6 th International Conference on Physics and Astrophysics of Quark Gluon Plasma
6 – 10 December 2010
Goa, India

The formation of hadrons inside the deconfined matter at RHIC & LHC

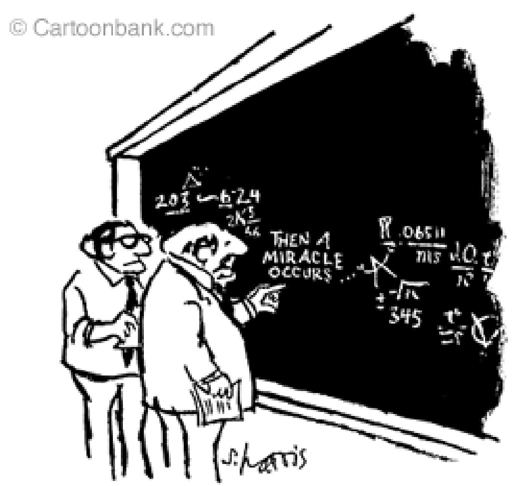
Rene Bellwied
University of Houston

with Christina Markert
University of Texas at Austin

Phys. Lett. B669, 92 (2008) = arXiv:0807.1509 (w. Ivan Vitev)
Phys. Lett. B691, 208 (2010) = arXiv:1005.5416

The fundamental questions

- **How do hadrons form ?**
  - Fragmentation or recombination
  - An early color neutral object (pre-hadron) or a long-lived colored object (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."

Not addressed by HEP because it is non-perturbative and can not be calculated

Fragmentation, Factorization

‘partonic’ energy loss

- Formation time is largely ignored in heavy ion collisions.
- Based on the simple Lorentz boost argument, which is insufficient for in-medium fragmentation, it was concluded early on that only colored partons will traverse the system and only fragment outside the medium i.e. in vacuum. This makes the energy loss calculation much easier.
- All energy loss models (ASW, AMY, GLV) are based on purely partonic energy loss, either collisional or radiative energy loss.
- Greiner, Gallmeister, Cassing (Phys. Rev. C67, 044905 (2003)) suggested early hadronization and hadronic energy loss.

The principle: a question of time

- There is per-se no reason to believe that a process such as fragmentation, which does not thermalize with the system (i.e. the surrounding medium), would take more or less time in-medium than in vacuum. (Almost true, see below).
- One could use in-vacuum formation time.
- Two aspects in-medium:
  - Lorentz boost: the higher the energy the longer the formation time (inside-outside cascade (Bjorken 1976))
  - Energy conservation: the higher the fractional momentum the shorter the formation time (since partons lose energy through bremsstrahlung in medium). (outside-inside cacsade (Kopeliovich 1992))
  - But the early formed hadron can not have a fully developed wave function because of the uncertainty principle = pre-hadron (quark content fixed but not all properties fixed)

Modeling of hadronization: Combining inside-out & outside-in in light cone variables

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

Inside-outside 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:

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

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

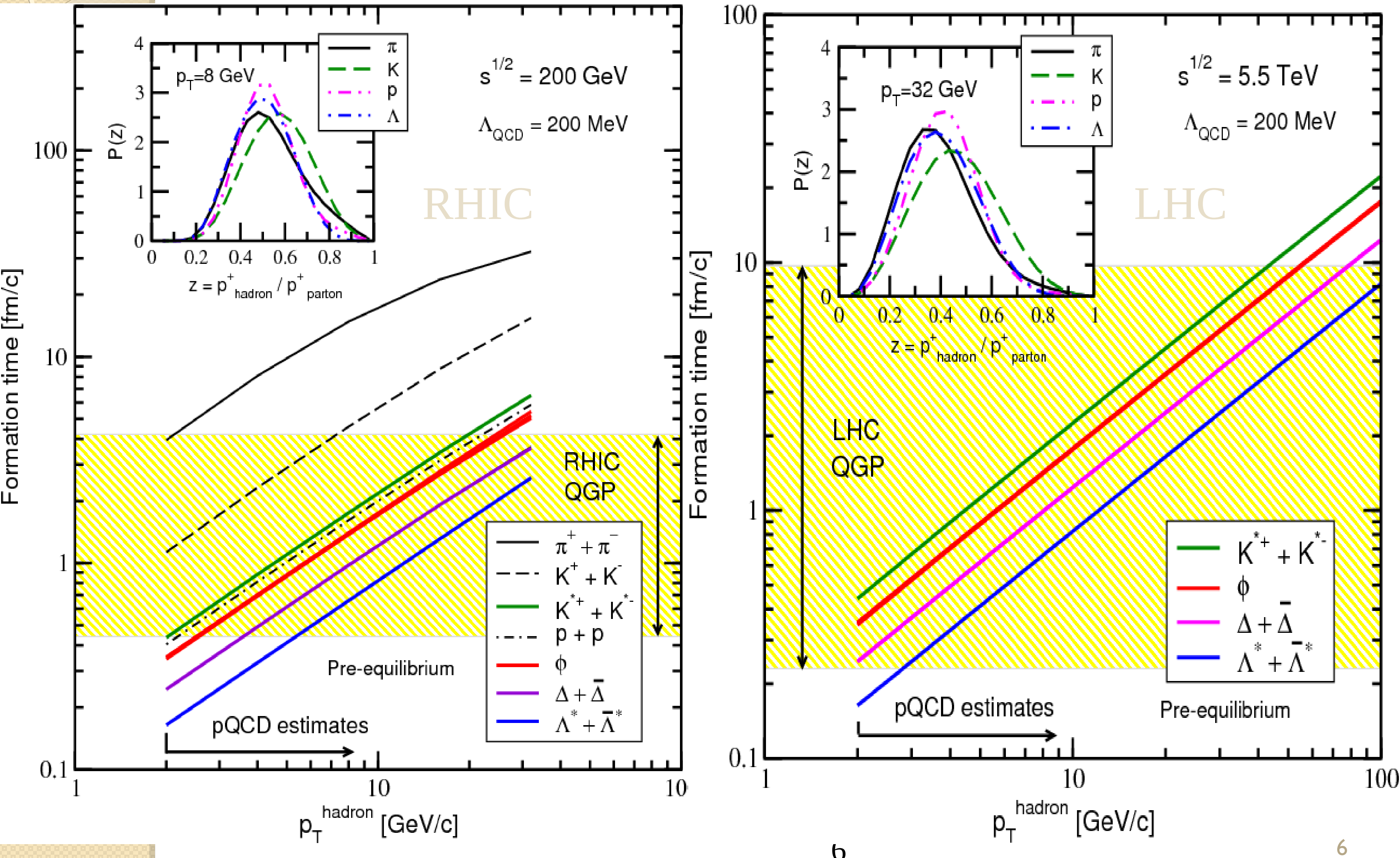
Outside-inside Cascade (pre-hadron formation)

large z (=ph / pq)

→ shortens formation time

5

Formation Time of Hadrons in RHIC / LHC QGP
(C. Markert, RB, I. Vitev, 0807.1509)



Two questions of increasing complexity – (1)

- What sets the scale in our light cone variable approach ?

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

The formation time then reads:

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

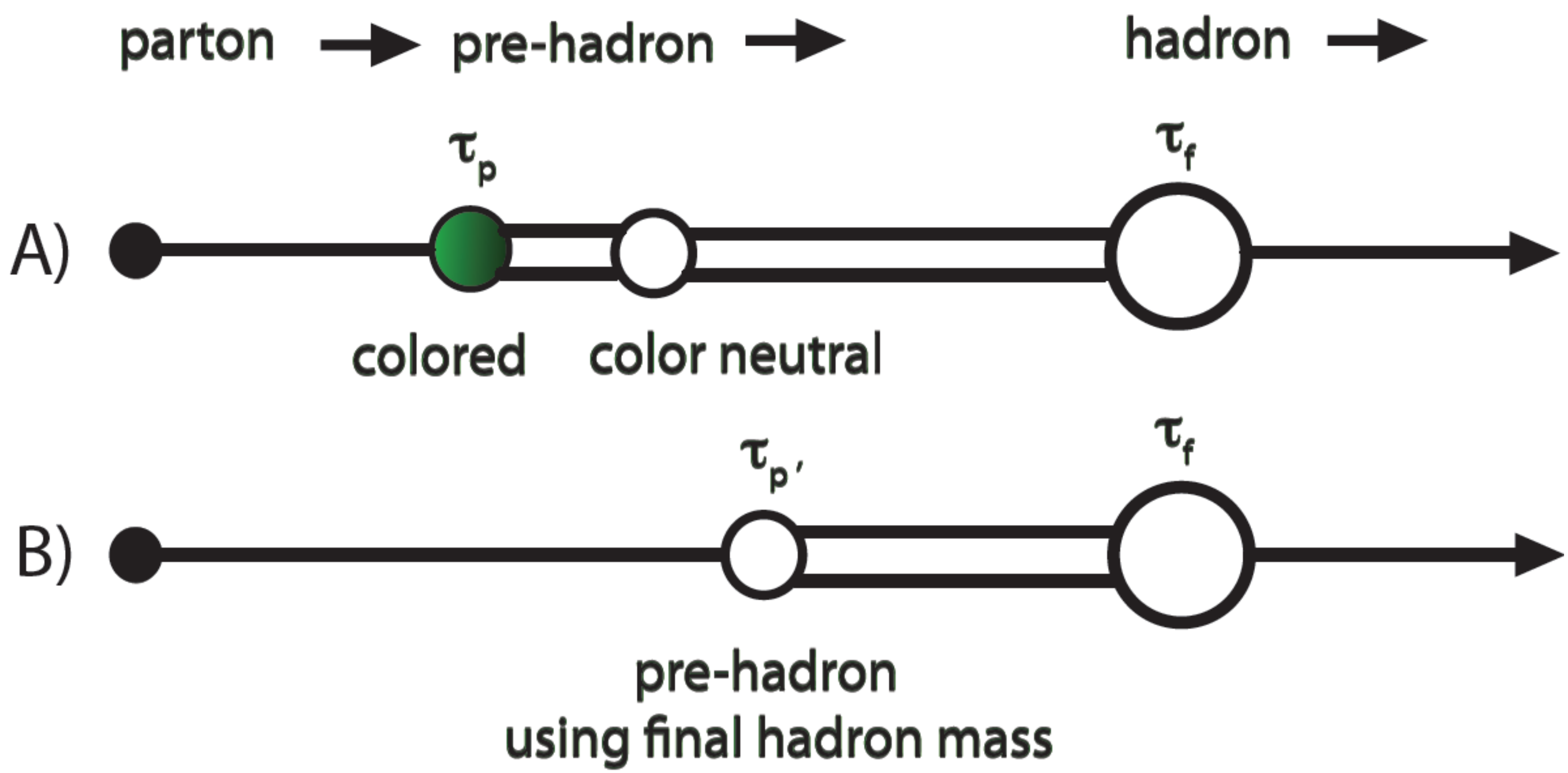
- The mass. Which mass ? Final hadron mass

(i.e.coherence length instead of formation time ?, (see Kopeliovich, arXiv:1009.1162))

Brodsky and Mueller (1988)

- First time distinction between τ_p (production time) and τ_f (formation time). Production time determines production of co-moving constituent quarks.
- Since all quark configurations are possible the order parameter becomes the mass difference between all possible states of the same quark configuration.
- Kopeliovich: approximate by the mass difference between the ground state and the 1st excited state (resonant state), e.g. for the pion this time is considerably shorter than the time when taking the final hadron mass.
- RB & CM: taking the final hadron mass can approximate the formation time of the final hadron wavefunction.

Accardi (0808.0656) vs. our approach



Using the final hadron mass will increase the formation time since the final mass is smaller than the difference between the ground and excited states.

Two questions of increasing complexity – (II)

- Is the in-medium state colored or color neutral ?

  Kopeliovich, Accardi: color neutral DOF (pre-hadrons)

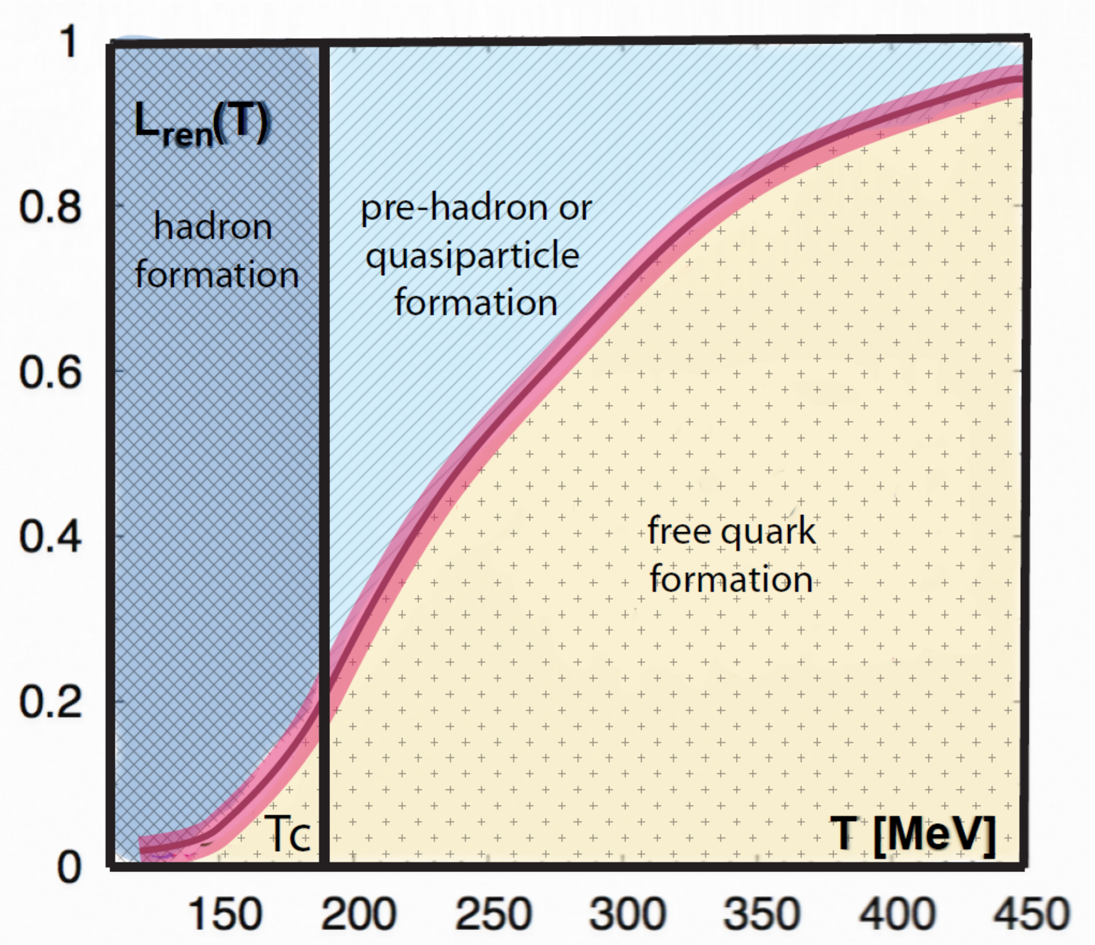
  Cassing et al.: colored DOF (quasi-particles)

- A colored object will continue to interact and not develop a hadronic wave function early on (constituent quark)
- A color-neutral object will have a reduced size and interaction cross section (color transparency) and develop wave function properties early
- Only a color neutral state can exhibit hadronic features

  (e.g. can pre-resonance decay prior to pion hadronization ?)

Does this make sense near the QCD phase transition ?

A re-interpretation of the Polyakov Loop calculation in lattice QCD



Color transparency
(P. Jain et al., Phys. Rep. 271, 67 (1996))

- An important concept in our paper, since it reduces (or eliminates) the interaction probability between color-neutral and colored objects.

- In the strictest sense only applicable to point-like configurations, i.e. directly produced color-neutral states from higher twist diagrams (Brodsky, Sickles).

- Kopeliovich showed that early produced objects (i.e. coalescing constituent quarks) also have reduced interaction cross section.

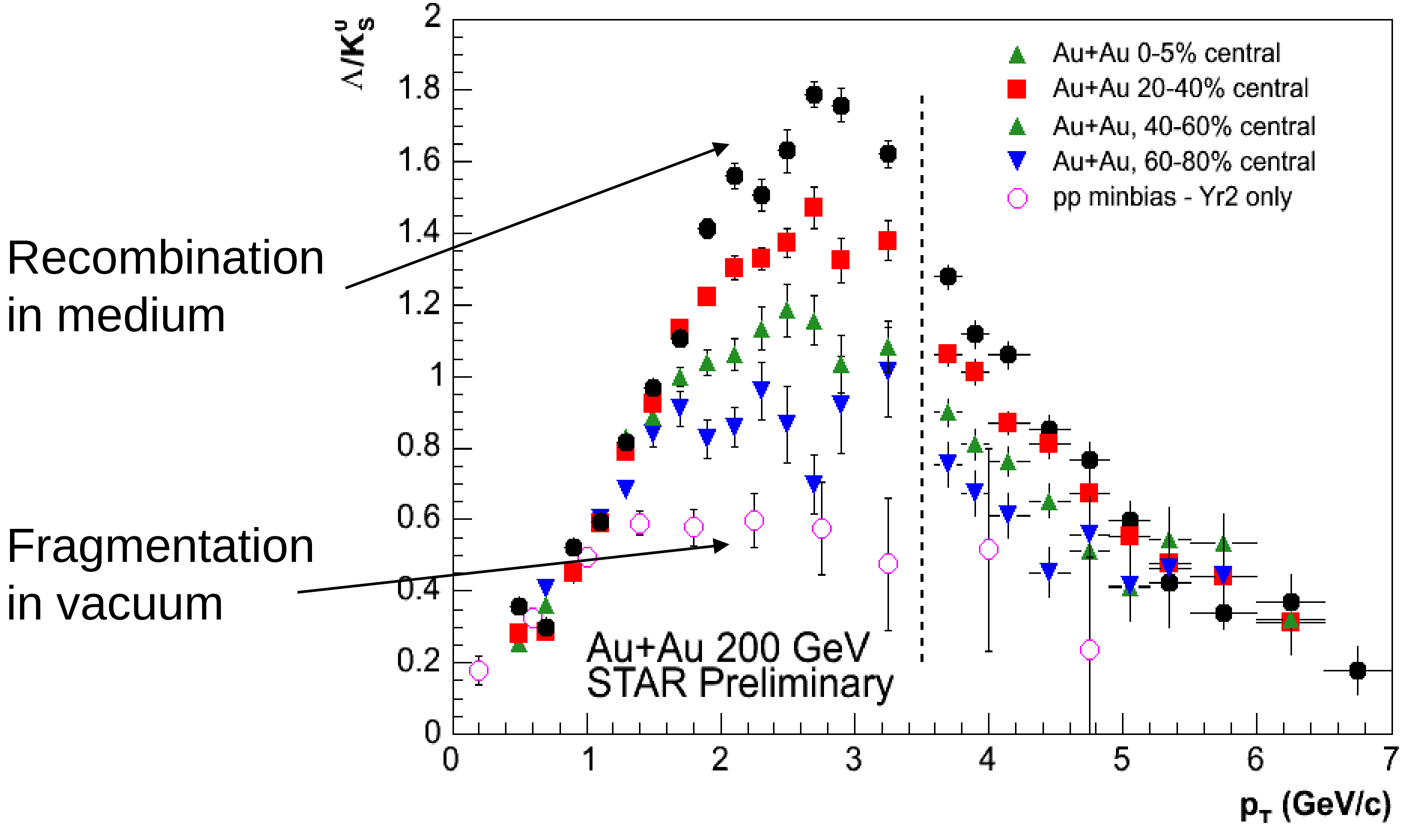
Experimental signatures

- Reduction in pT broadening due to color transparency in medium

- *Reduction in energy loss due to color transparency in medium of color-neutral pre-hadrons. Alternate explanation for high B/M ratio in intermediate to high pT range*

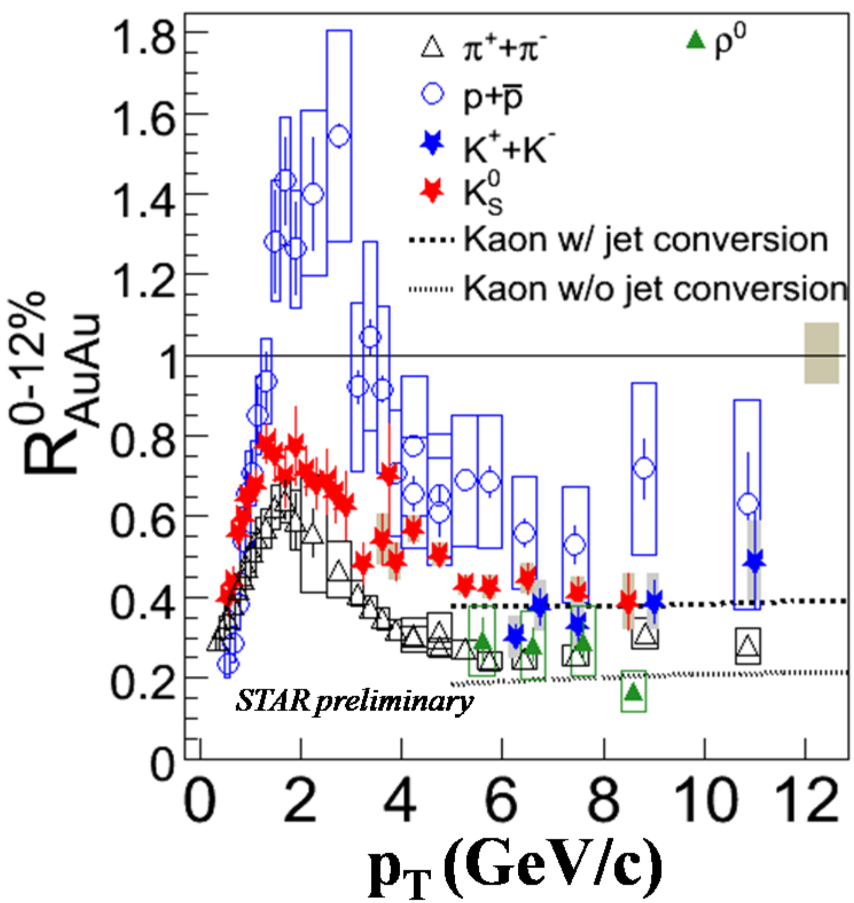
- Medium modification of early produced resonances due to chiral restoration

B/M ratio in AA can be attributed to recombination or to color transparency
(Sickles & Brodsky, PLB 668 (2008))



A directly (or early) produced proton (color-neutral) will undergo almost no rescattering, thus its high pT yield is enhanced relative to later formed mesons.

Nuclear suppression patterns in HI collisions become more complex



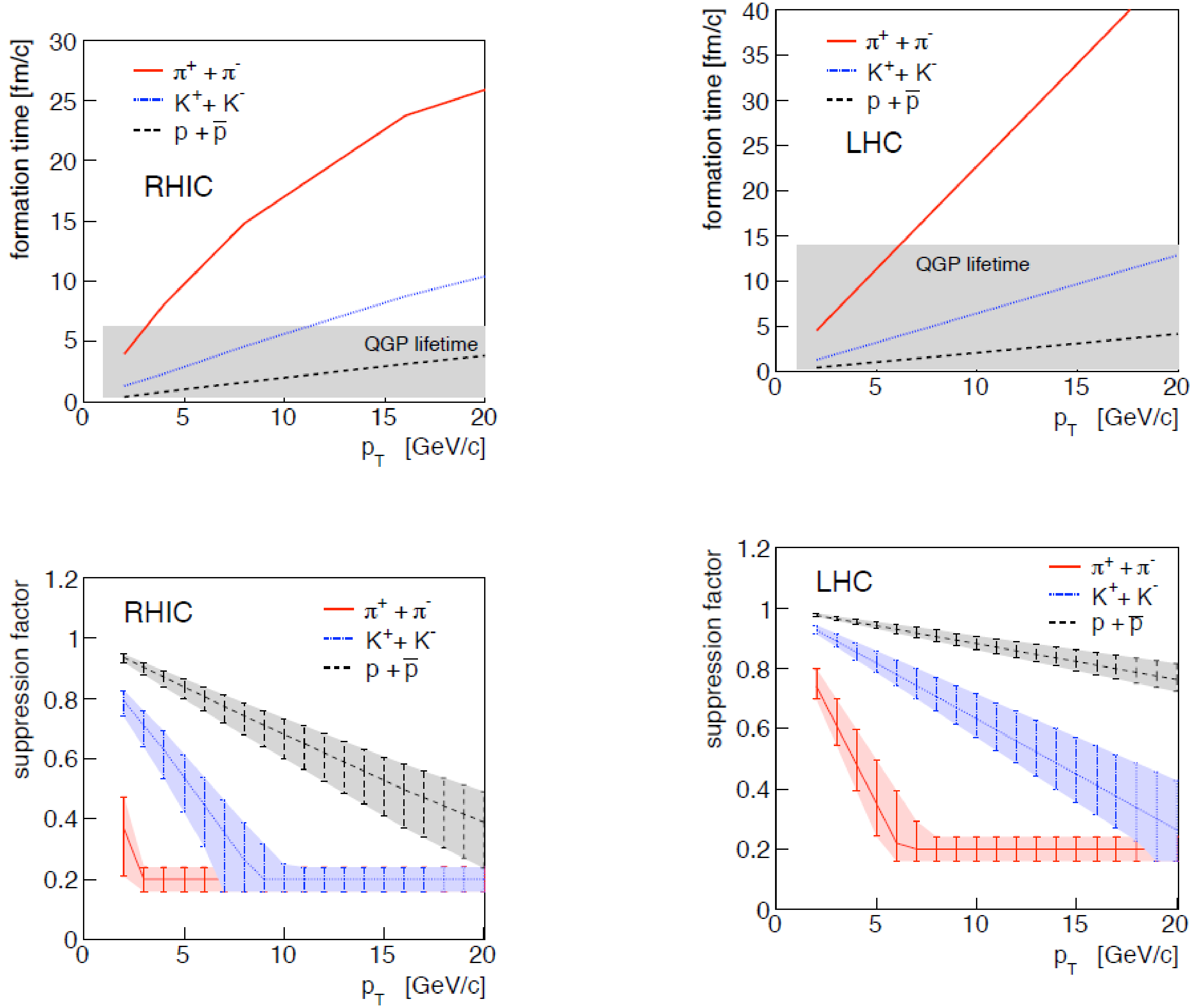
Ruan, Xu (STAR), SQM 2009

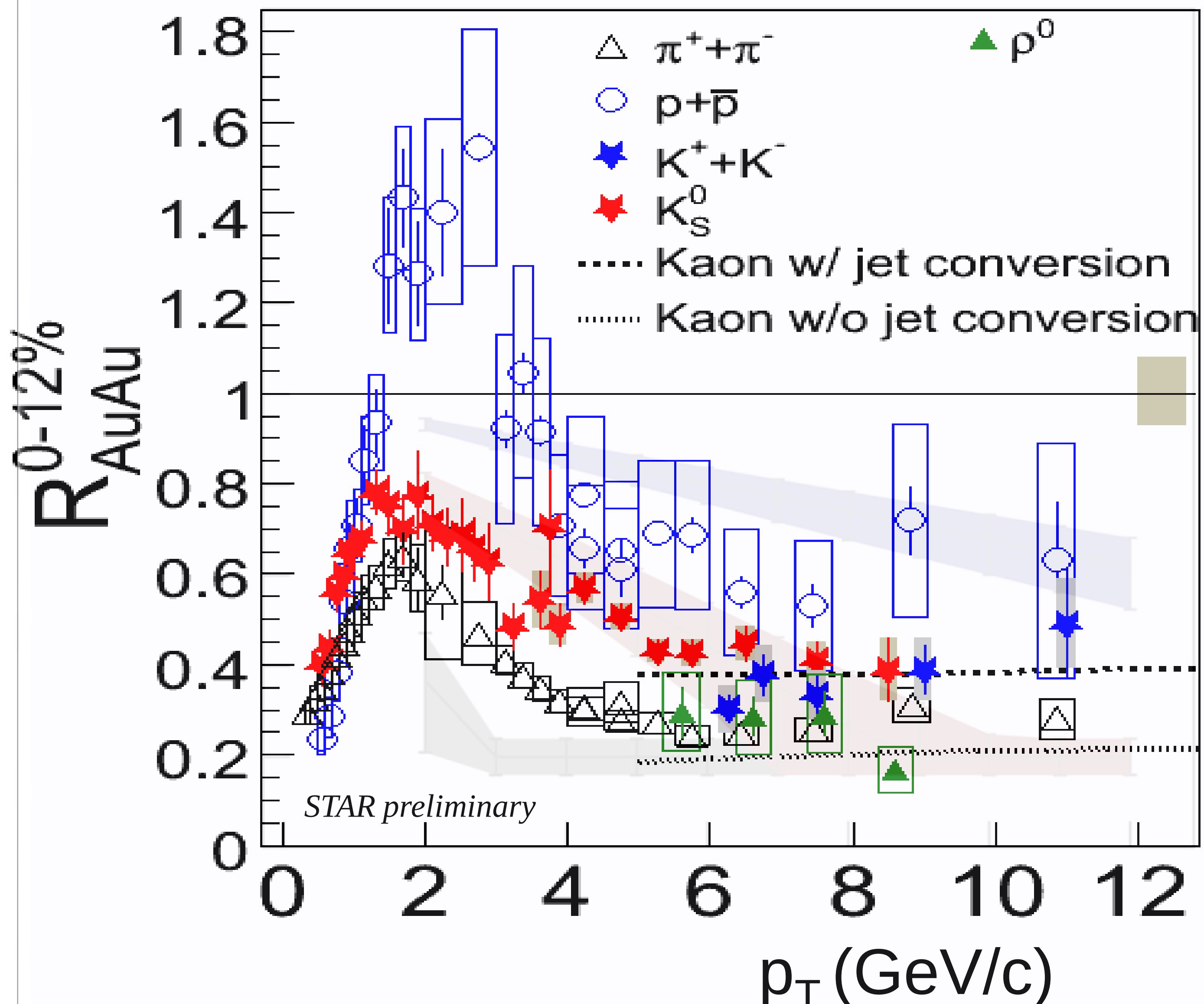
Surprising particle dependence in R_{AA} (hadro-chemistry or flavor change) ? This is not simple partonic energy loss.

Early hadronization or enhanced species dependent gluon-splitting factors (Sapeta & Wiedemann)

S&W use a parameter in their splitting probability that depends on the final hadron mass (ad-hoc parametrization)

Our predictions for energy loss





$R^{0-12\%}_{AuAu}$
$\pi^{+}+\pi^{-}$
$p+\bar{p}$
$K^{+}+K^{-}$
K^{0}_{S}
ρ^{0}
Kaon w/ jet conversion
Kaon w/o jet conversion
STAR preliminary
p_T (GeV/c)

Summary

- The question of hadronization in QCD is highly relevant for the evolution of the initial deconfined and chirally symmetric QCD phase.
- Studies of pT, width, mass broadening, nuclear suppression, yields and ratios of identified particles and resonances in the fragmentation/recombination region of their spectrum gives us a unique tool to answer these many decade old questions:
  - Is there local parton-hadron duality ?
  - Is hadronization due to recombination or fragmentation ?
  - Do color neutral objects form early and are they less likely to interact with the colored medium ?
  - When does the hadronic wave function (or mass) form ?
- The year-1 ALICE PbPb data (in particular R_{AA}) already indicate interesting differences in B/M ratio.