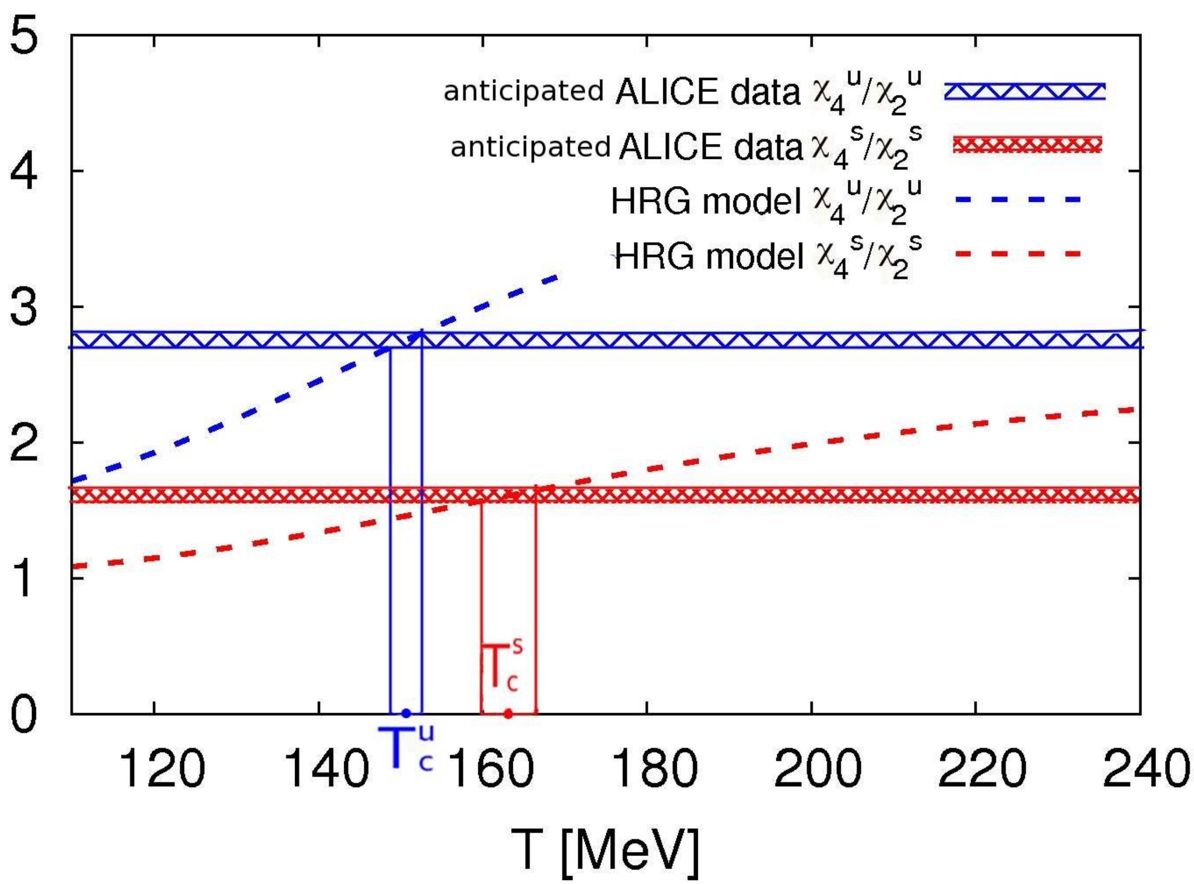
# Electric charge kurtosis




- We plot the V-independent ratio $\kappa\sigma^2 = c_4/c_2$

# Proposal: measure the flavor-specific kurtosis

- light and strange quark $\chi_4/\chi_2$
- comparison to experimental measurement will give the flavor-specific freeze-out temperatures



# Defining the experimental measurement

- Problem: we need to go from the $B, Q, S$ basis to the basis of $u,\ d,\ s$ quark flavors

- In principle we need to measure all light and strange quark final states

  - Experimentally impossible, most resonances are too rare and cannot be reconstructed

- Most resonances decay one to one to their ground state

- Strange weak decays need to be reconstructed

$$\kappa_s\sigma_s^2 = \kappa\sigma^2(K, K^0, \Lambda, \Xi, \Omega \text{ incl. } K^*, \Lambda^*, \Sigma, \Xi^*)$$
$$\kappa_u\sigma_u^2 = \kappa\sigma^2(\pi, p \text{ incl. } \rho, \omega, \Delta, N^*)$$

Ongoing project with P. Alba, W. M. Alberico, R. Bellwied, M. Bluhm, D. Chinellato and M. Weber

# Conclusions

- High precision (continuum limit) lattice QCD predicts flavor separation in the crossover from the partonic to the hadronic matter.
- this could lead to a short mixed phase of degrees of freedom in which strange particle formation is dominant
- this should lead to measurable effects in the strange hadron yields (evidence from ALICE)
- new model-independent comparison between theory and experiment: $\chi_4/\chi_2$
- work in progress: define a meaningful experimental measurement

# Backup slides

# Alternate explanation: non-equilibrium proton annihilation after hadronization

Idea based on enhanced in-medium annihilation cross sections in hadronic transport codes, e.g. UrQMD

Steinheimer, Aichelin, Bleicher, arXiv:1203.5302
Karpenko, Sinyukov, Werner, arXiv:1204.5351
Becattini et al., arXiv:1201.6349

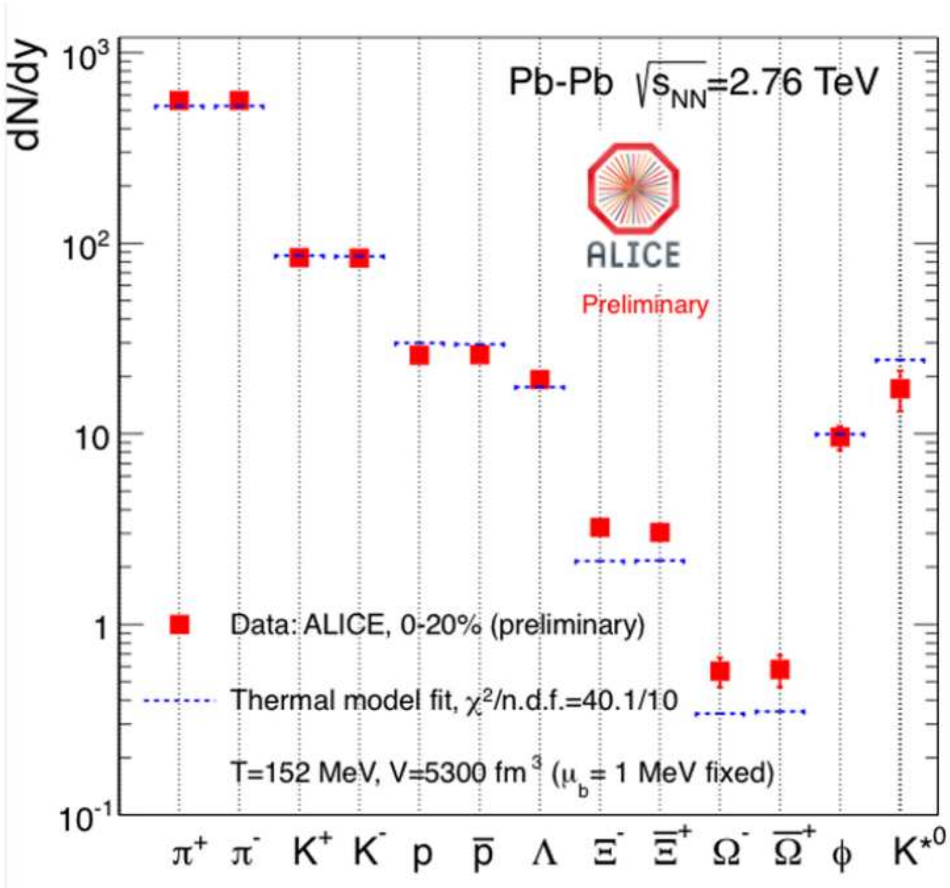
A hydro-based model which modifies the chemical freeze-out temperatures in a species dependent way due to viscous corrections exists as well (but slightly over predicts proton yield and under predicts multi strange yield).

Bozek, arXiv:1110.6742, arXiv:1111.4398, arXiv:1203.6513

Method to exclude in-medium proton suppression (annihilation models):
*Compare Npart scaled proton yield as a function of centrality in PbPb and in pp. If proton is suppressed in medium then scaled yield has to drop with centrality.*

# SHM yield fit

- Simultaneous fit gives $T = 152$ MeV

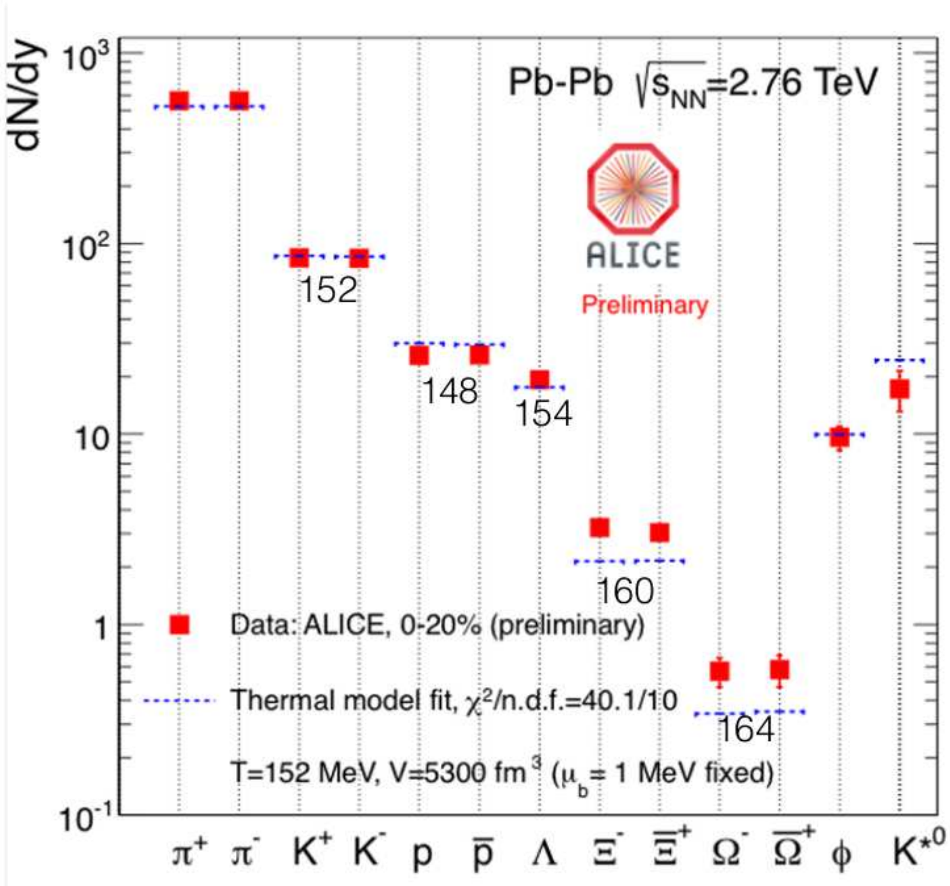



L. Milano for ALICE, QM 2012

- However, protons are overestimated and strange baryons are underestimated

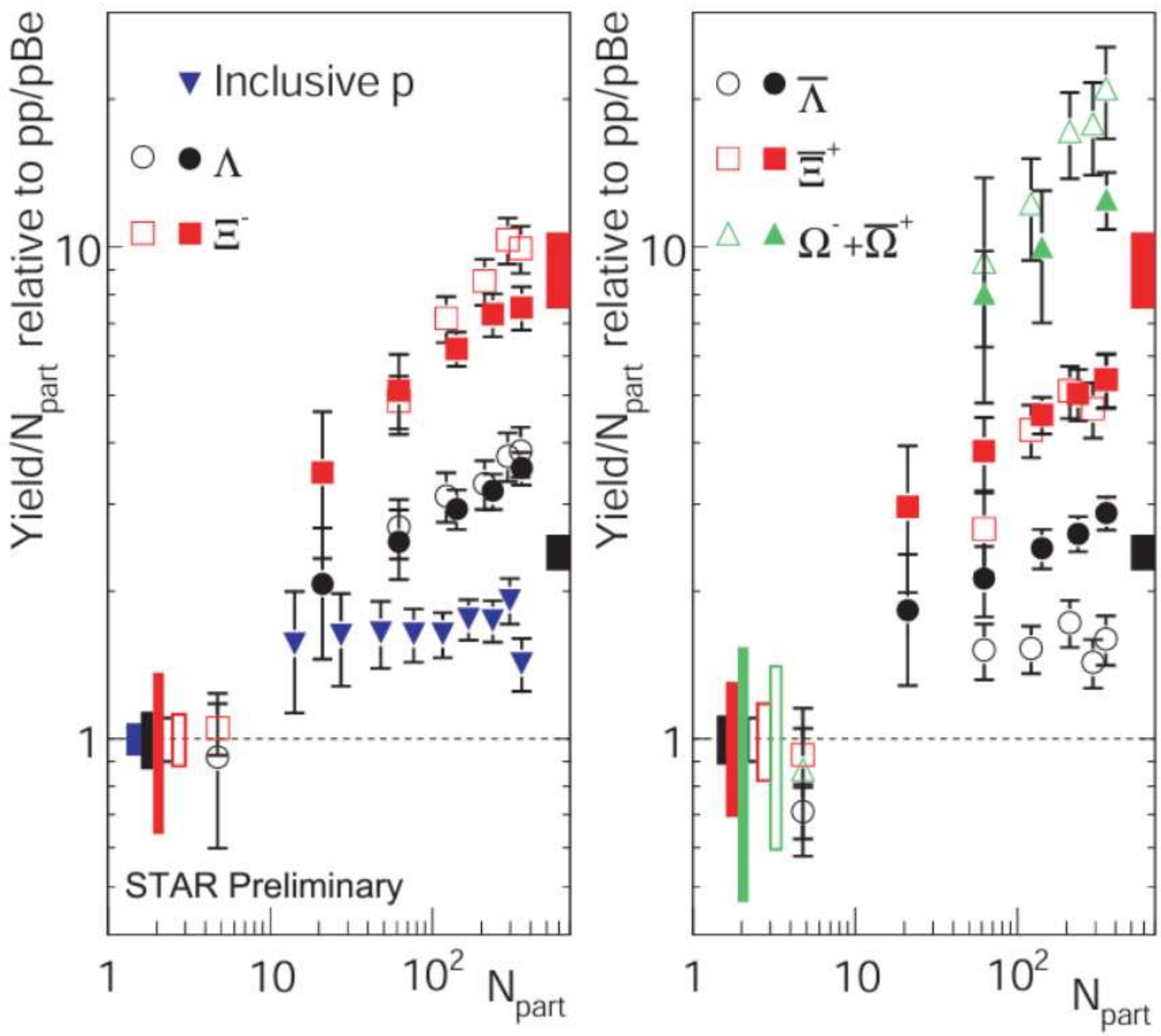
# SHM yield fit

- Fitting them separately, a hierarchy is evident



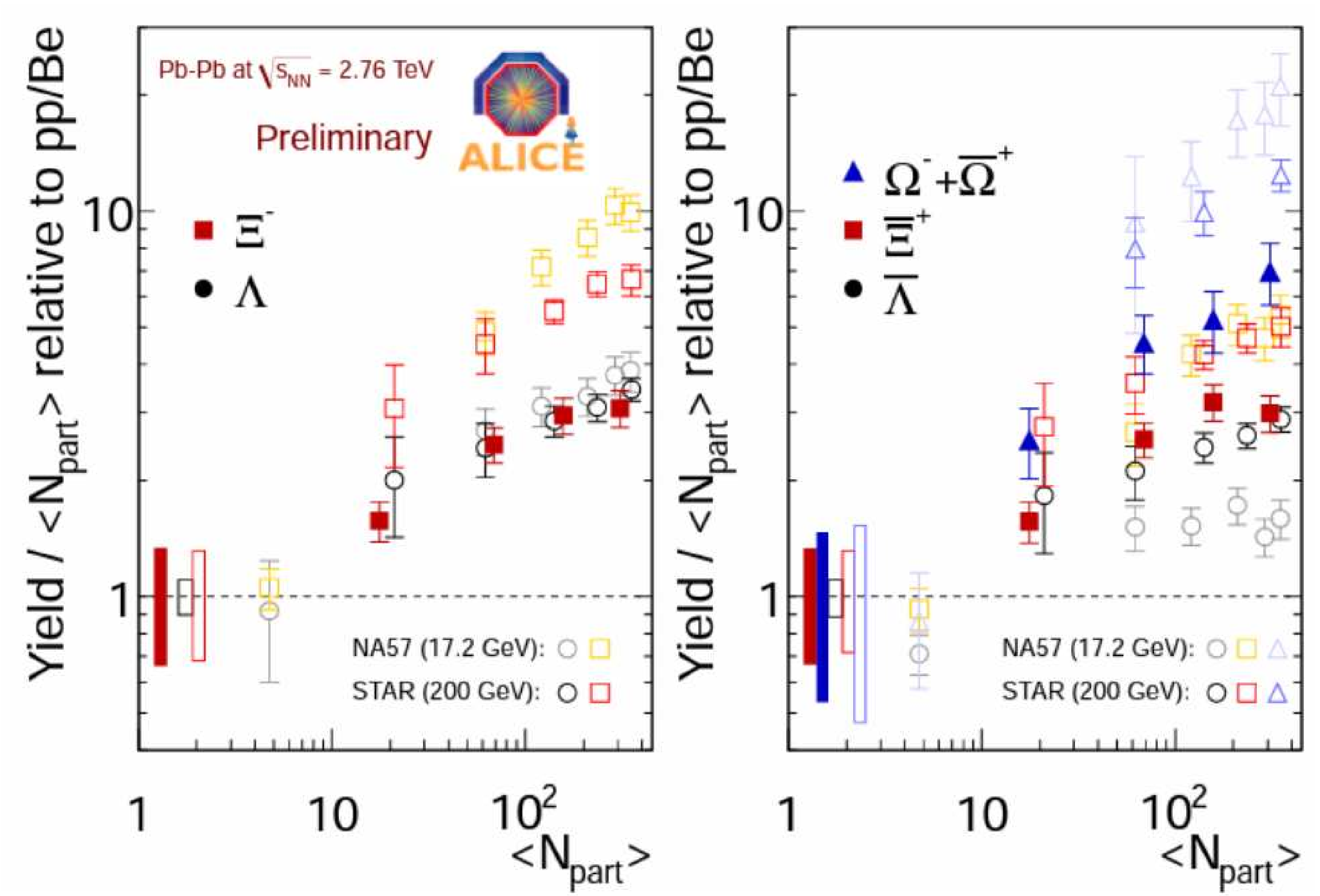

R. Bellwied (2012)

# At RHIC the proton is not suppressed but rather slightly enhanced



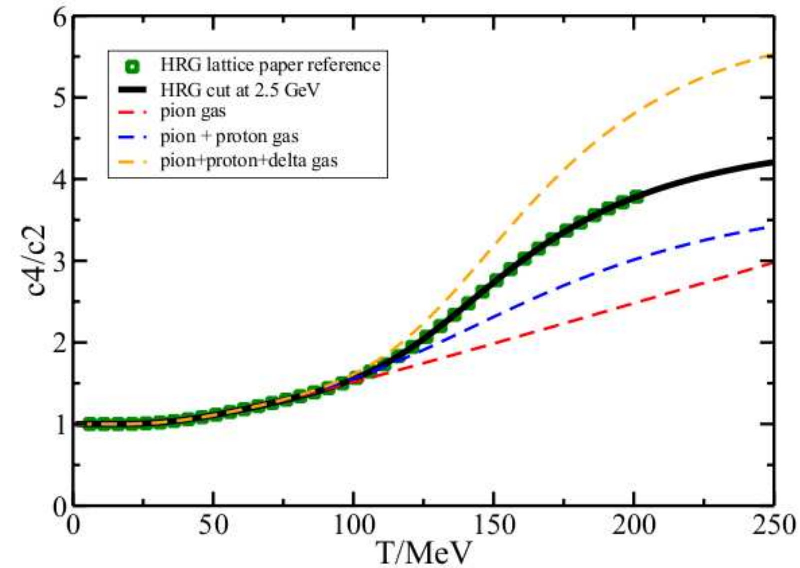

H. Caines for STAR
SQM 2006
nucl-ex/0608008
J.Phys.G32 (2006) S171

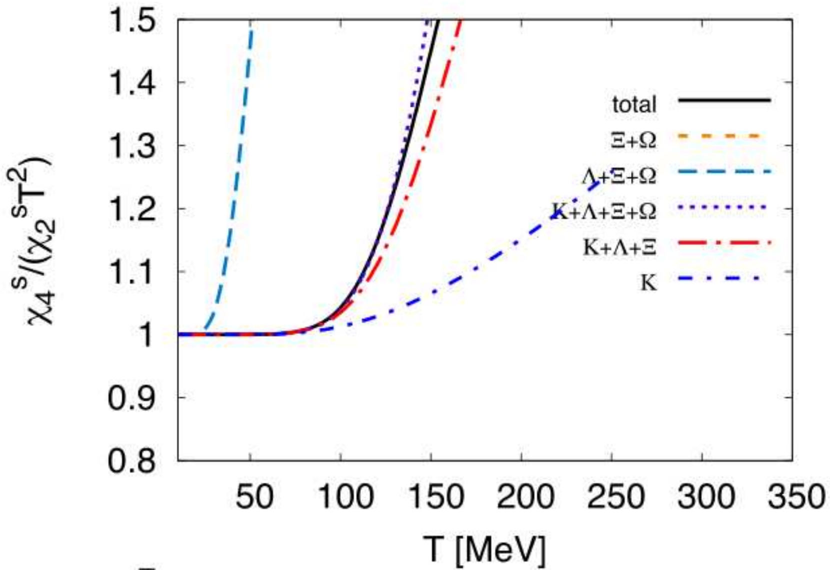
# Strangeness enhancement in ALICE

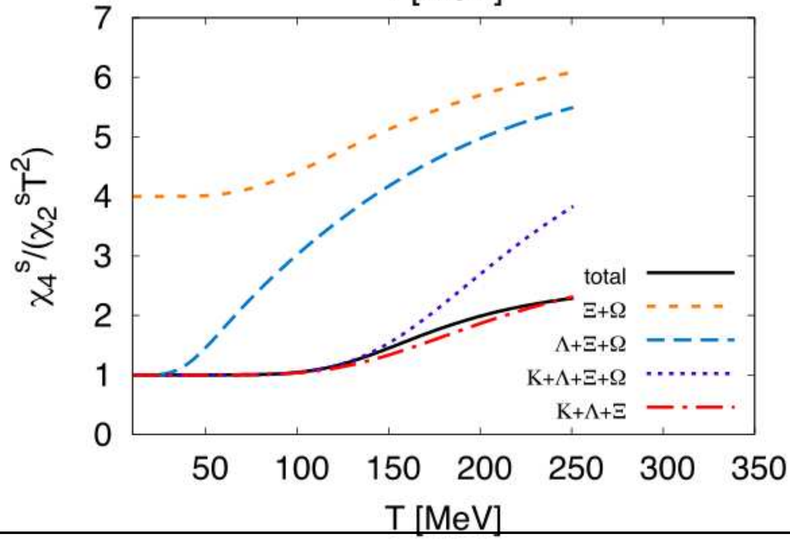



B. Hippolyte
for ALICE
SQM 2011
arXiv:1112.5803

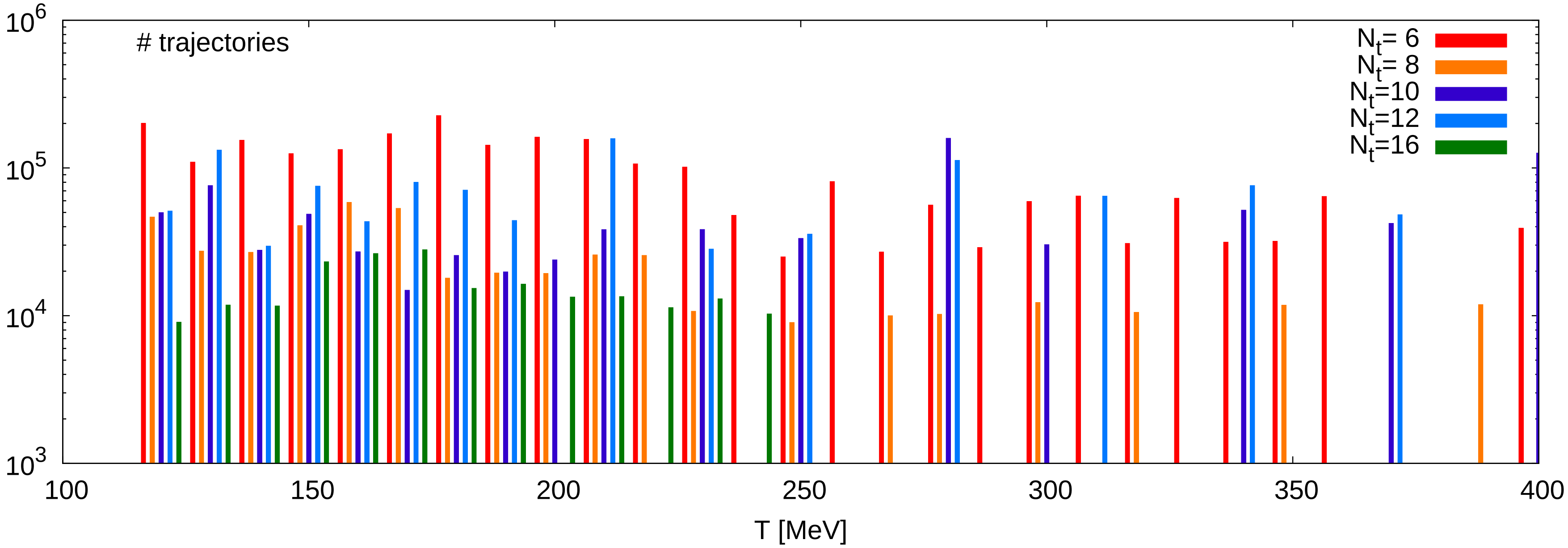
# HRG calculations are very sensitive to particle composition



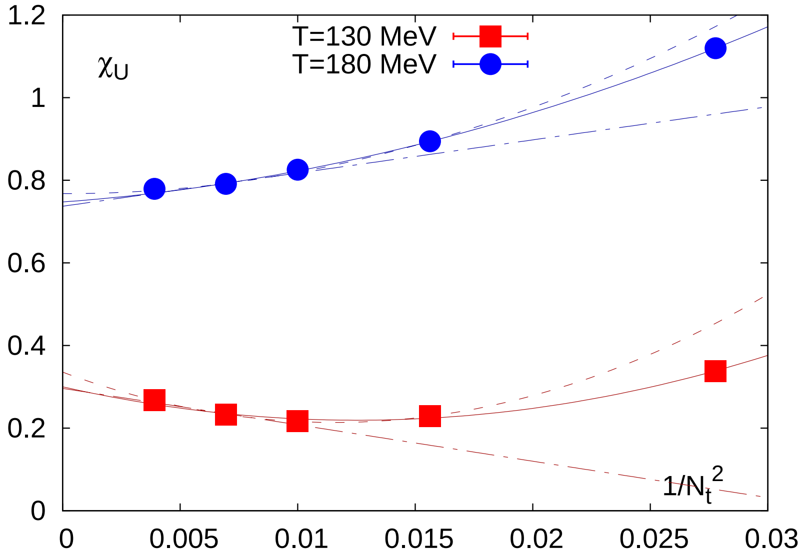



# Statistics and continuum extrapolation



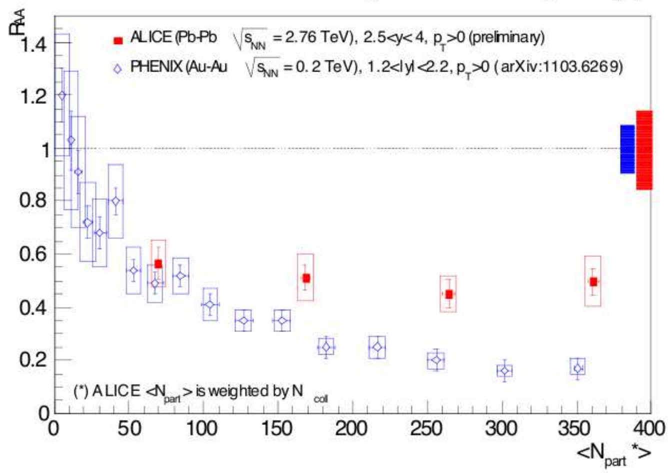

- all observables are continuum extrapolated
  - ➜ obtained by measuring them at several $a \sim 1/N_t$ and taking the limit $a \to 0$
- parabolic fit is perfomed



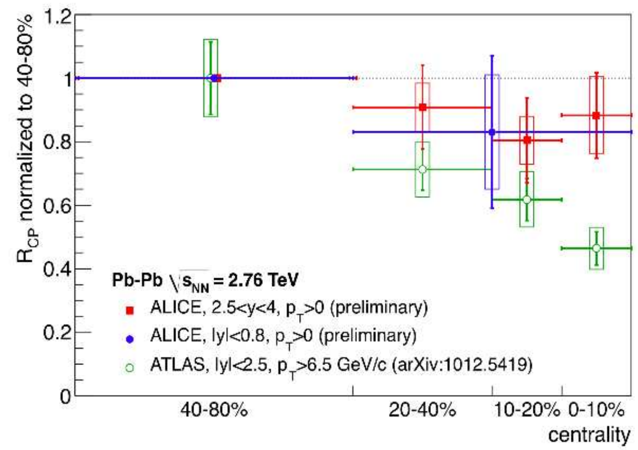
# There are evidences for deviations from statistical model predictions at the LHC

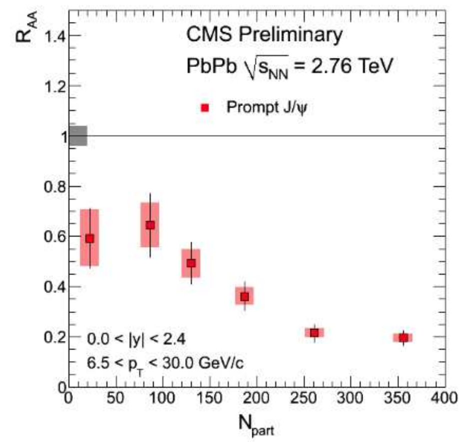
## - J/ψ production -

Data: ALICE/ PHENIX (forward rapidity) - QM 2011

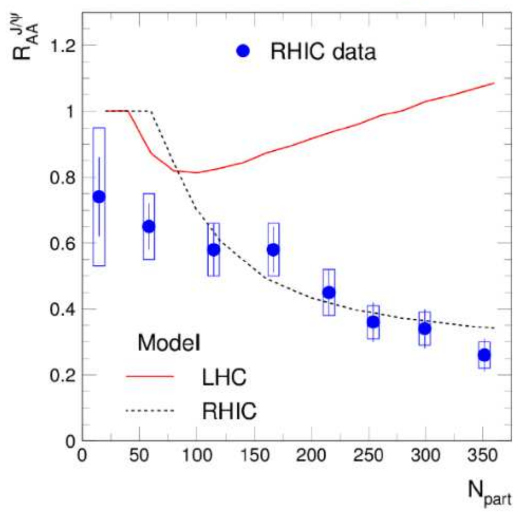



Data: ALICE / ATLAS / CMS (mid rapidity) - QM 2011



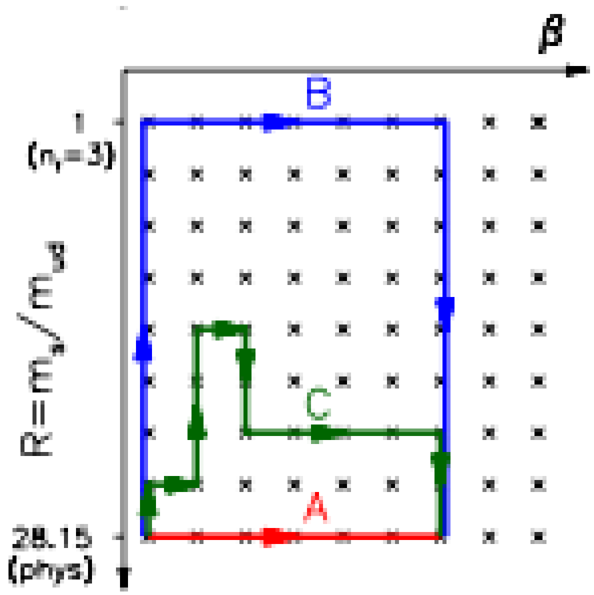

Prediction: Braun-Munzinger, Stachel arXiv:0901.2500




Conclusion:
All datasets (forward and mid-rapidity, low and high pT) show significant J/ψ suppression in central collisions in contradiction to statistical model predictions: possibly no common freeze-out surface or no strong partonic recombination ?

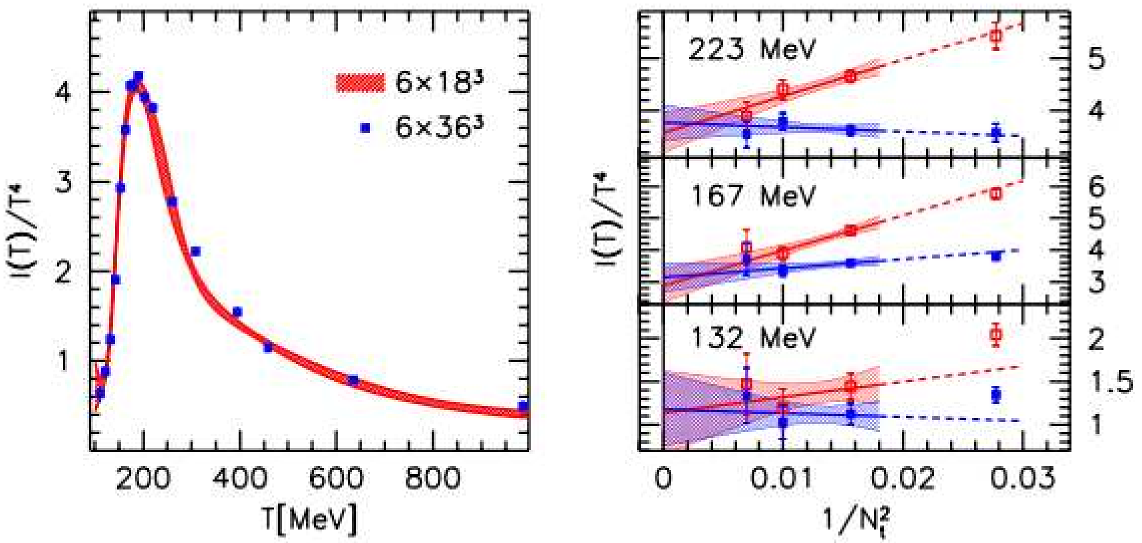
# All path approach

- Our goal:
  - determine the equation of state for several pion masses
  - reduce the uncertainty related to the choice of $\beta^0$




- conventional path: A, though B, C or any other paths are possible
- generalize: take all paths into account

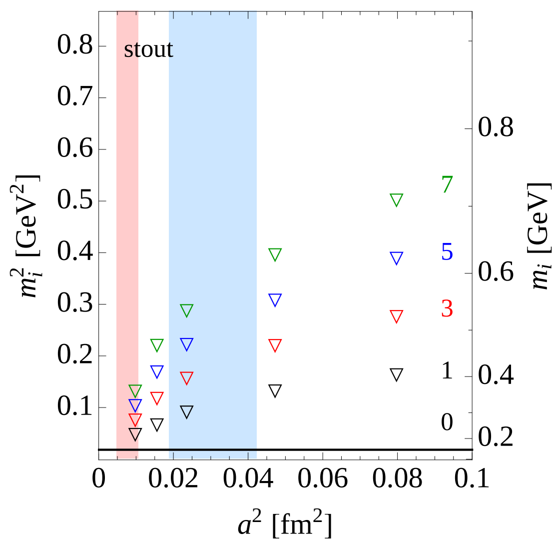
# Finite volume and discretization effects

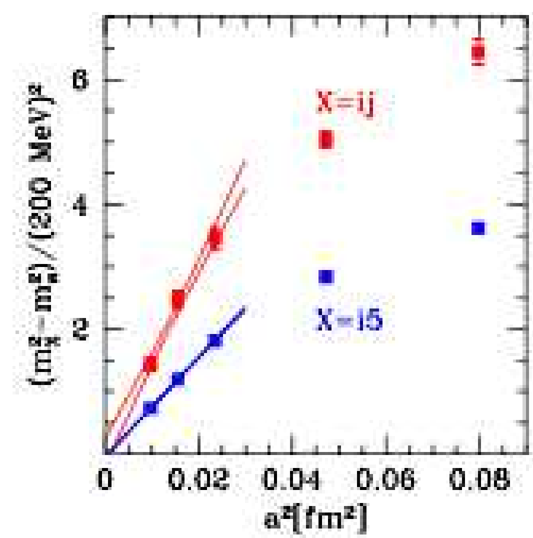



- finite $V$ : $N_s/N_t = 3$ and 6 (8 times larger volume): no sizable difference
- finite $a$: improvement program of lattice QCD (action observables)
  - tree-level improvement for $p$ (thermodynamic relations fix the others)
  - trace anomaly for three $T$-s: high $T$, transition $T$, low $T$
  - continuum limit $N_t = 6, 8, 10, 12$: same with or without improvement
- improvement strongly reduces cutoff effects: slope$\simeq 0$ ($1 - 2\sigma$ level)

# Pseudo-scalar mesons in staggered formulation

- Staggered formulation: four degenerate quark flavors (‘tastes’) in the continuum limit
- Rooting procedure: replace fermion determinant in the partition function by its fourth root
- At finite lattice spacing the four tastes are not degenerate
  - each pion is split into 16
  - the sixteen pseudo-scalar mesons have unequal masses
  - only one of them has vanishing mass in the chiral limit




- Scaling starts for $N_t \geq 8$.