Theoretical and experimental evidence for hadron formation above the QCD critical temperature

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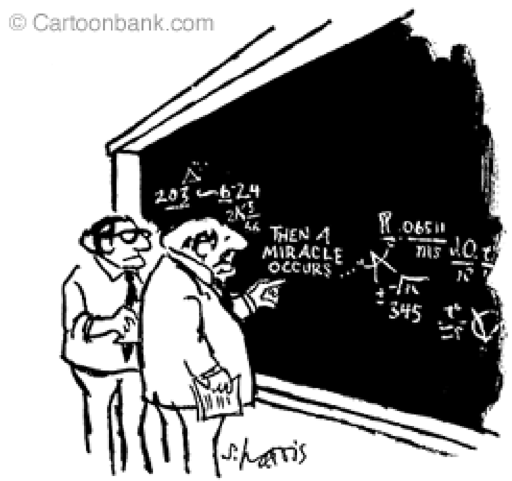
The fundamental questions

- **How do hadrons form ?**
  - Parton fragmentation or string fragmentation or recombination
  - An early color neutral object (pre-hadron) or a long-lived colored object (quasi-particle or constituent quark)
- **When do hadrons form ?**
  - Inside the deconfined medium or in the vacuum ?



"I think you should be more explicit here in step two."

Why investigate it now ?

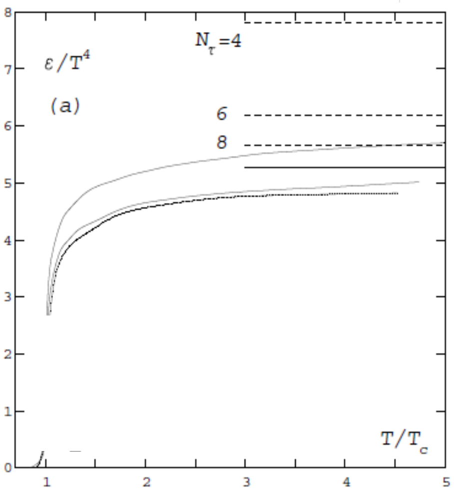
1.) more precise lattice QCD calculations for the case of formation out of equilibrium

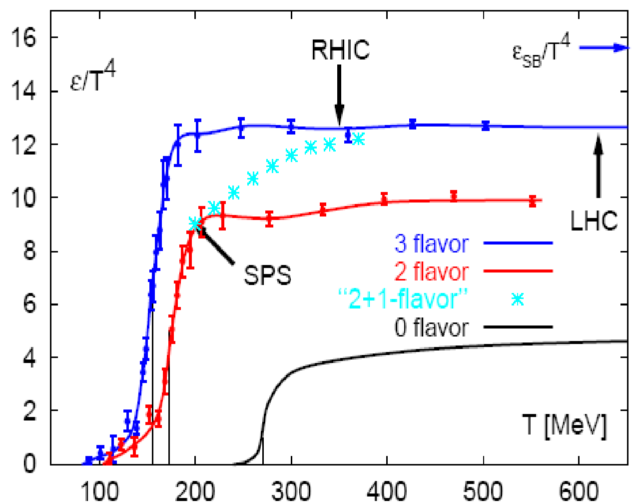
2.) a better understanding of fragmentation (non-equilibrium formation)

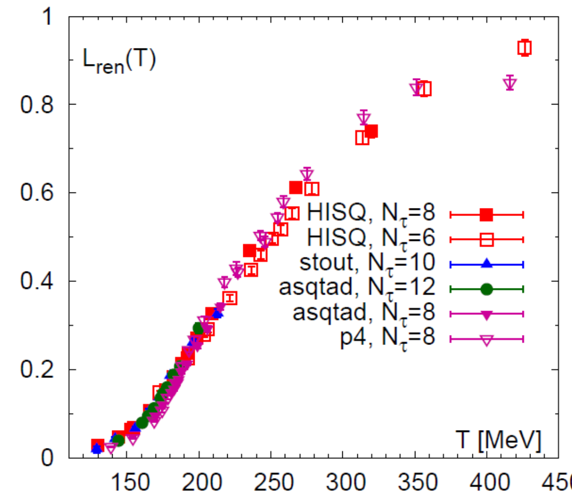
3.) better data from RHIC and LHC to follow formation as a function of time, temperature and particle momentum

What happened to the QCD phase transition (in lattice QCD) over the past decades ?

80's	90's	> 2004
from 1st order	to 2nd order	to crossover







Main reasons: continuous improvements in lattice spacing (continuum limit) and realistic quark mass ratios (pion mass).

Are order parameters still order parameters ?

Is an inflection point equivalent to a critical temperature ? (and if so, what happens between the inflection point and the weak coupling limit) ?

Is an order parameter still an order parameter ?

<u>The long list of QCD order parameters:</u>

Chiral condensate (chiral symmetry)

Polyakov Loop (deconfinement)

Trace Anomaly (interaction strength)

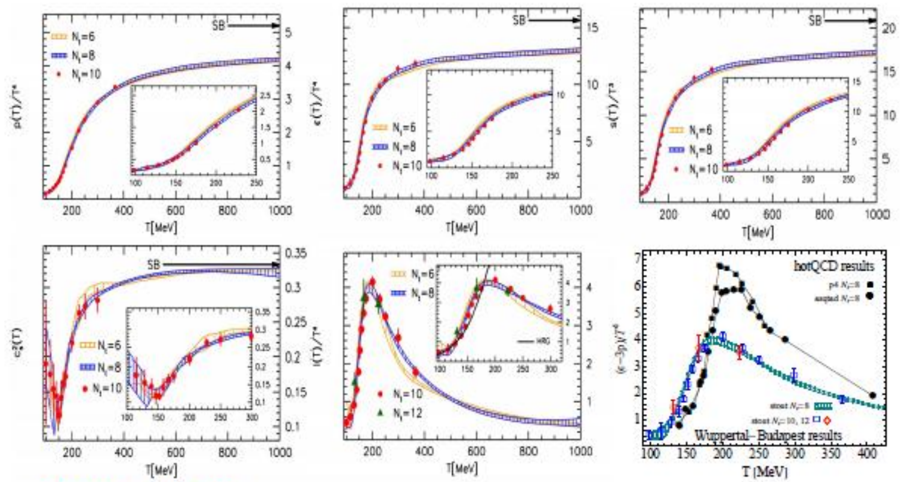
Quark Correlators (interaction or binding)

Susceptibilities (interaction strength)

Energy Density

Entropy

Pressure



S. Borsanyi *et al.*, 1007.2580

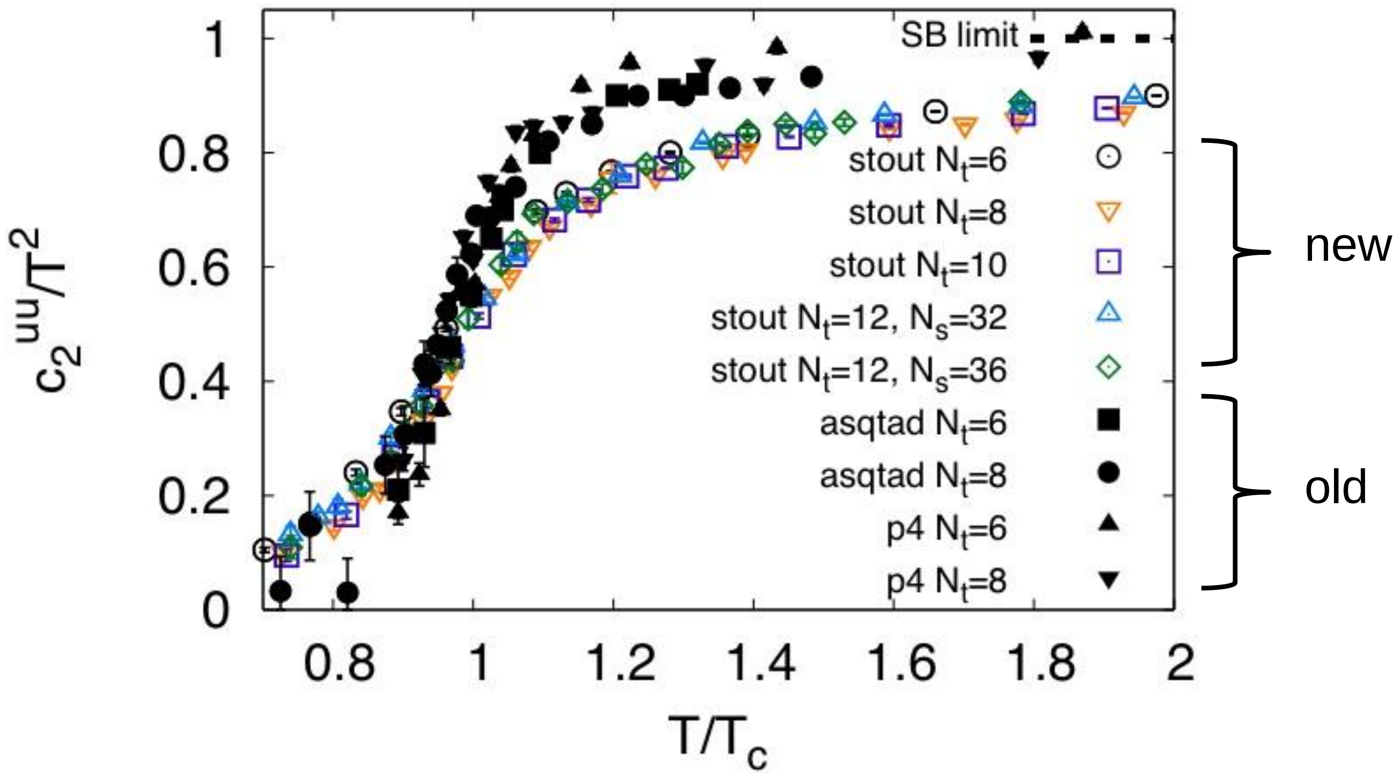
<u>Lattice approach: the multitude of parameters tell (more or less) the same story</u>

list of pseudocritical temperatures (various observables)

	$\chi_{\bar\psi\psi}/T^4$	$\Delta_{l,s}$	$\langle\bar\psi\psi\rangle_R$	χ_2^s/T^2	ϵ/T^4	$(\epsilon\text{-}3p)/T^4$
WB'10	147(2)(3)	157(3)(3)	155(3)(3)	165(5)(3)	157(4)(3)	154(4)(3)
WB'09	146(2)(3)	155(2)(3)	-	169(3)(3)	-	-
WB'06	151(3)(3)	-	-	175(2)(4)	-	-

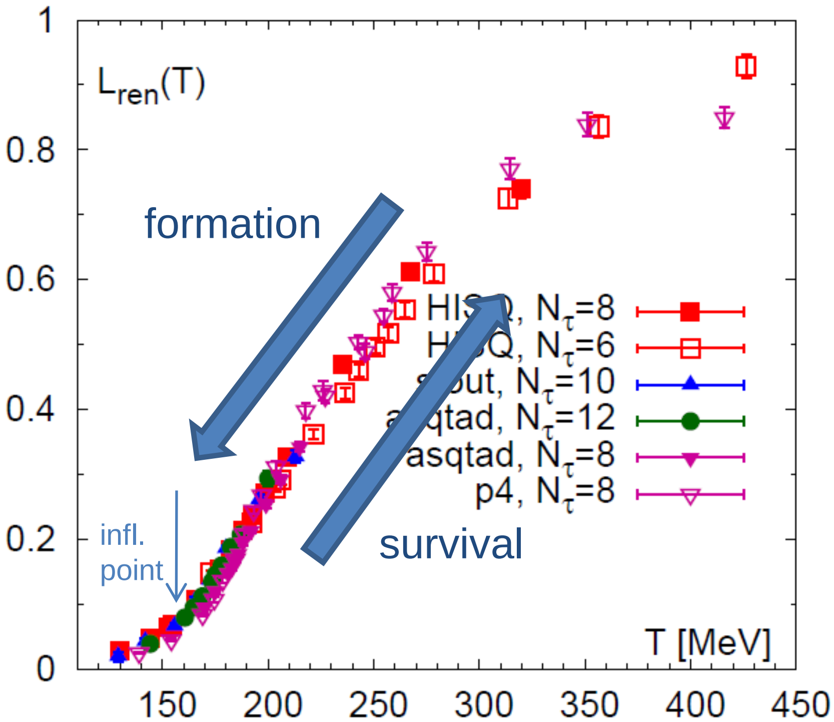
Evolution of the phase transition as a function of finer lattice spacing & realistic quark masses

(the cross-over becomes smoother = a longer mixed phase ?)



Are there bound states above T_c ?

- Survival or formation – a question of perspective
- The deconfinement order parameter in lQCD: Polyakov loop



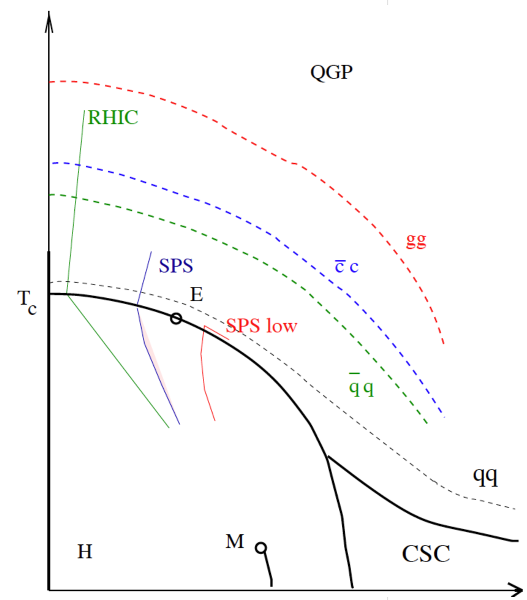
Bazavov et al., arXiv:1105.1131

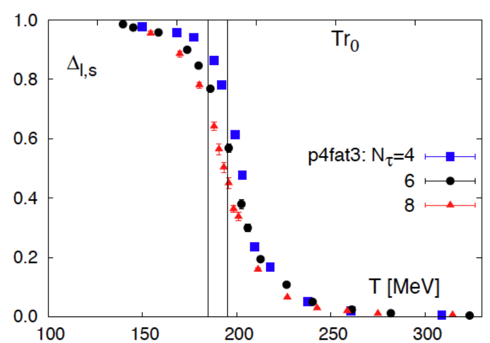
- Low energy collisions (AGS, SPS, RHIC scan, FAIR): survival of resonant states
- High energy collisions (RHIC, LHC): formation of pre-hadronic states

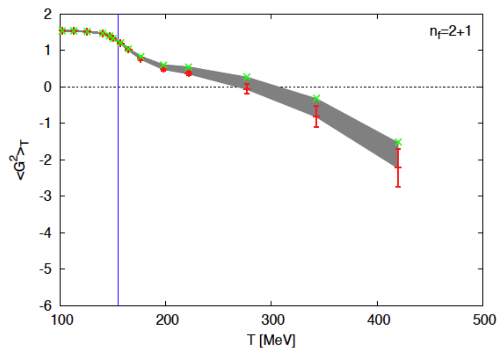
Are there bound states above T_c ?

<u>A long standing question in the literature</u>

- Survival: Rapp et al. (arXiv:0901.3289) – chiral symmetry restoration signatures in the transition region (mass shifts, width broadening, Brown-Rho scaling, etc. of surviving resonant states in particular of heavy quarks)



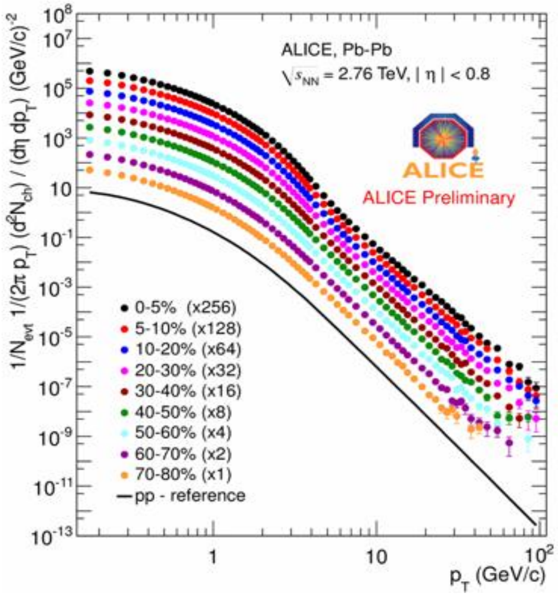




- Formation: Shuryak (PRD 70 (2004)054507) – colored bound states. Leads to phase diagram with differing quark condensates

Why distinguish between equilibrium and non-equilibrium ?

- There is plenty of evidence for two components in the particle spectra at RHIC and LHC. Breakdown of hydrodynamics at high pT, power law at high pT



- Two component model:

  soft (bulk, equil.) / hard (fragmentation, non-equil,)

- Kharzeev / Nardi scaling for yield: $\frac{dn}{d\eta} = (1-x)\, n_{pp} \frac{\langle N_{part} \rangle}{2} + x\, n_{pp} \langle N_{coll} \rangle$
- Levi-Tsallis fit for spectra (exponential + power-law):

$$\frac{d^2N}{dy dp_t} = \frac{(n-1)(n-2)}{nT[nT + m_0(n-2)]} \times \frac{dN}{dy} \times p_t \times (1 + \frac{m_t - m_0}{nT})^{-n}$$

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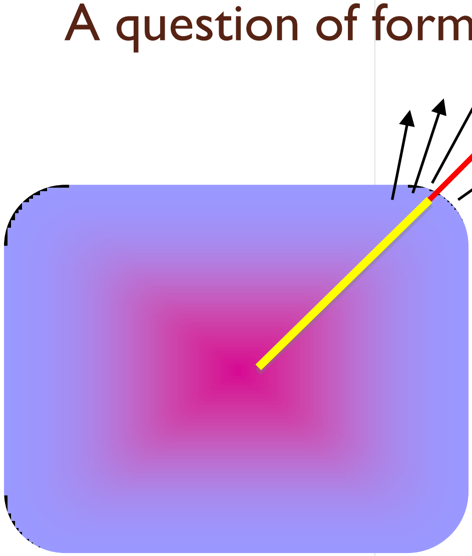
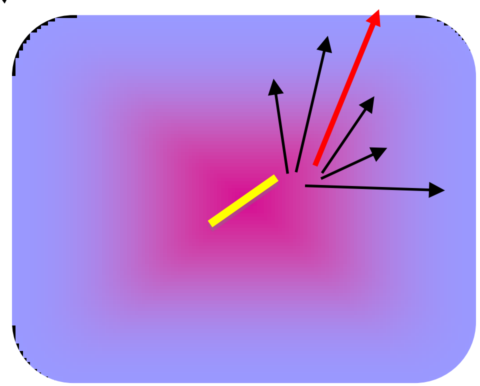
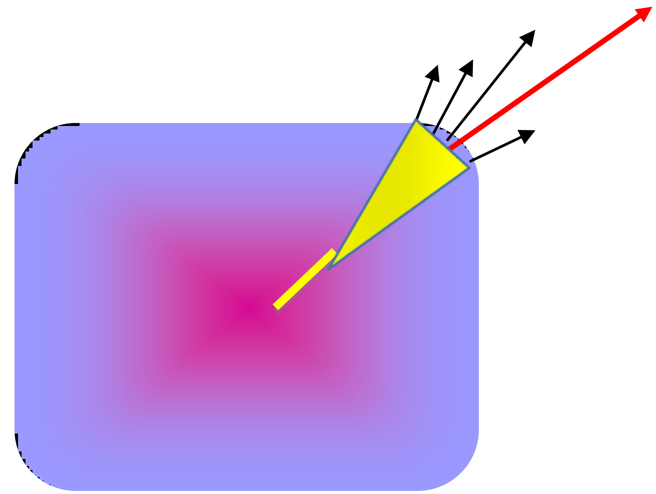
The non-equilibrium case – a high momentum probe in a deconfined medium
A question of formation time (RB & C. Markert, PLB 691, 208 (2010))



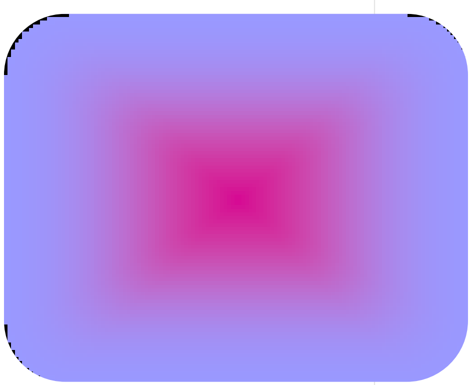
A parton traverses the medium and fragments outside



A parton fragments inside the medium



A parton converts into a pre-hadronic state or a quasi-particle which traverses the medium and fragments outside



The equilibrium case – particle formation out of the thermalized medium

A question for lattice QCD

(C. Ratti, RB et al., PRD 85, 014004 (2012))

The non-equilibrium case

Schematic Modeling of Hadronzation in medium

Bjorken (1976): The higher the energy and the lighter the final state, the later the hadron will form (inside-outside cascade) (Lorentz boost)

Kopeliovich (1979): A high z particle has to form early otherwise the initial parton loses too much energy (outside-inside cascade) (Energy conservation)

$$\tau_{\text{form}} = \tau_0 \frac{E}{m}$$

Inside-out cascade (boost)

τo ~ 1 fm/c : proper formation time in hadron rest frame
E : energy of hadron
m: mass of hadron   E/m = γ

→ high energy particles are produced later
→ heavy mass particles are produced earlier

$$\Delta y^+ \simeq \frac{1}{\Delta p^-} = \frac{zp^+}{m_h} \times 2 \left[m_h + \frac{\mathbf{k}^2}{(1-z)m_h} - \frac{zm_q^2}{m_h} \right]^{-1} . \quad (3)$$

The formation time then reads:

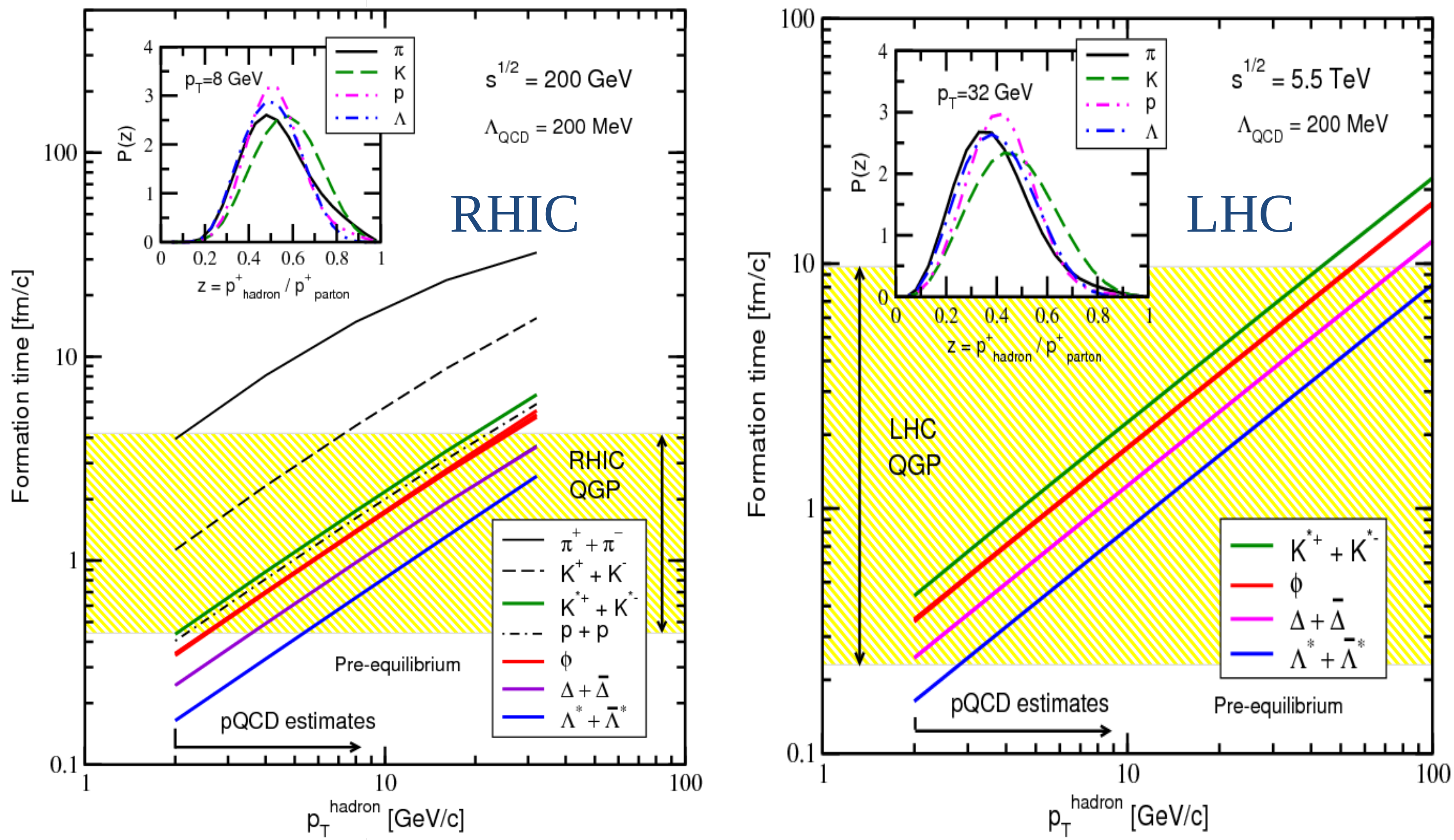
$$\tau_{\text{form}} = \frac{\Delta y^+}{1+\beta_q} , \quad \beta_q = \frac{p_q}{E_q} . \quad (4)$$

C. Markert, RB, I. Vitev (PLB 669, 92 (2008))

Outside-in Cascade (pre-hadron formation)

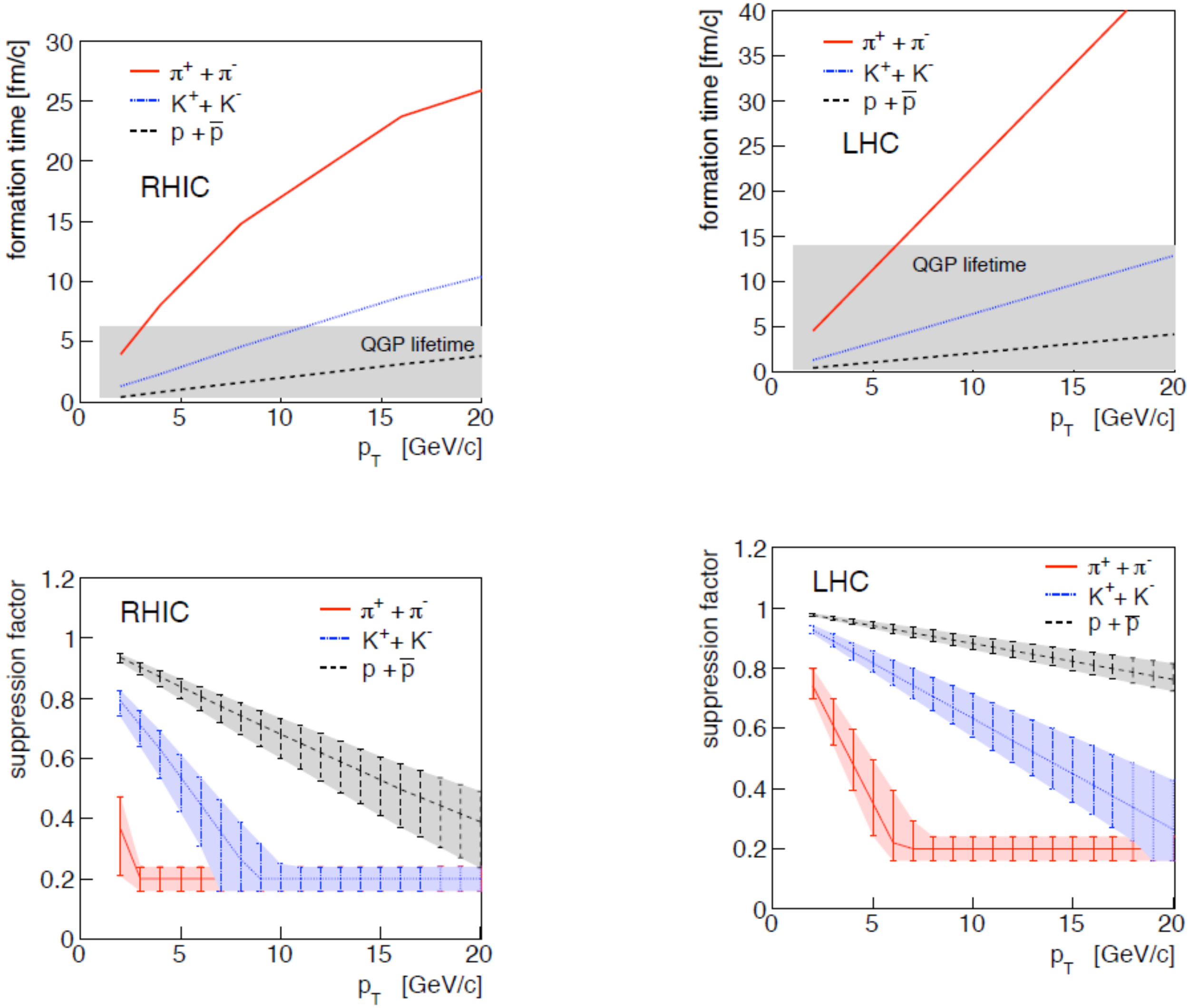
large z (=ph / pq) = leading particle
→ shortens formation time

Formation Time of Hadrons in RHIC / LHC QGP

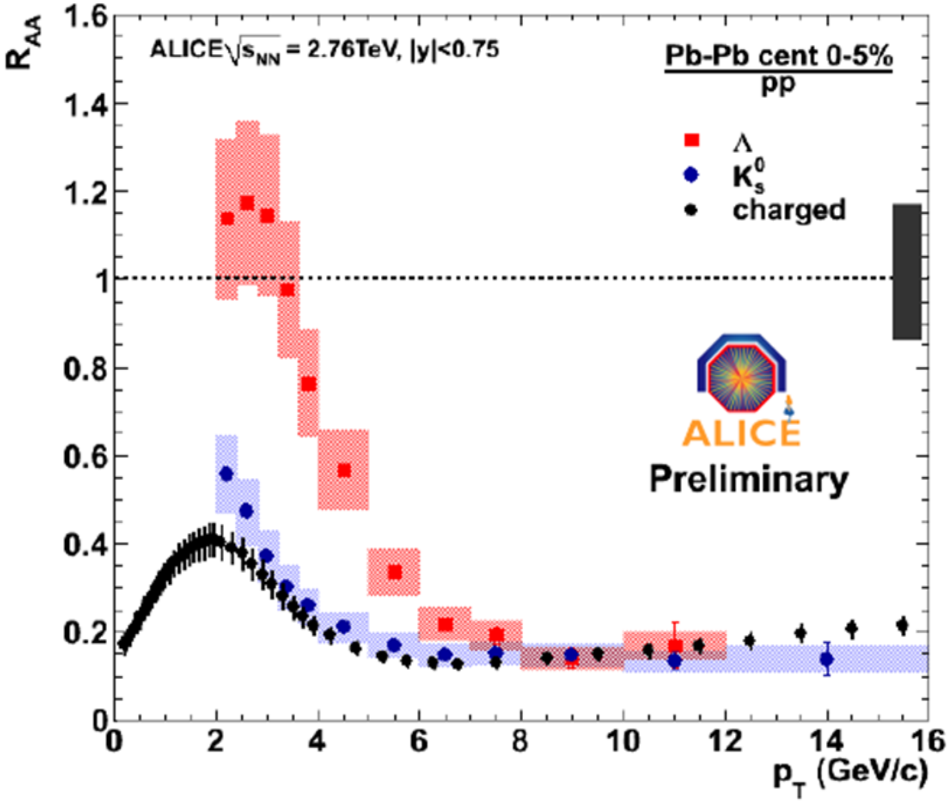


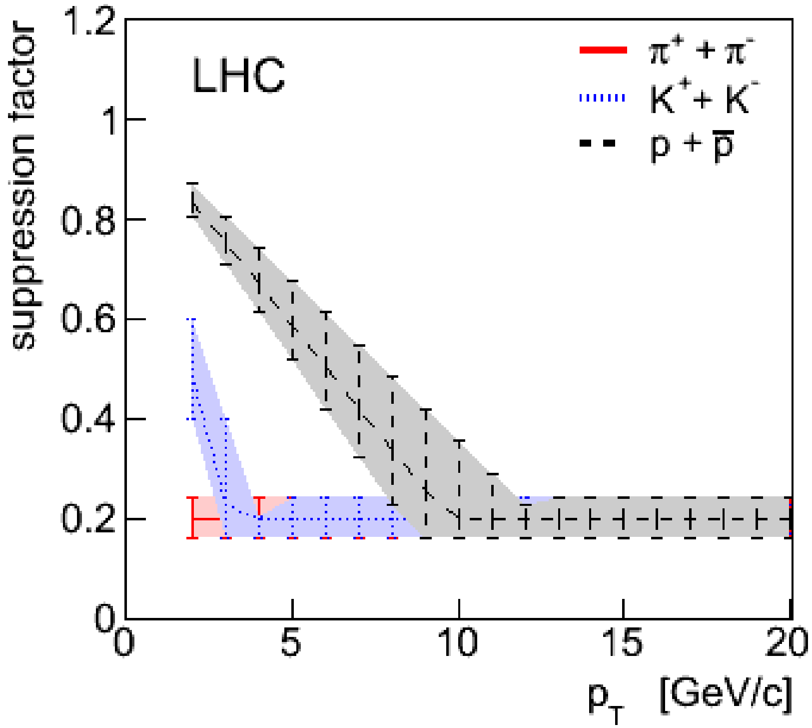
Predictions for energy loss

RB & C. Markert (PLB 691, 208, 2010))



Flavor dependence at the LHC





Data can be described with differing formation time for baryons and mesons, if one assumes rather short existence of pre-hadron in mixed phase (late formation)

Alternative: recombination

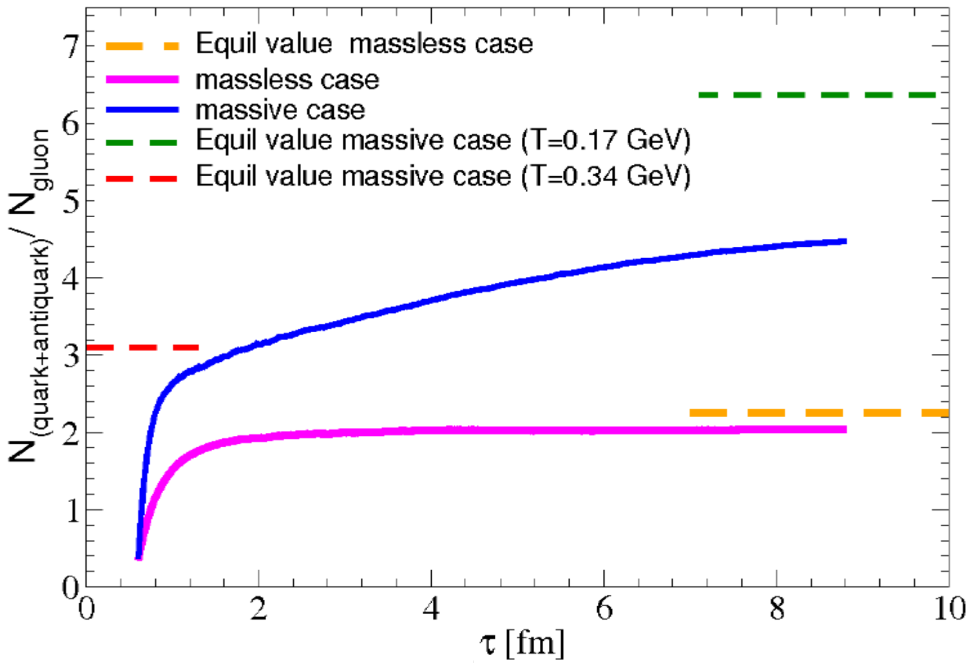
The equilibrium case

C. Ratti, RB, M. Cristoforetti , M. Barbaro

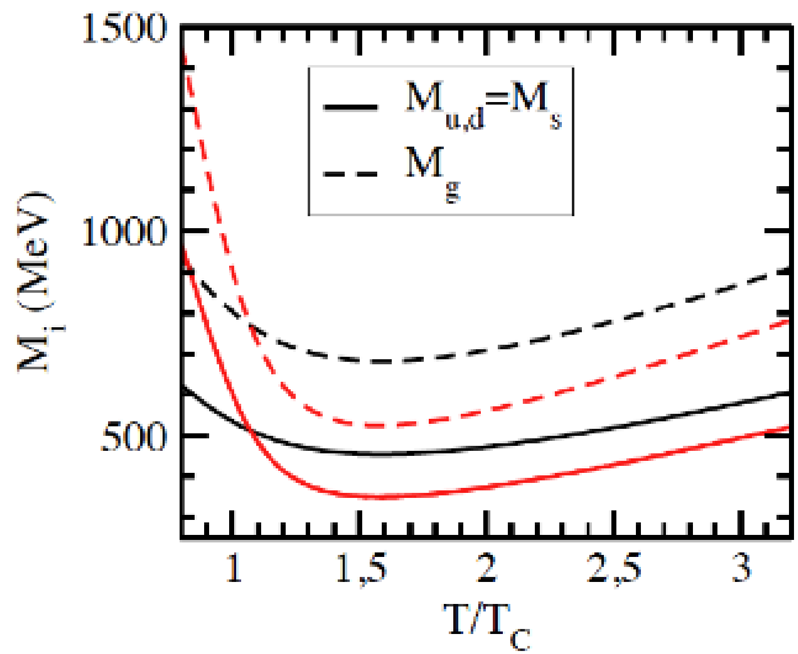
PRD 85, 014004 (2012) & arXiv:1109.6243

Is Lattice QCD the right approach ?

Greco et al., arXiv:1202.2262
No gluons near T_c

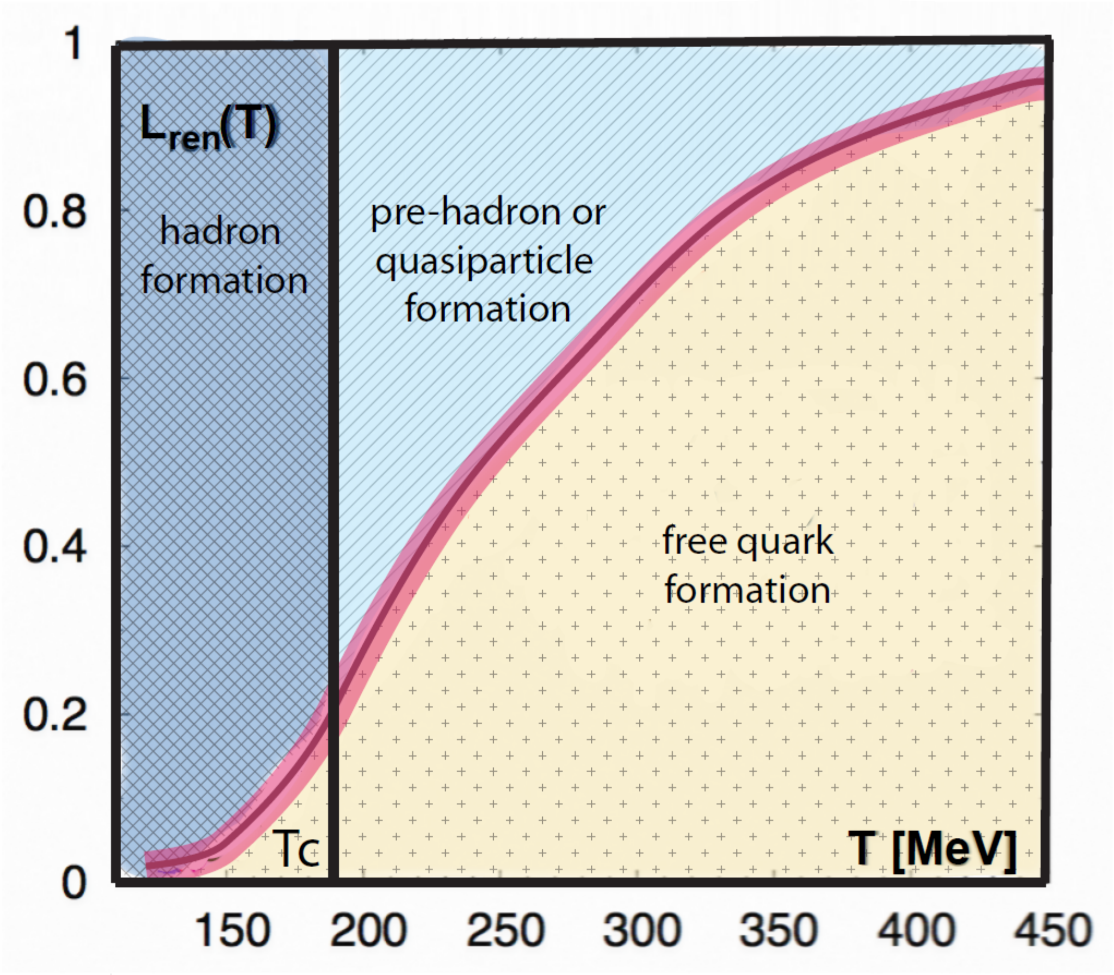


Ratti, Greco et al., arXiv:1103.5611
Evidence for massive states above Tc



Slight difference in temperature dependence of the quasi-particle masses for two lattice QCD actions

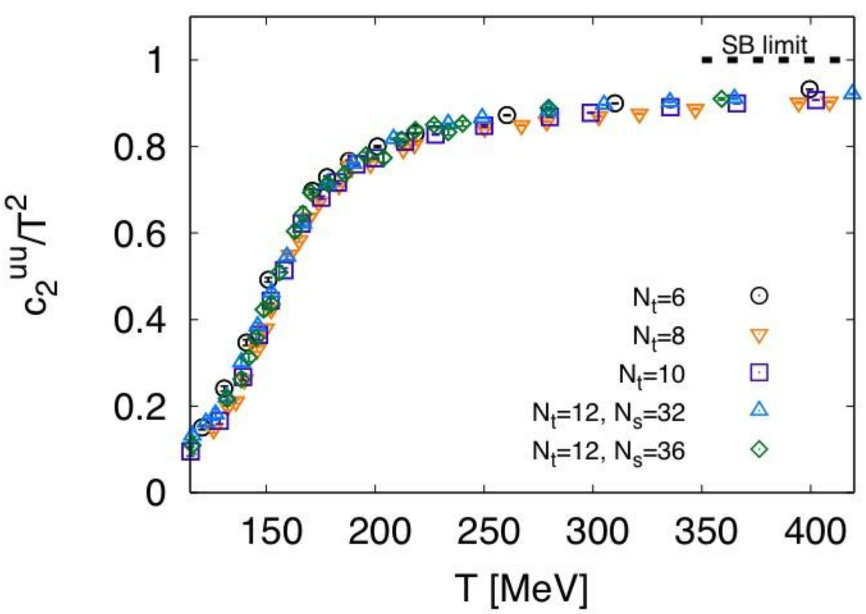
But could there be color-neutral bound states ?
A re-interpretation of the Polyakov Loop in lattice QCD
(measure of deconfinement)



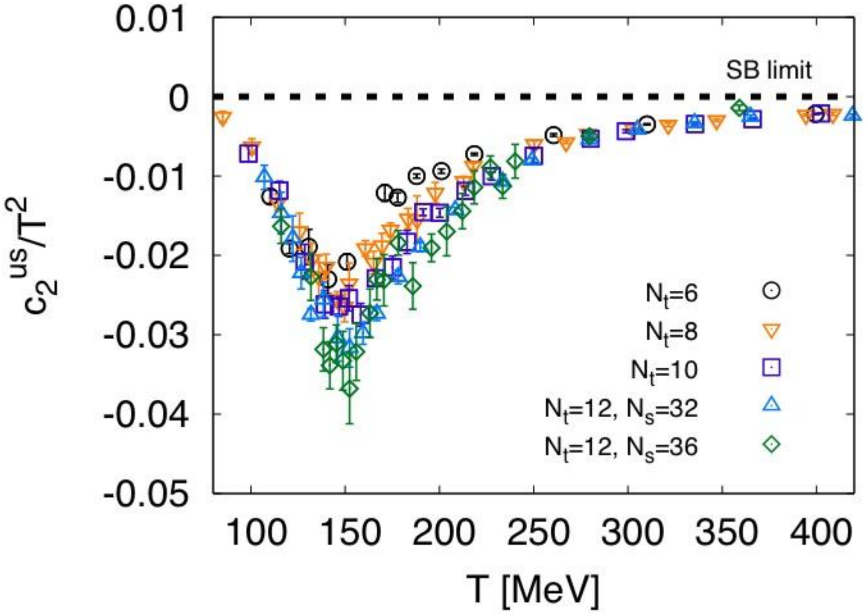
New lattice results: diagonal and non-diagonal correlators in limited T-range above T_c

(arXiv:1109.5030 & C. Ratti talk on Wednesday))

diagonal correlators

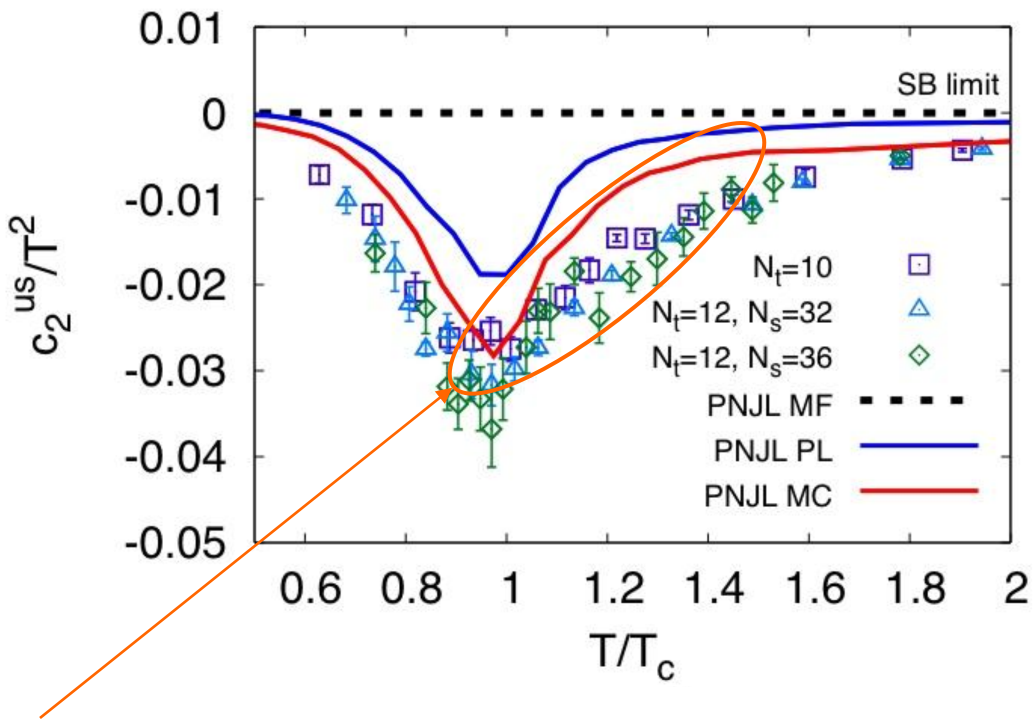


non-diagonal correlators



How much of this is due to fluctuations in the deconfined medium rather than bound states ?

Comparison of lattice to PNJL *(PRD 85, 014004 (2012))*



<u>PNJL variations</u>

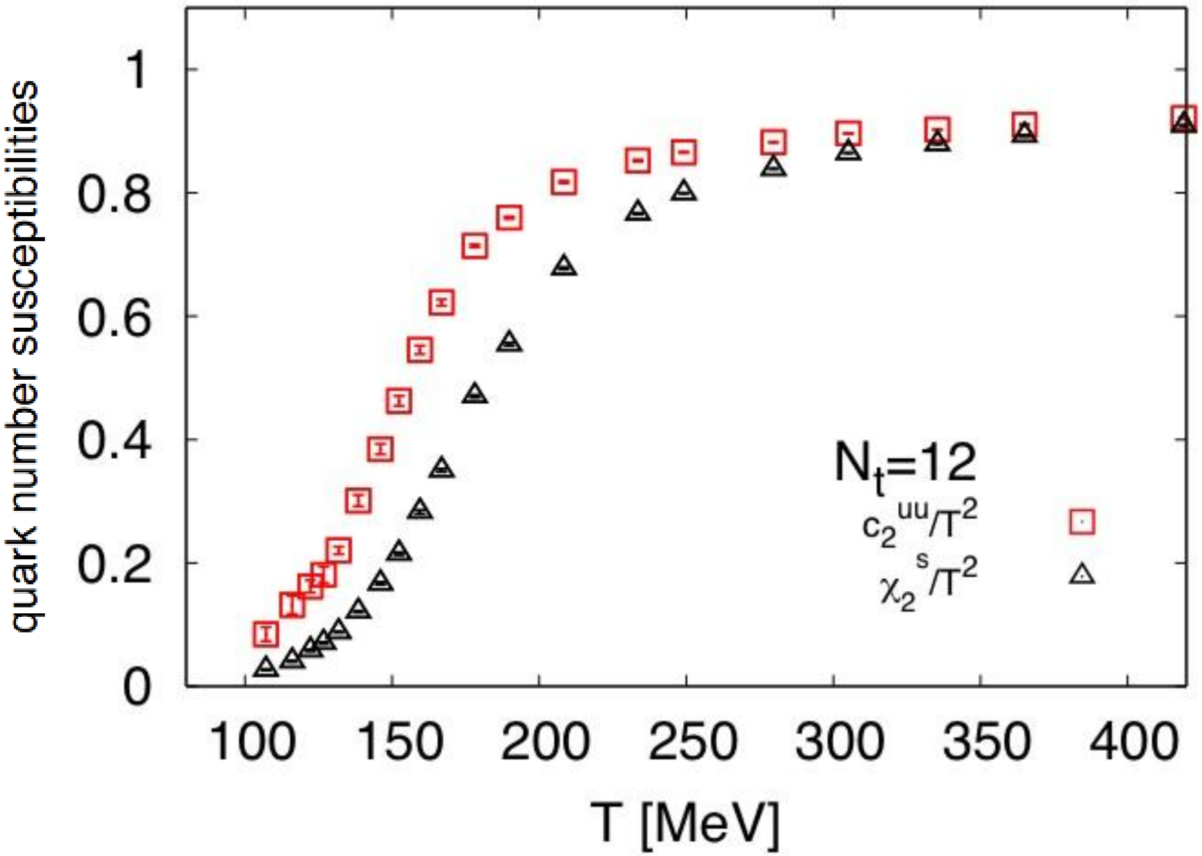
PNJL-MF:
pure mean field calculation

PNJL-PL:
mean field plus Polyakov loop fluctuations

PNJL-MC:
mean field plus all fluctuations (incl. chiral and Kaon condensate fluctuations)

Conclusion: even the inclusion of *all possible flucutations* is *not sufficient* to describe lattice data above Tc. *<u>There has to be a contribution from bound states</u>*

Properties of bound states above T_c: Flavor dependence even in the light sector

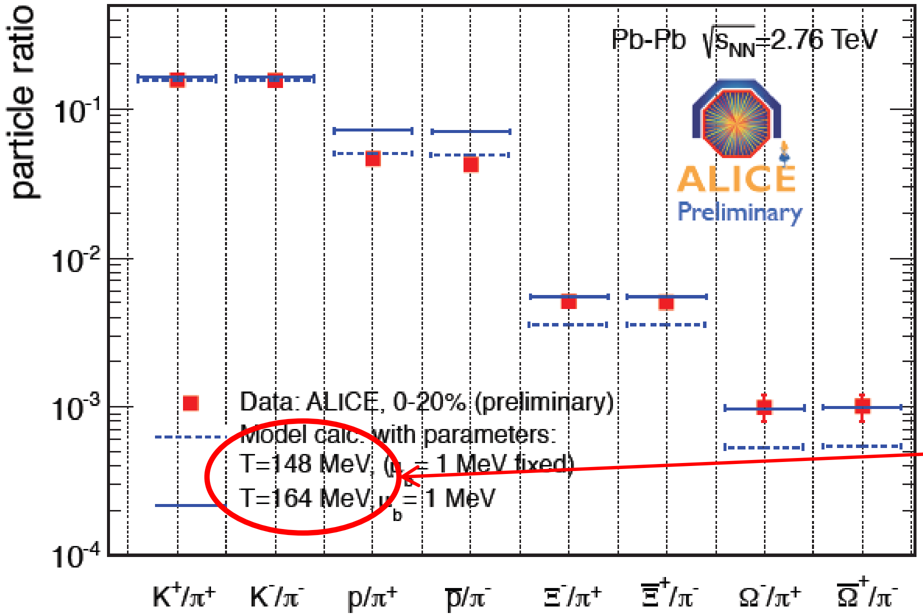


The heavier the quark the longer the mixed phase

More strange bound states than light bound states above T_c ?

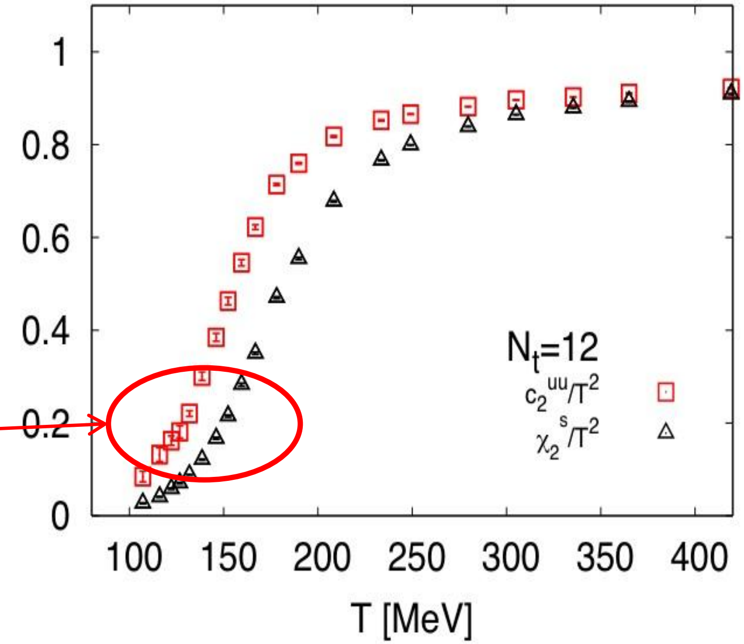
Potential evidence of flavor dependence in equilibrium freeze-out

Data: ALICE, SQM 2011

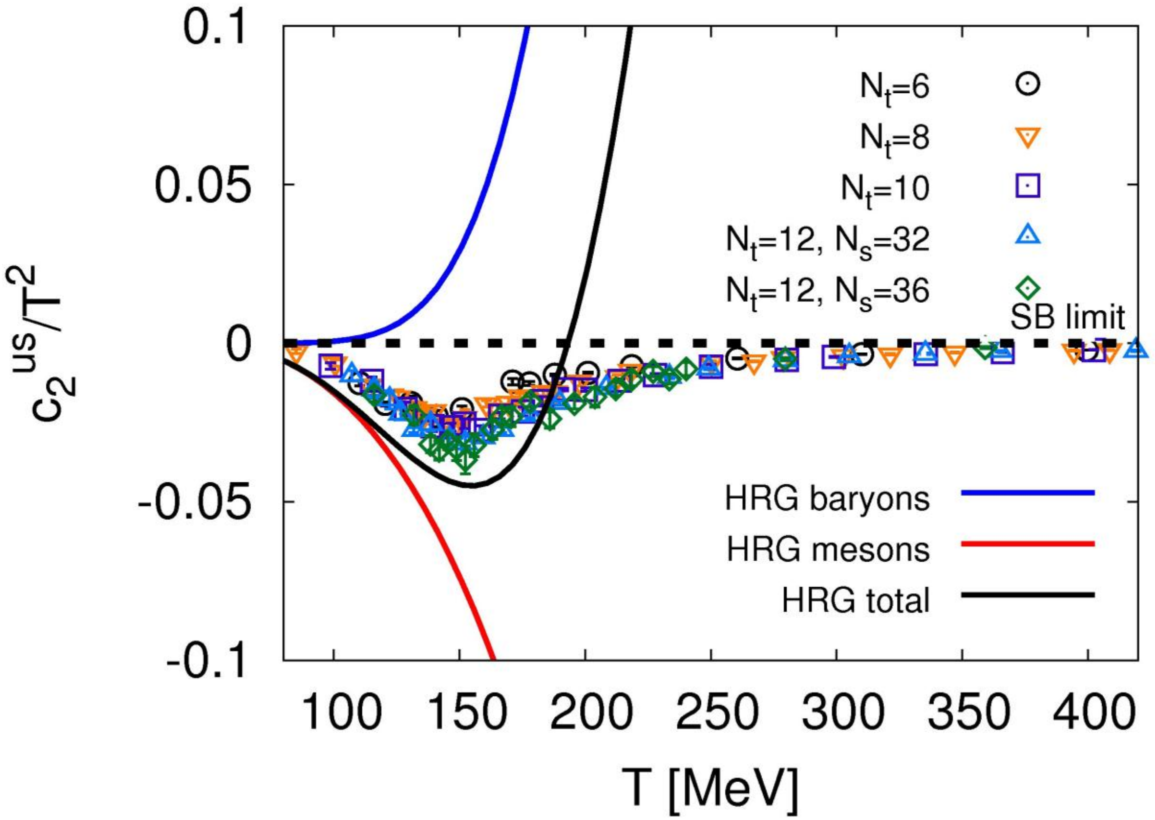


Model: A. Andronic et al., Phys. Lett. B 673:142-145,2009

Theory: Ratti et al., QM 2011



Properties of bound states above T_c: Baryon-meson dependence in correlator



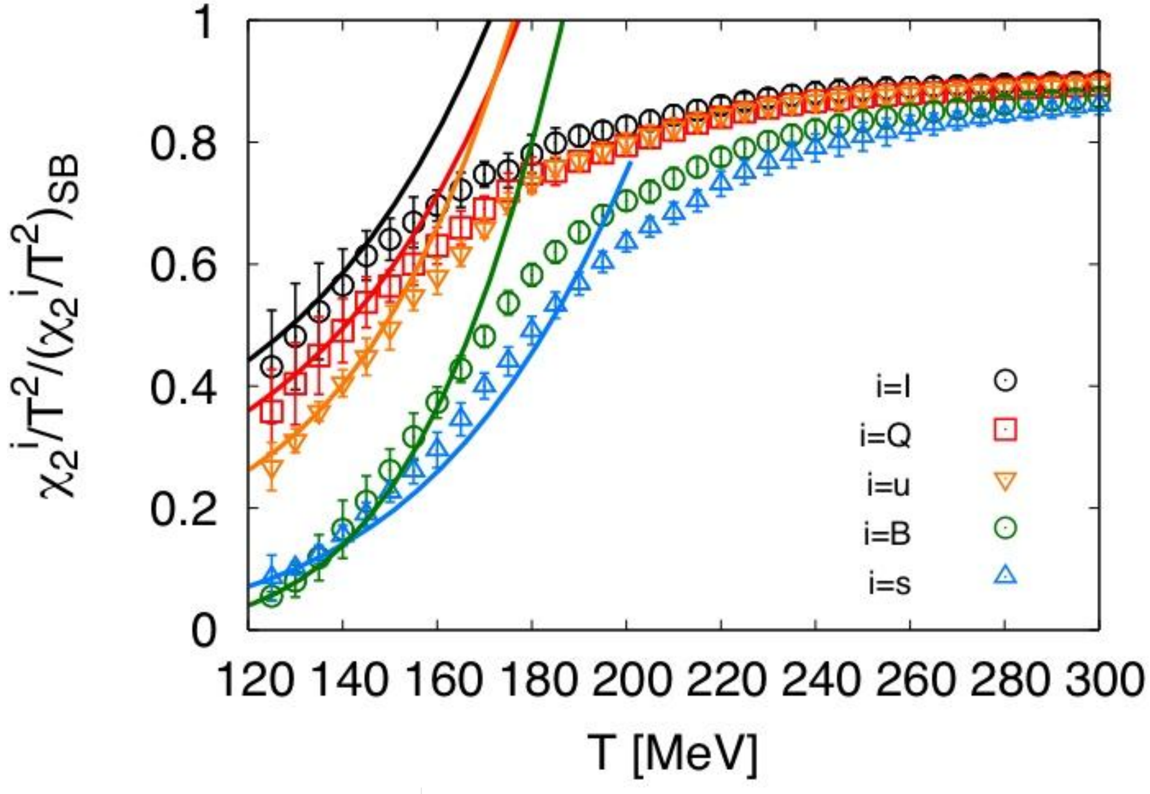
C. Ratti,
Hadronic resonance gas (HRG) calculation:

Baryonic bound states dominate at T>190 MeV.

Confirmed by lQCD:
S. Borsanyi et al., accepted at JHEP arXiv:1112.4416

Upswing in lattice correlator shows that baryon contribution rises with T, but the correlator never turns positive -> the contribution of bound states above T_c must be predominantly of mesonic nature until final deconfinement

Properties of bound states above T_c: Strange baryons form at higher T

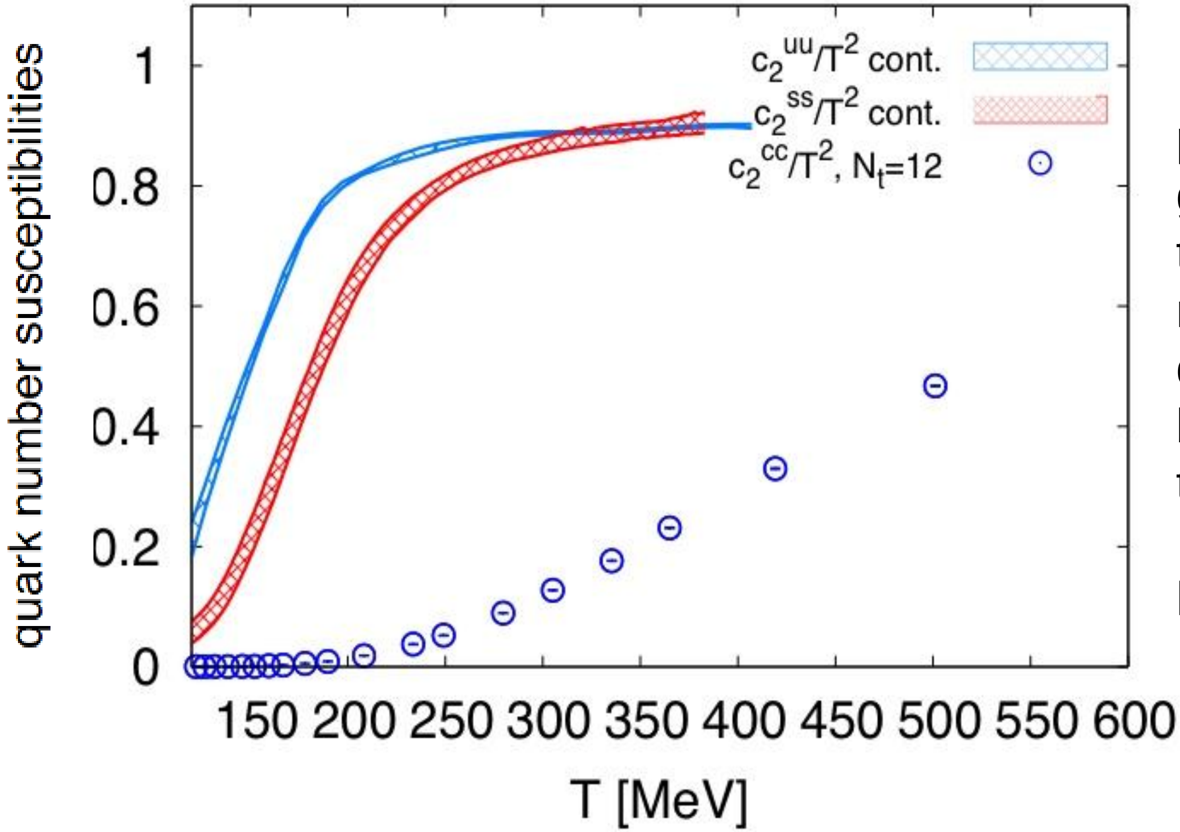


S. Borsanyi et al., accepted at JHEP arXiv:1112.4416

Strange baryonic bound states should form at higher T

The effect of mass on the correlator inflection point (T_c?)

S. Borsanyi et al.,arXiv:1204.0995



If not all heavy quark production is from initial gluon fusion but due to thermal production in the medium, then the heavy quark particle ratios will be sensitive to the transition temperature

Let's measure D/π or Λ_c/π

Summary

- There is evidence for flavor and mass dependent color-neutral bound state formation in the medium above the QCD phase transition based on lattice QCD *and* fragmentation studies. <u>*There is likely no common phase transition behavior (hadronization) for different flavor hadrons.*</u>
- A comparison of lattice QCD to HRG and PNJL calculations allows us to quantify the relative abundance of the confined and deconfined states in the equilibrated mixed phase around the critical temperature as a function of T. SHM for different particle species might be sensitive to transition temperature.
- Experimental studies of p_T, width, mass broadening, nuclear suppression, yields and ratios of identified particles and resonances give us a unique tool to answer fundamental questions of hadron formation.