The Non-equilibrium Parton Matter
from a Multiphase Transport Model

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Mostly based on *arXiv:1403.6321*
= PRC 90 (7), 014904 (2014)

Only addresses partons within space-time rapidity $|\eta|<1/2$

Outline

- Motivation
- Constraining parameters of the AMPT-String Melting model
- Evolution of flow, densities and energy-momentum
- Evolution of extracted effective temperatures
- Over-population of partons
- Summary

Motivation

Use thermodynamic variables to describe
the bulk parton matter (*usually in non-equilibrium*) modeled by transport

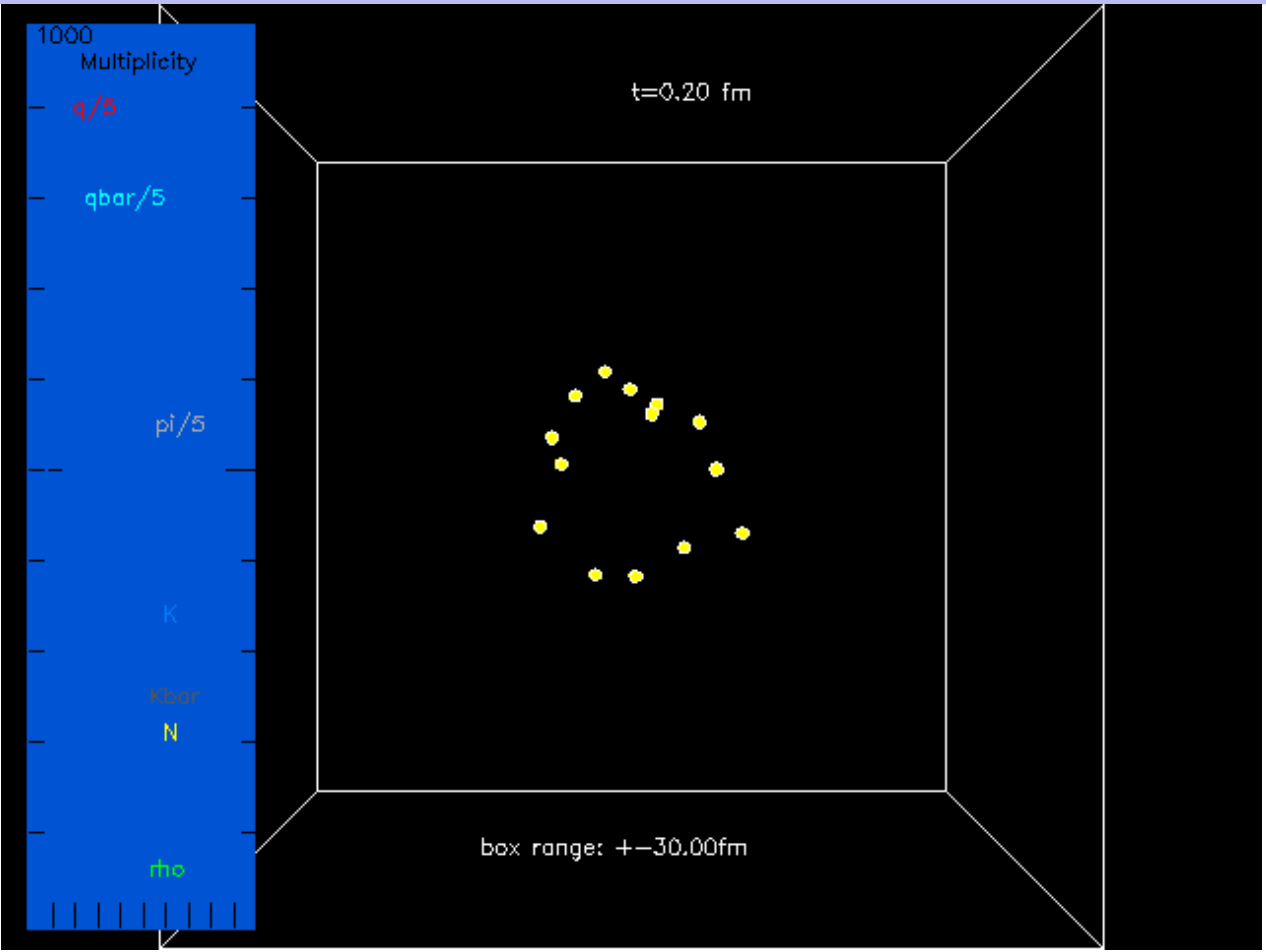
This provides a link between
transport model and

- Hydrodynamics
- Other studies that use thermodynamic variables (*T*, ε, ...) to model the physics:
  example: evolution of thermodynamic variables of the bulk parton matter

provides another soft background for jet quenching and energy loss studies.

Evolution data from this study have been posted at
http://myweb.ecu.edu/linz/ampt/evolutiondata/ ;
also linked at the JET Collaboration wiki page
https://sites.google.com/a/lbl.gov/jetwiki/code-packages/hydro-evolution/

A central Au+Au event at 200AGeV from the String Melting AMPT



View on the beam axis

σ_p=3mb

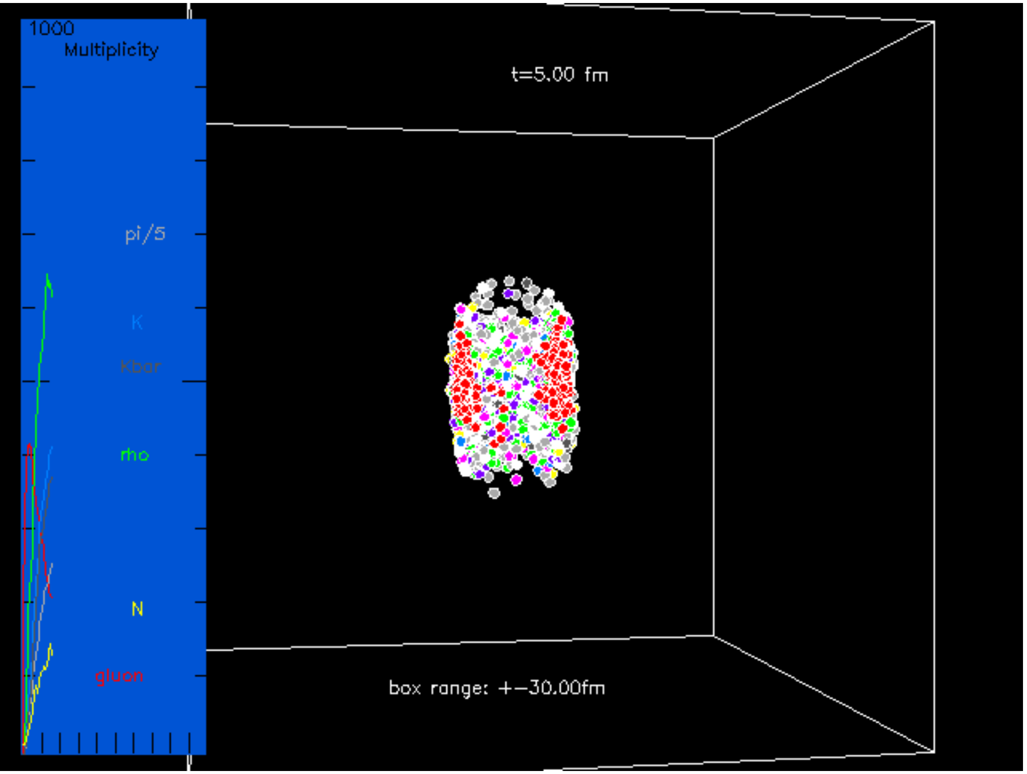
Box size 60fm

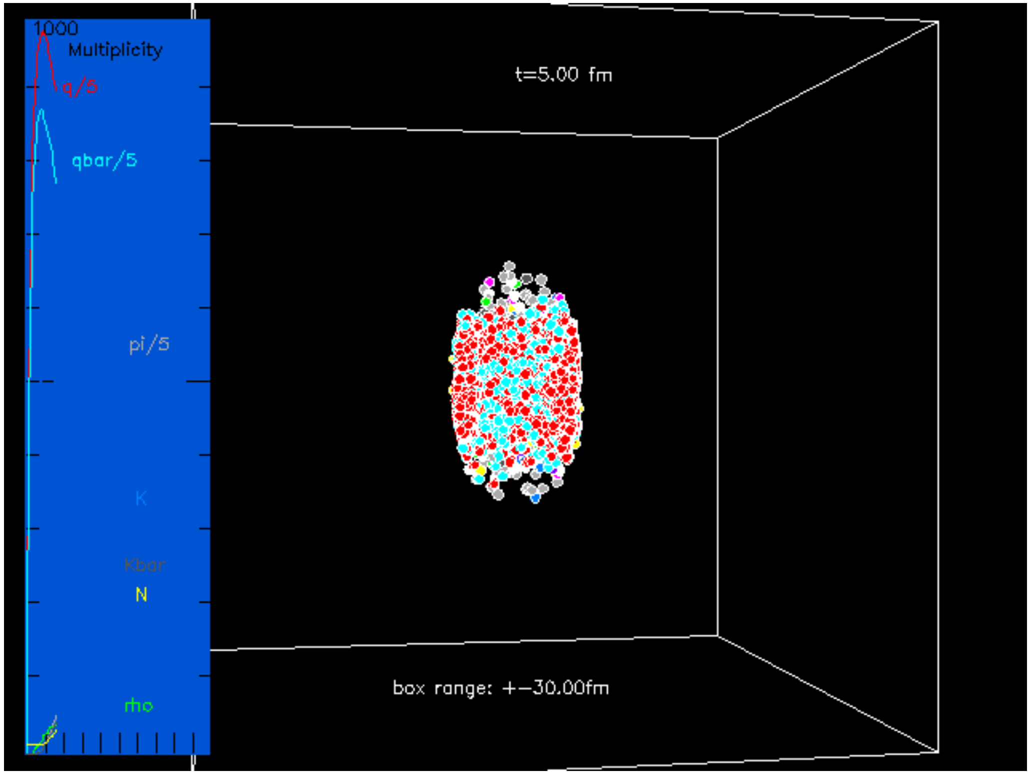
E.g. middle region (near mid-rapidity): coalescence of q (red) and **qbar (cyan)**

Constraining parameters of the AMPT-SM model

The same central 200AGeV Au+Au event (*at t=5 fm/c*) from

AMPT-Default vs AMPT-String Melting (SM)



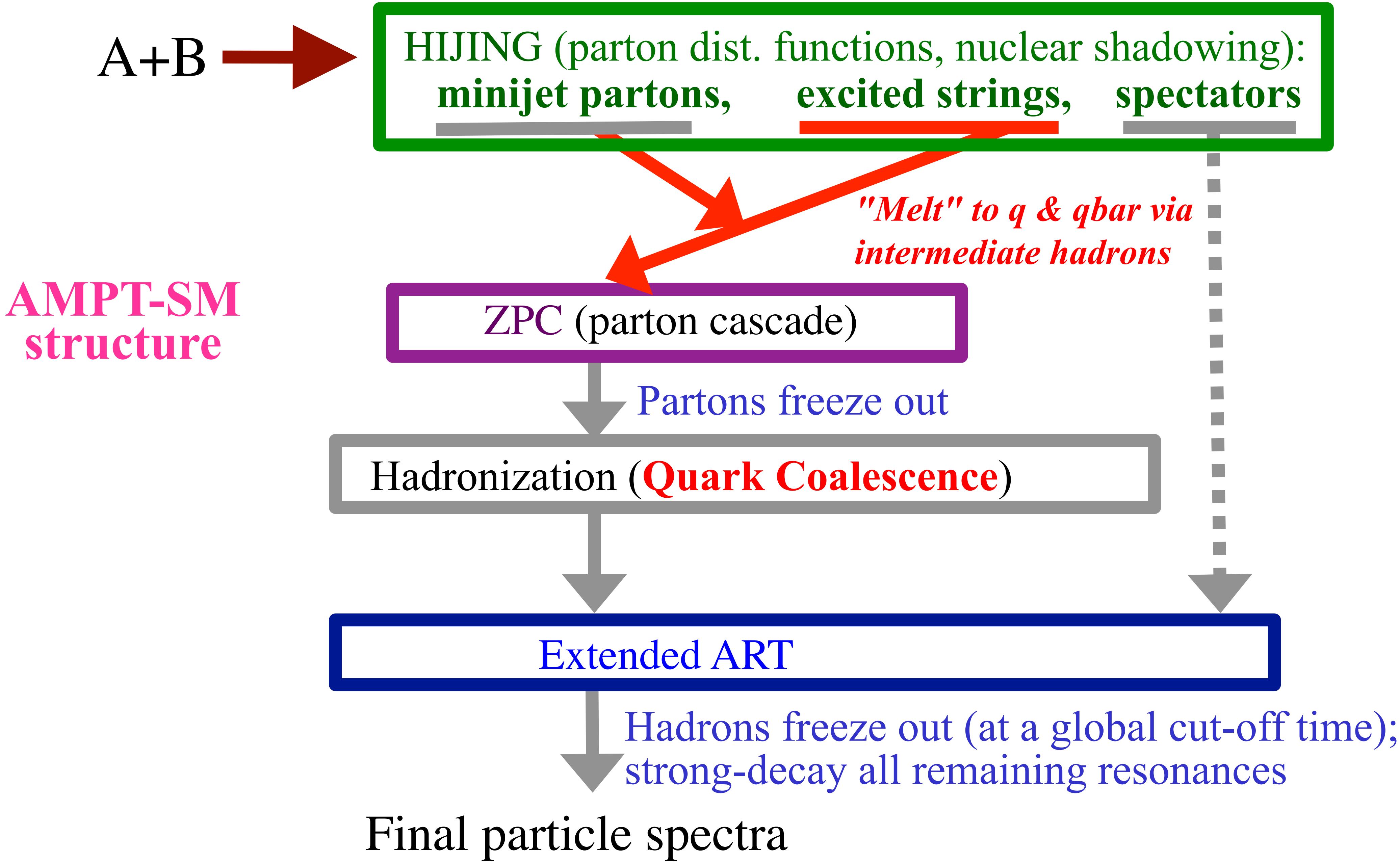


Beams from the left & right sides

AMPT-Default:
only minijets are in parton cascade, dense hadron stage starts early.

AMPT-SM:
early parton stage dominates; hadron stage starts later.

Constraining parameters of the AMPT-SM model



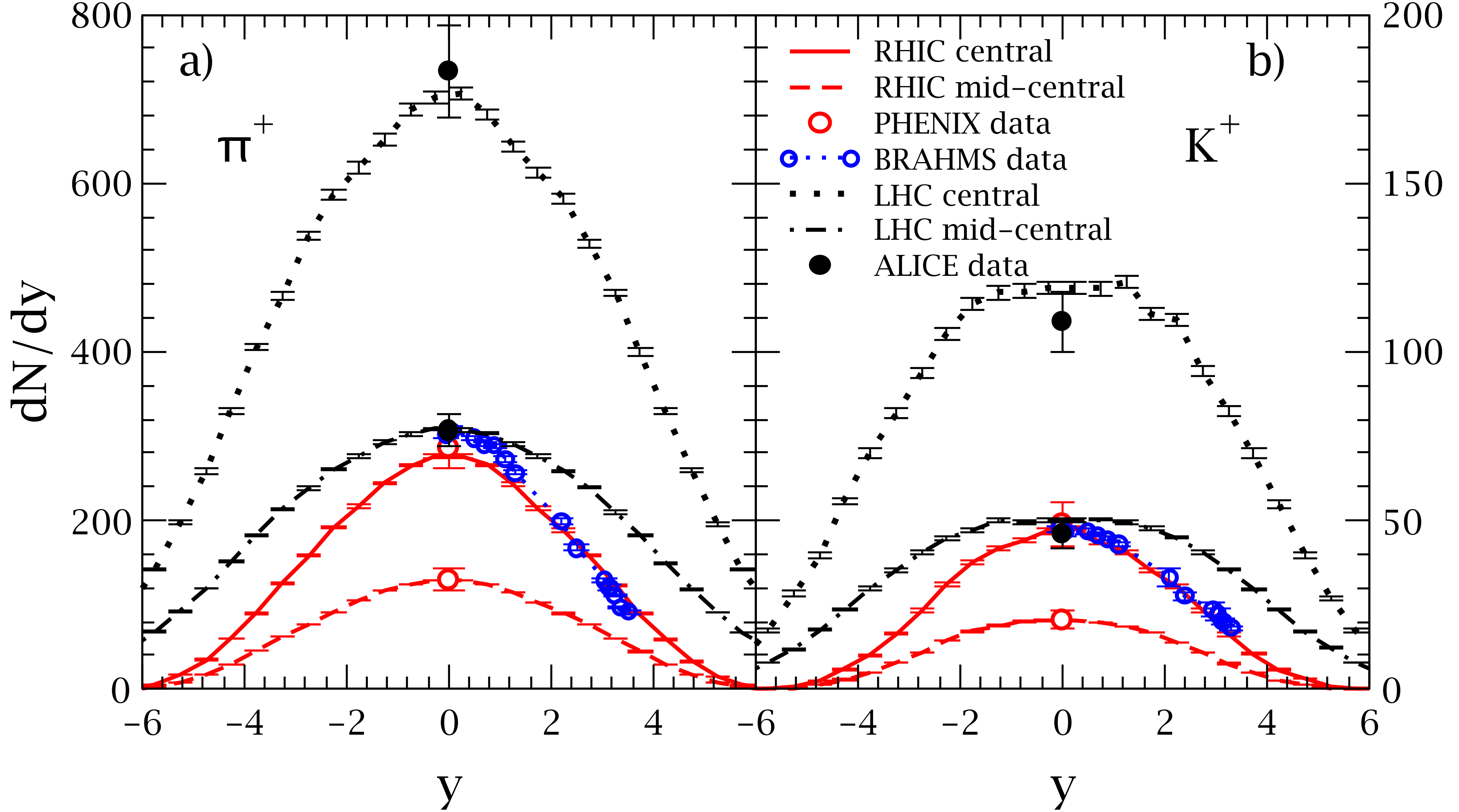
Constraining parameters of the AMPT-SM model

Goal: fit low-pt (<2GeV/c) π & K data on *dN/dy*, *p_T*–spectra & *v2*
*in **central** (0-5%) and **mid-central** (20-30%)*
*200AGeV Au+Au collisions (**RHIC**) and 2760AGeV Pb+Pb collisions (**LHC**).*

	HIJING1.0	**AMPT-SM [1]**	**AMPT-SM in [2]**	**AMPT-SM in this Study**
Lund string a	0.5	2.2	0.5	0.55 for RHIC, 0.30 for LHC
Lund string b (GeV^{-2})	0.9	0.5	0.9	0.15
α_s in parton cascade	N/A	0.47	0.33	0.33
Parton cross section	N/A	~ 6 mb	1.5 mb	3 mb
Model describes	*pp*, …	v2 & HBT not dN/dy or p_T	dN/dy & v2 (LHC) not p_T	dN/dy, p_T & v2 (RHIC & LHC)

[1] Lin, Ko, Li, Zhang and Pal, Phys Rev C 72, 064901 (2005); etc.
[2] Xu and Ko, Phys Rev C 83, 034904 (2011).

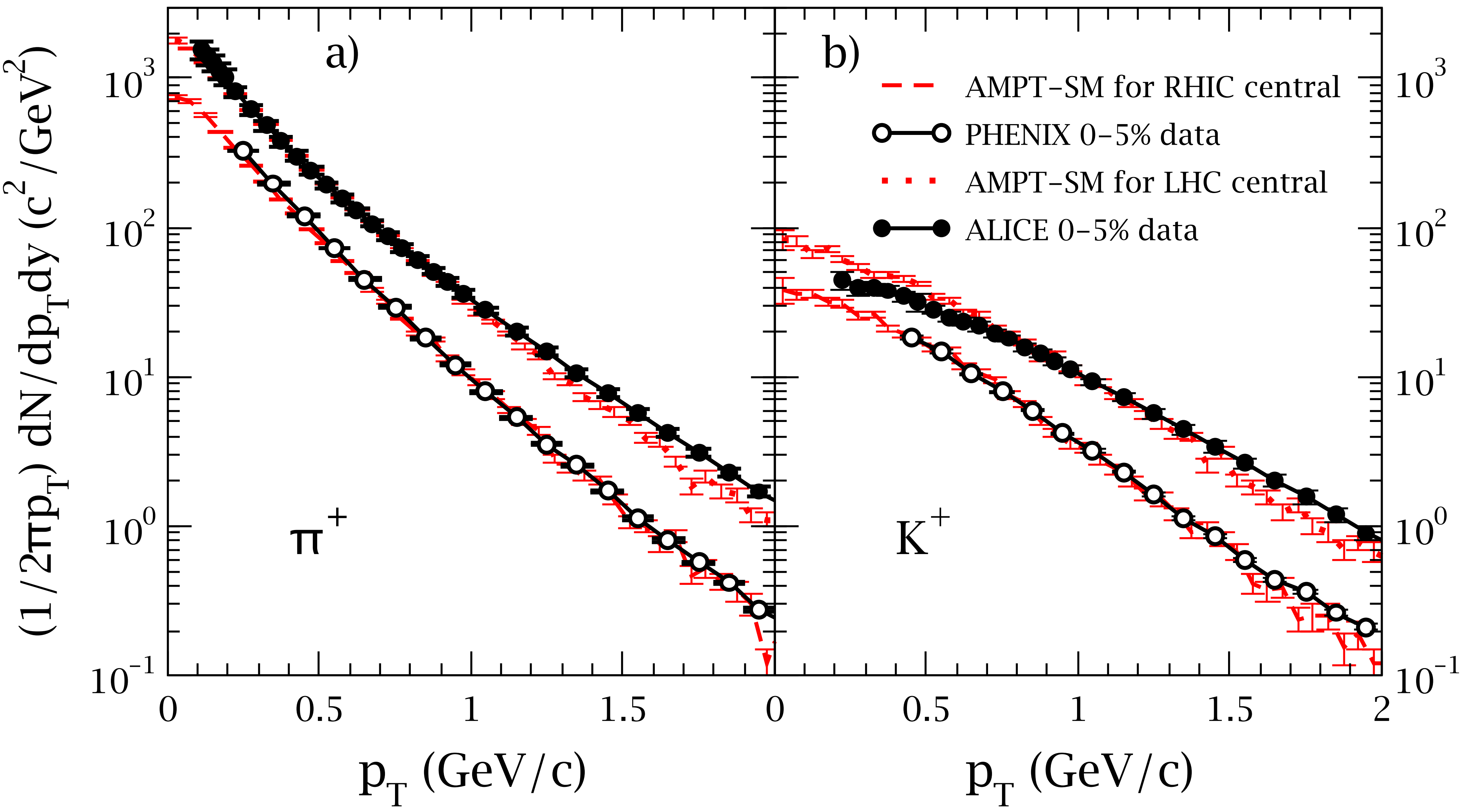
dN/dy of π & K:



a)
π^+
b)
K^+
RHIC central
RHIC mid−central
PHENIX data
BRAHMS data
LHC central
LHC mid−central
ALICE data
dN/dy
y
y
800
600
400
200
0
200
150
100
50
0
−6
−4
−2
0
2
4
−6
−4
−2
0
2
4
6

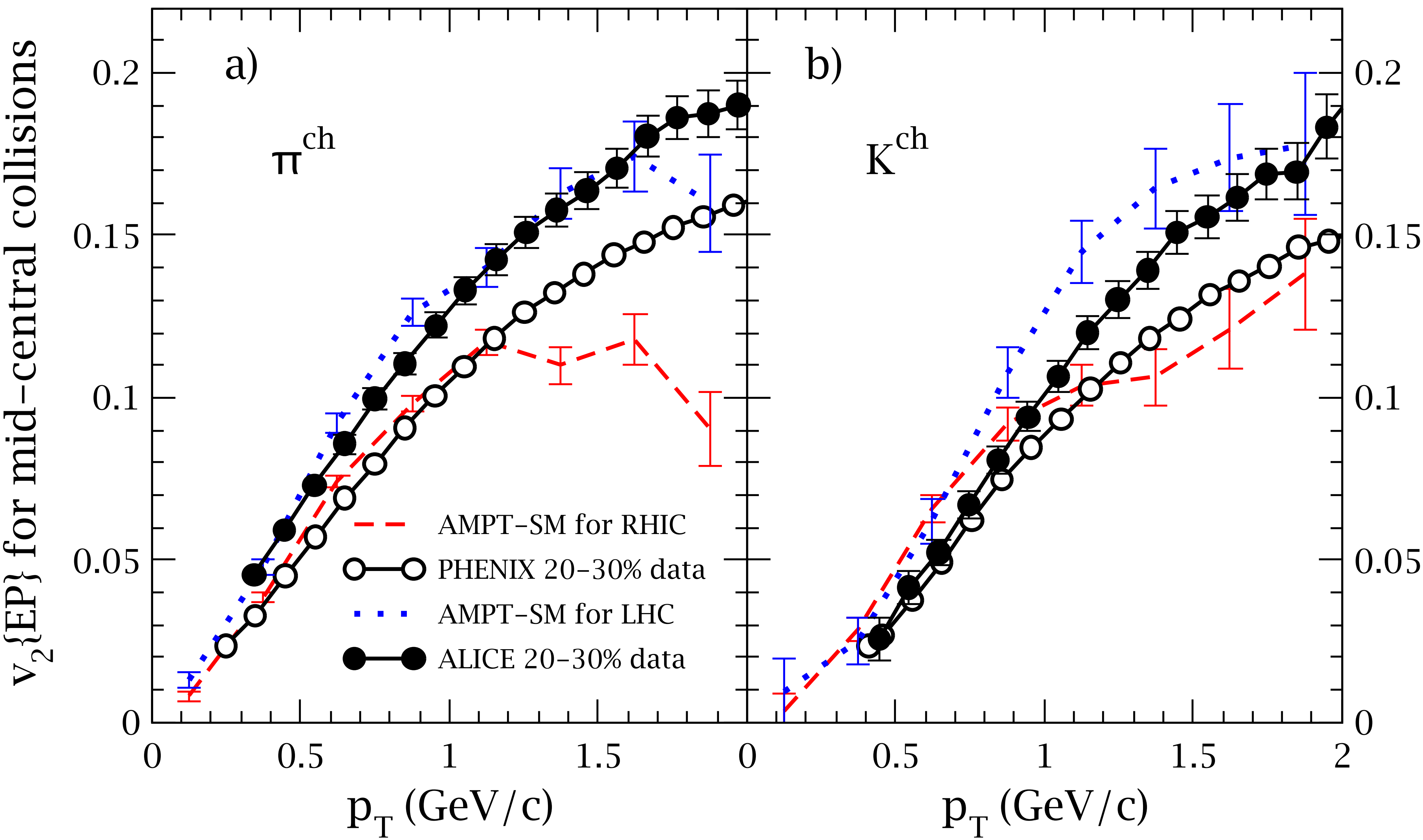
Constraining parameters of the AMPT-SM model

p_T -spectra of π & K (in central collisions):



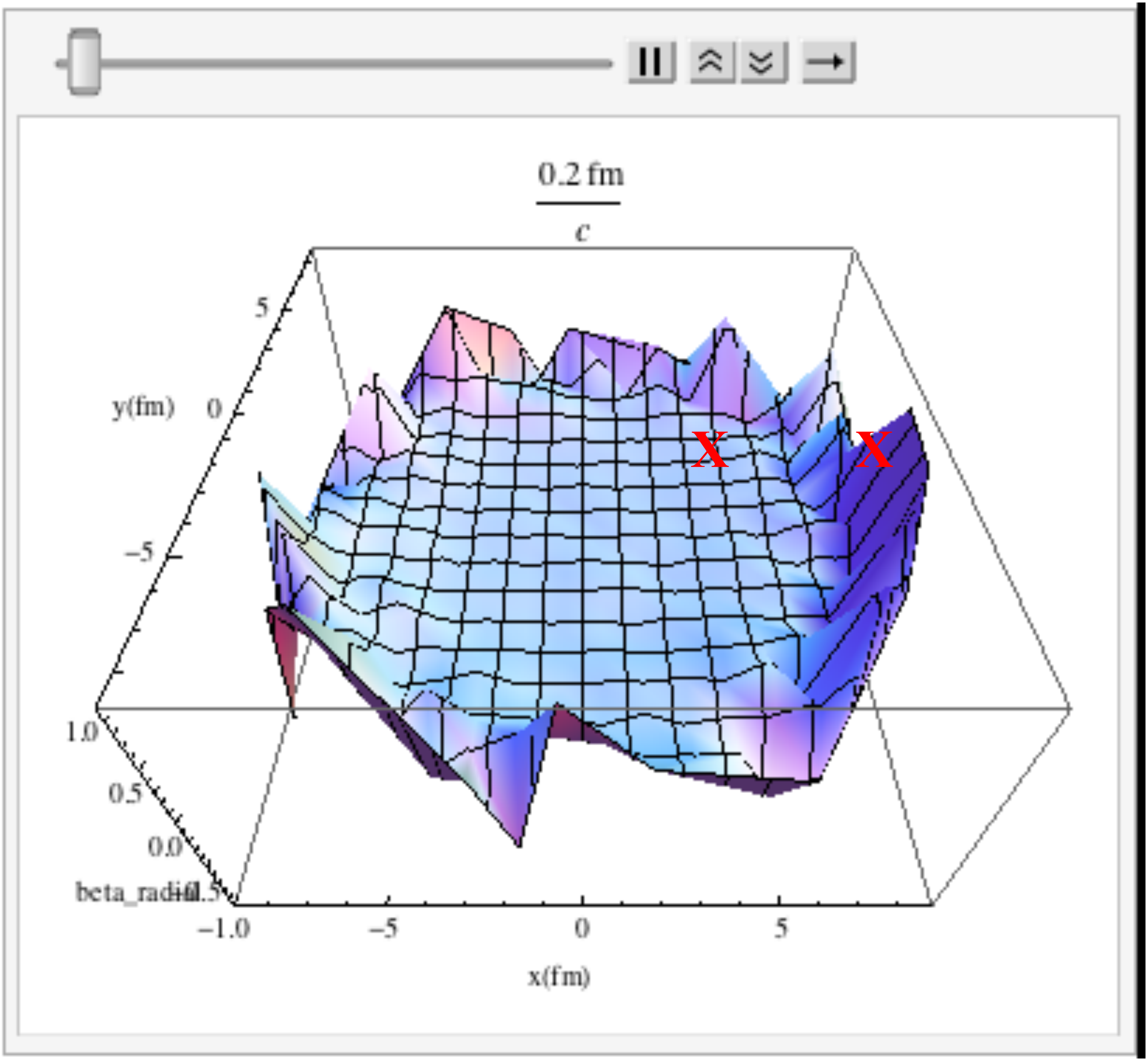
Constraining parameters of the AMPT-SM model

v2 of π & K (in mid-central collisions):



Flow in a cell is defined as

$$\vec{\beta} = \left(\sum \vec{p}_i\right) / \left(\sum E_i\right)$$



Transverse flow
in RHIC central:
the transverse plane
at 1 fm resolution:

This study averages over many events
(for the same collision system at the same centrality);

thus e-by-e fluctuations are neglected

Evolution of flow, densities and energy-momentum

Transverse flow
in RHIC central:

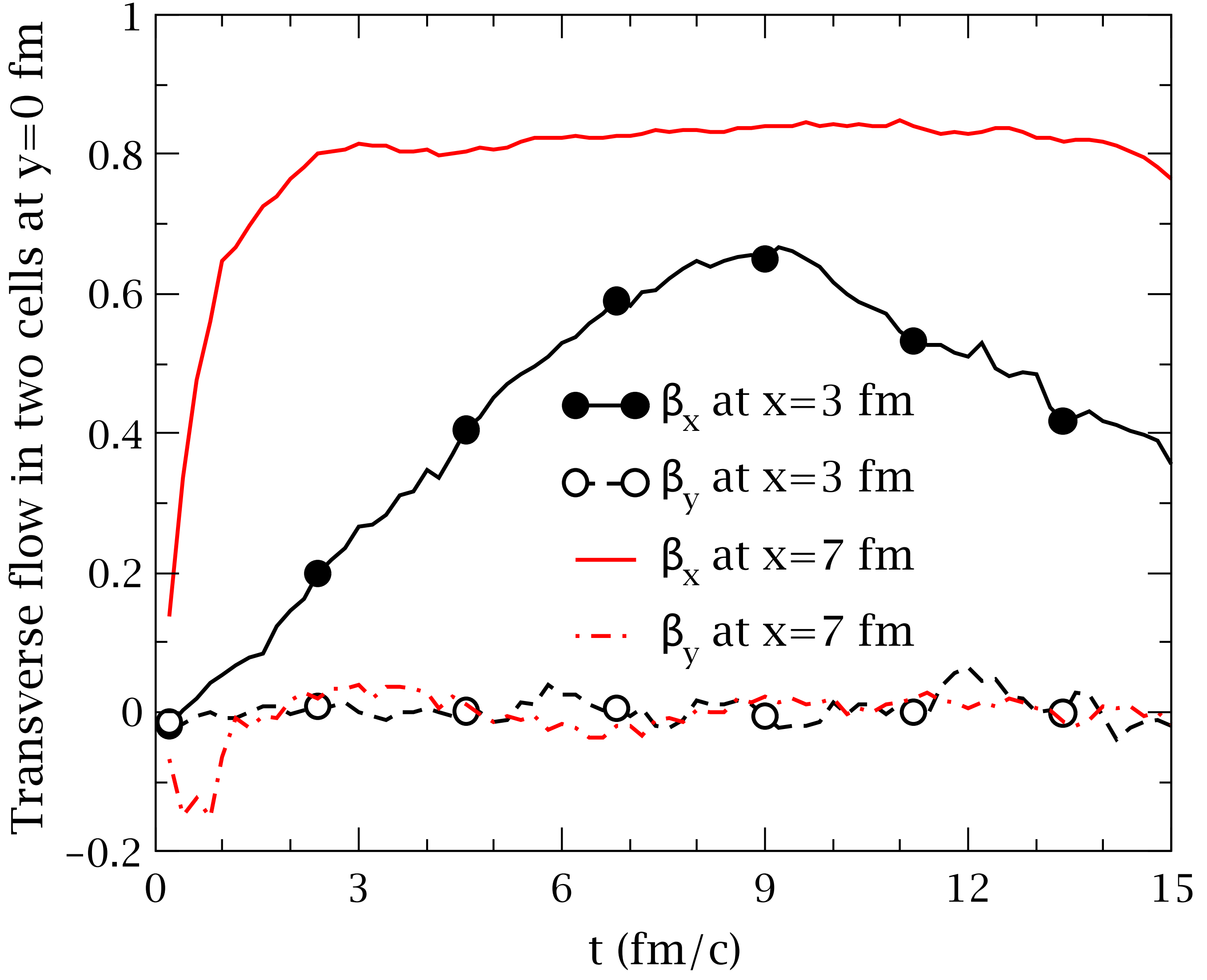
at 2 locations along x:

$\beta_y \approx 0$ due to symmetry

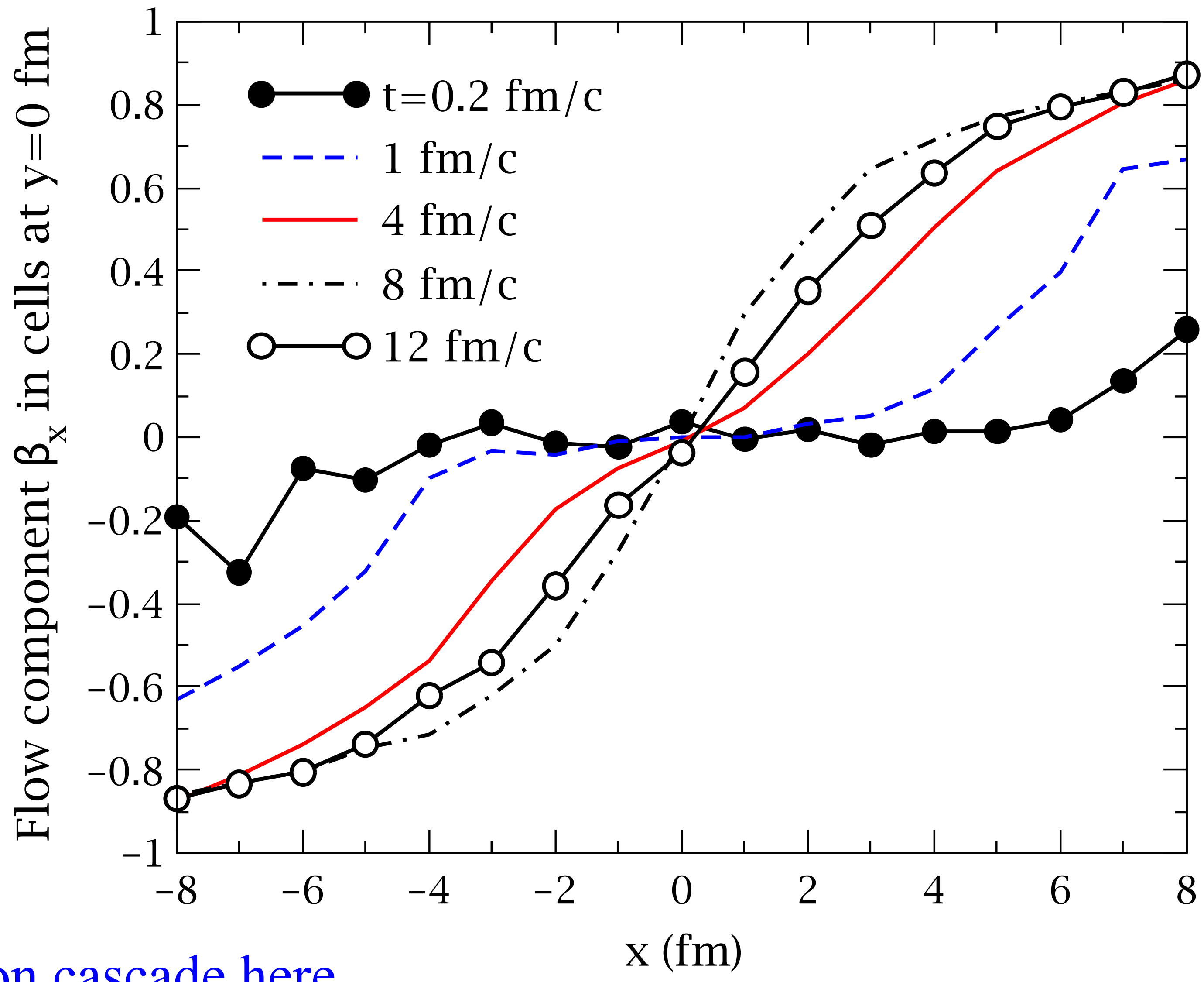
Flow $\approx \beta_x$:
shape depends on location;

decrease seen at late times;

develops fast near
edge of overlap volume



Transverse flow
in RHIC central:



Significant flow
near the edge
even at *t=1fm/c*

Flow at early times:
~ *Pre-equilibrium flow,*
modeled by elastic parton cascade here

Evolution of flow, densities and energy-momentum

We then evaluate variables in the **local rest frame** of partons in each volume cell:

energy density ε

number density n

average P_T, P, E_T, E,

then extract the "effective" temperature using each variable.

If partons in a sub-volume are in complete chemical and thermal equilibrium, all these "effective" temperatures would be the same.

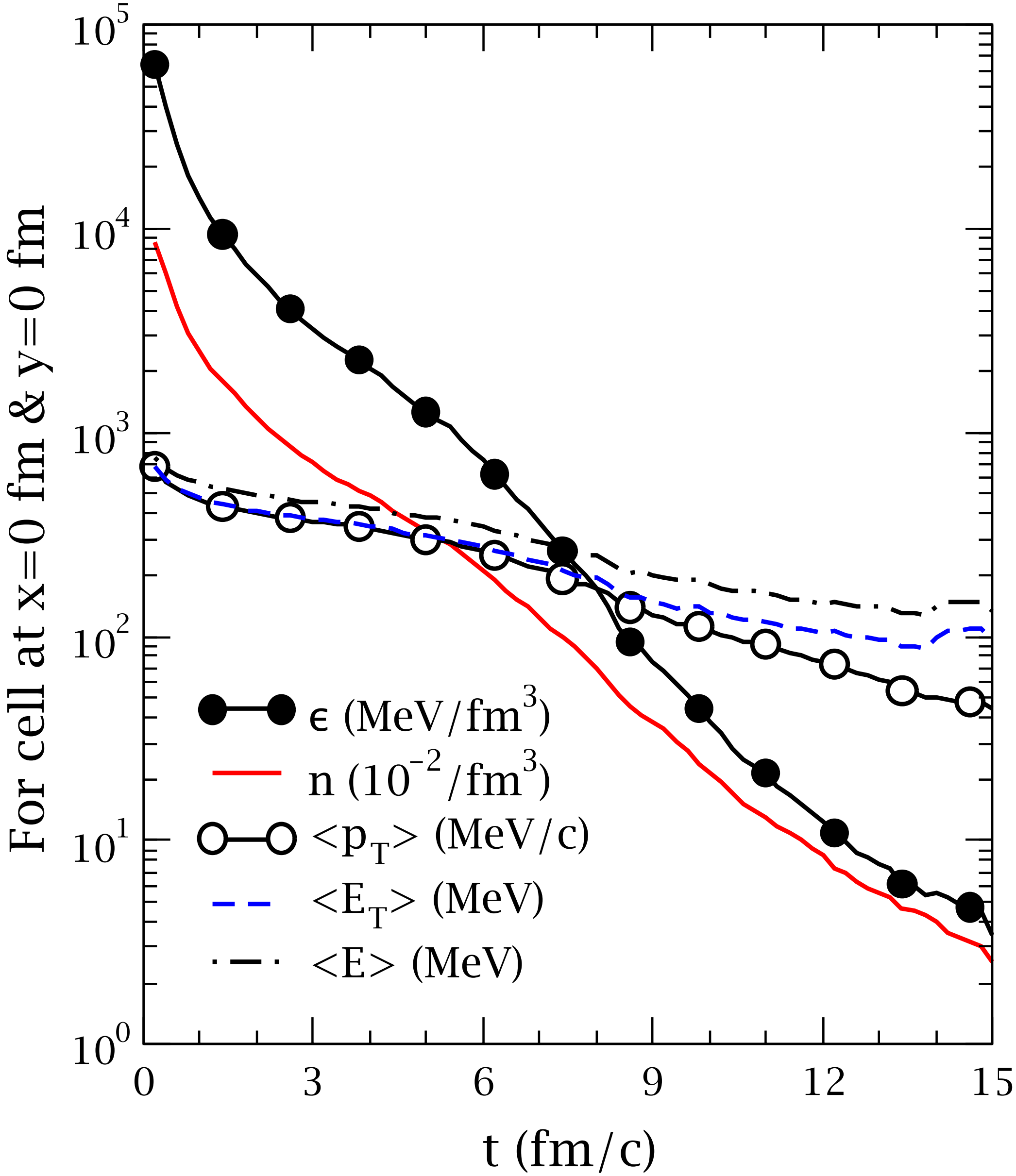
OR

If these "effective" temperatures are different in a sub-volume, the partons are not in complete (local) chemical and thermal equilibrium.

The **local rest frame** is defined according to its velocity in the CMS frame:

$$\vec{\beta} = \left(\sum \vec{p}_i\right) / \left(\sum E_i\right)$$

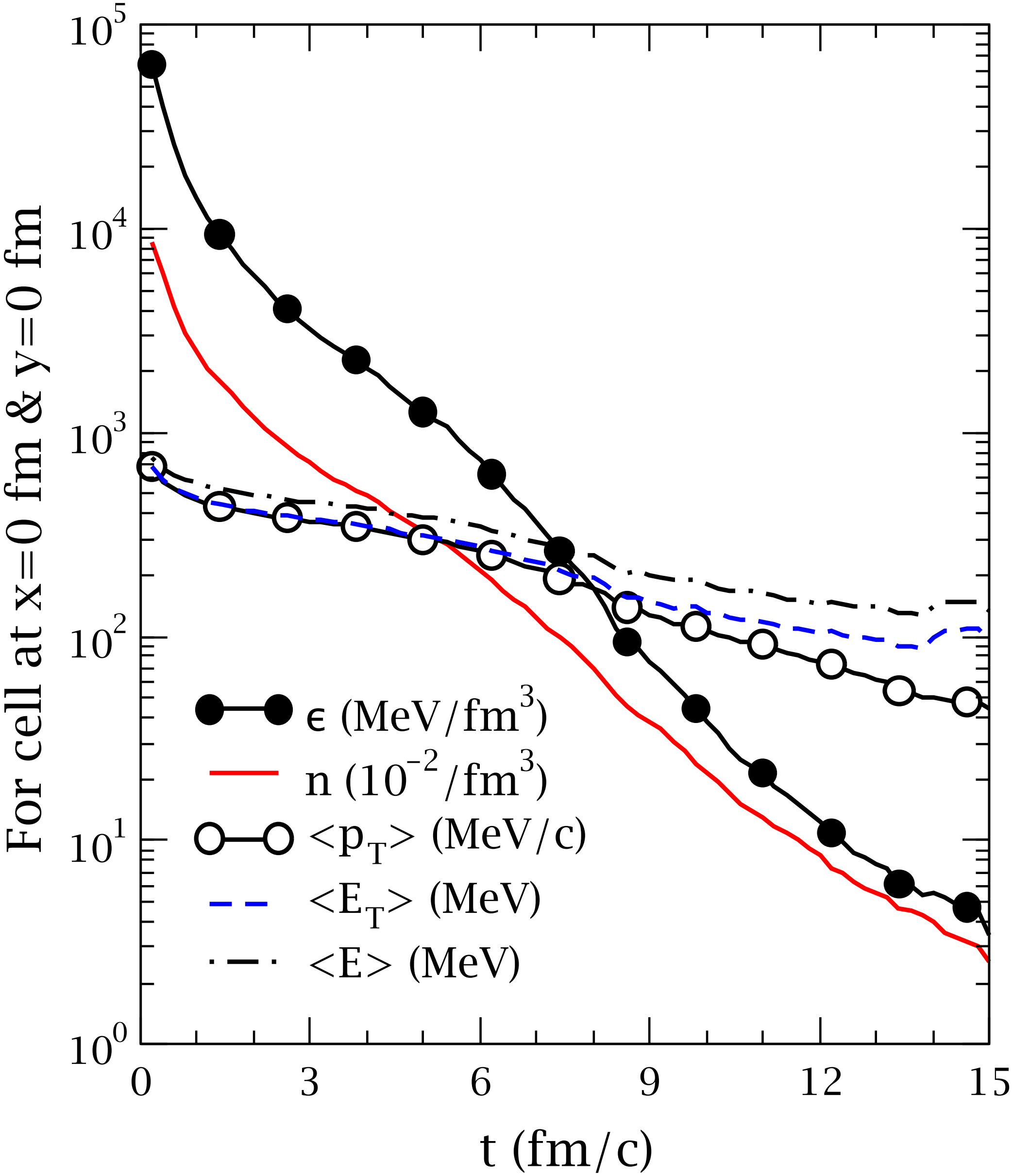
Evolution of flow, densities and energy-momentum



Example:
the center cell
in RHIC central

All evaluated in the rest frame of each cell

Evolution of extracted effective temperatures



Difference between Boltzmann and quantum distributions is very small for these relations

➔ Extract effective temperatures using relations for a massless ideal QGP with the Boltzmann momentum distribution:

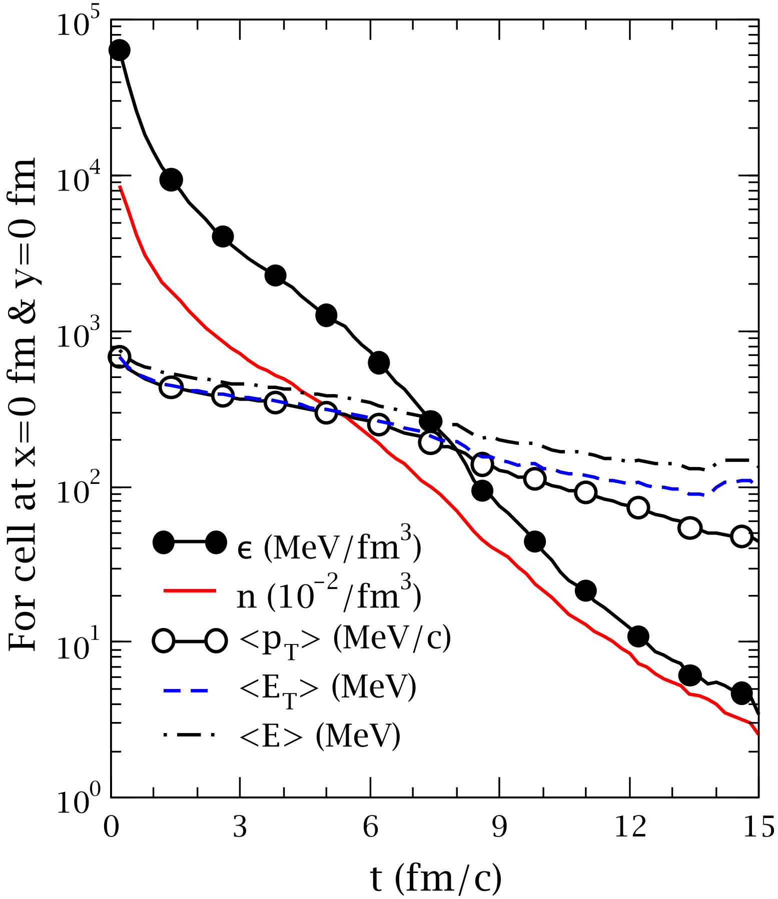
$$T_{<p>} = \frac{<p>}{3}, T_{<p_T>} = \frac{4<p_T>}{3\pi}, T_{<p_T^2>} = \sqrt{\frac{<p_T^2>}{8}},$$

$$n = g_B \frac{T_n^3}{\pi^2}, \varepsilon = 3g_B \frac{T_\varepsilon^4}{\pi^2}, \varepsilon_T = 3g_B \frac{T_{\varepsilon_T}^4}{4\pi}.$$

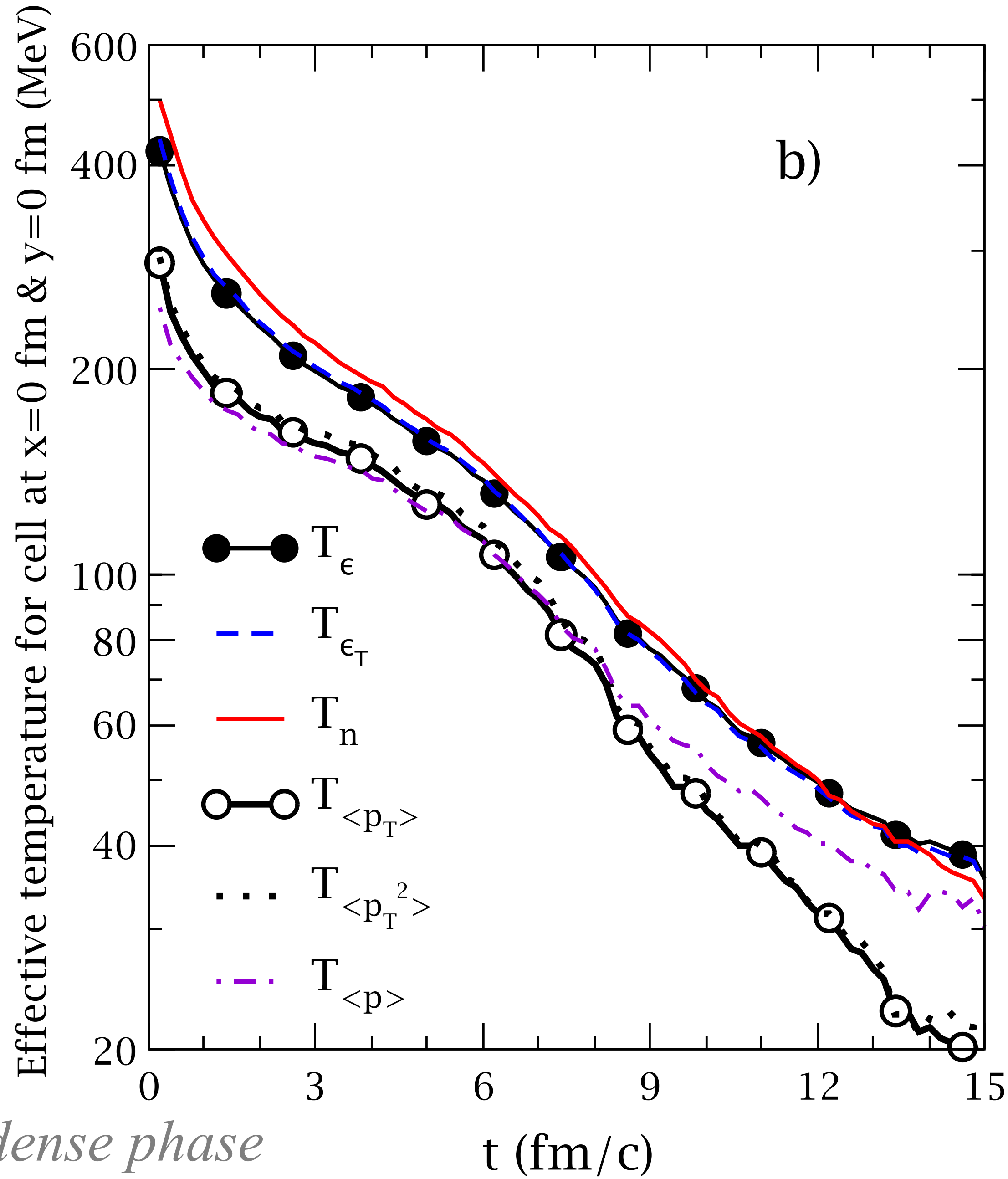
Each variable yields an “effective” temperature.

$g_B = 16 + 12N_f$, $N_f = 3$ used in this study

Evolution of extracted effective temperatures



➔



The effective temperatures are all different.

For the center cell in RHIC-central:

$$T_n > T_\varepsilon \;>>\; T_{<p_T>}$$

in the dense phase

Evolution of extracted effective temperatures

Check temperature in a side cell:

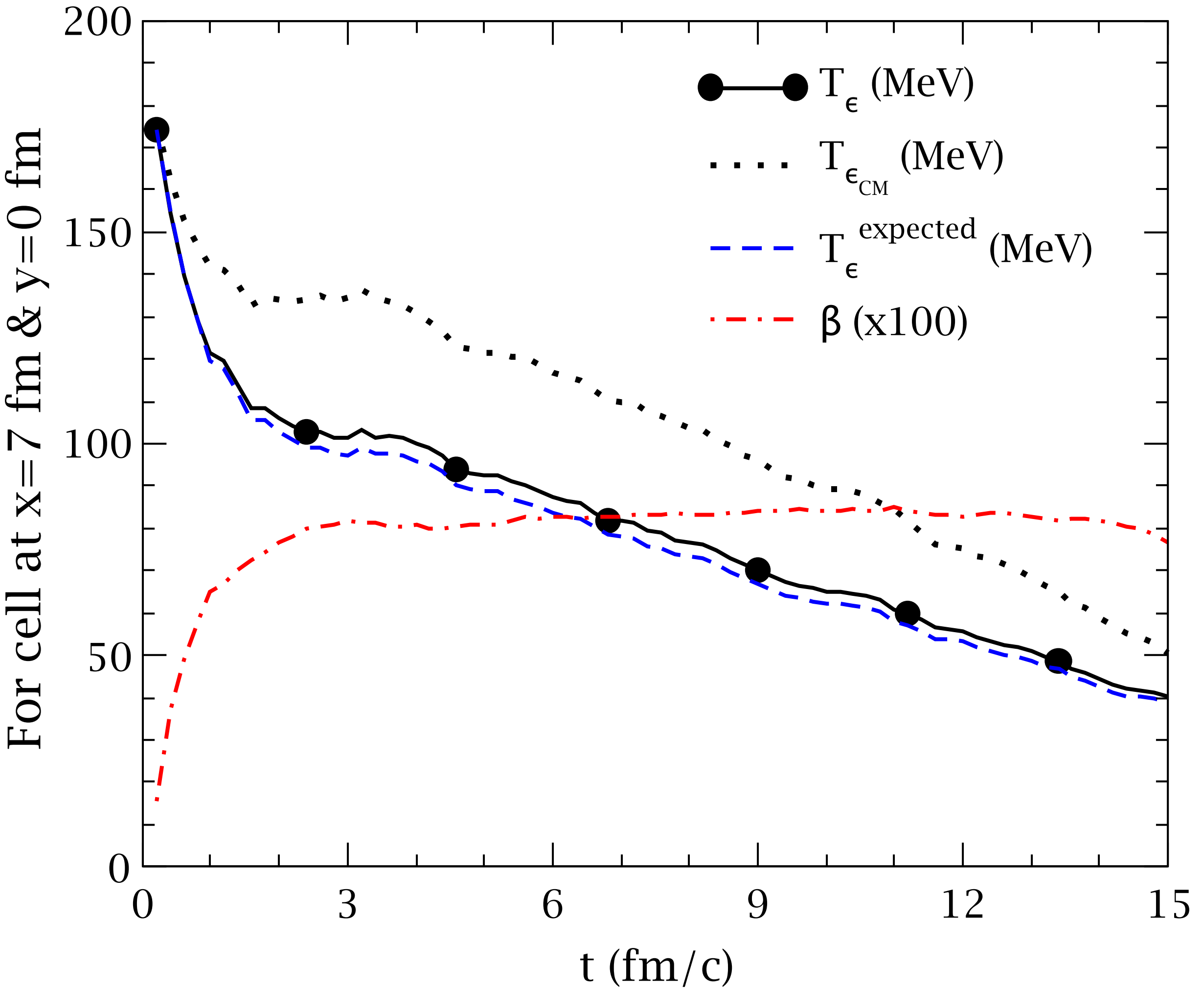
T_ε in its rest frame

vs T_ε^{cms} in the center-of-mass frame

For massless partons in a cell that can be described by ε and P, we can obtain

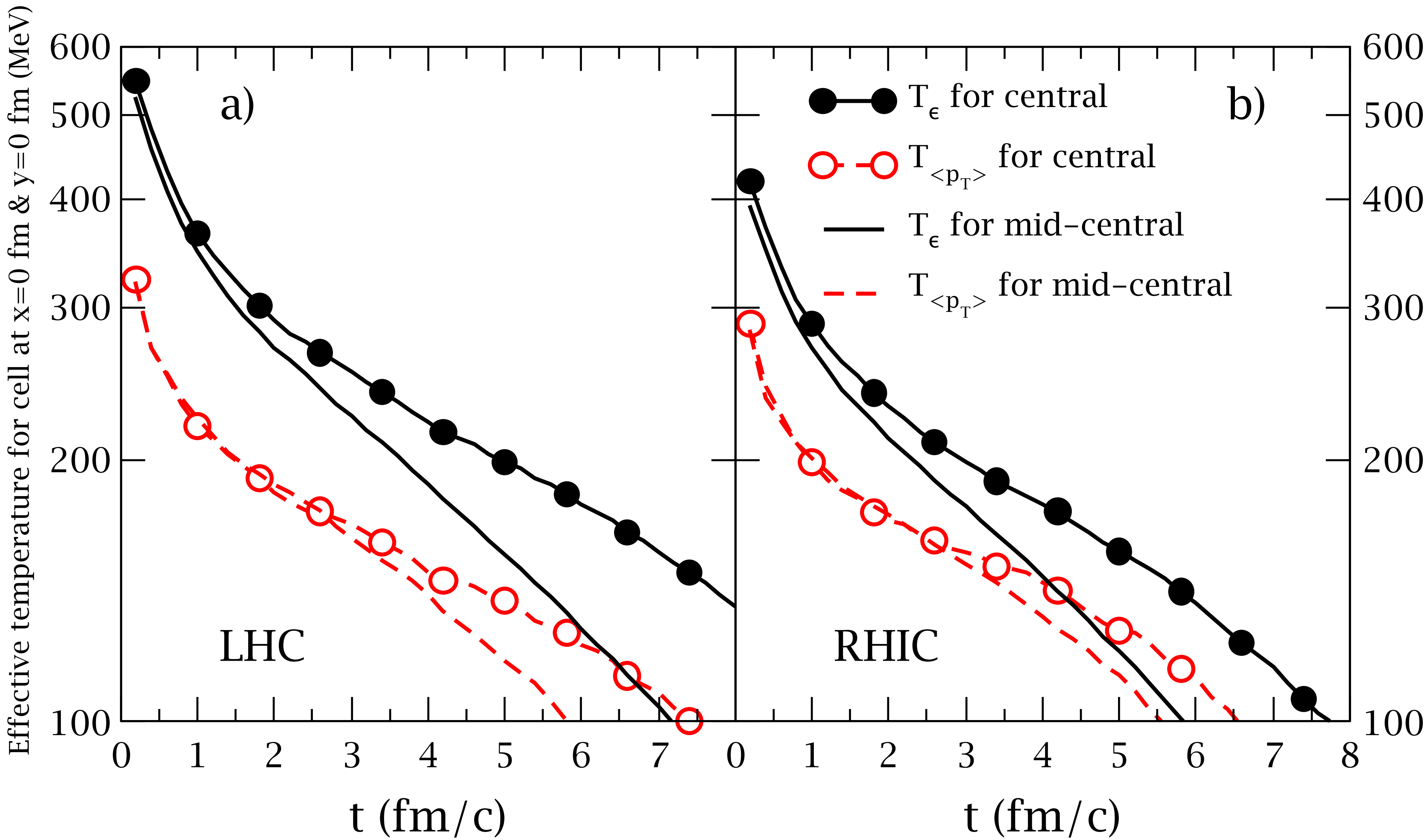
$$T_\varepsilon^{expected} = T_\varepsilon^{cms}\left(\frac{1-\beta^2}{1+\beta^2/3}\right)^{1/4}$$

$\boldsymbol{\beta}$: flow of the cell in the center-of-mass frame



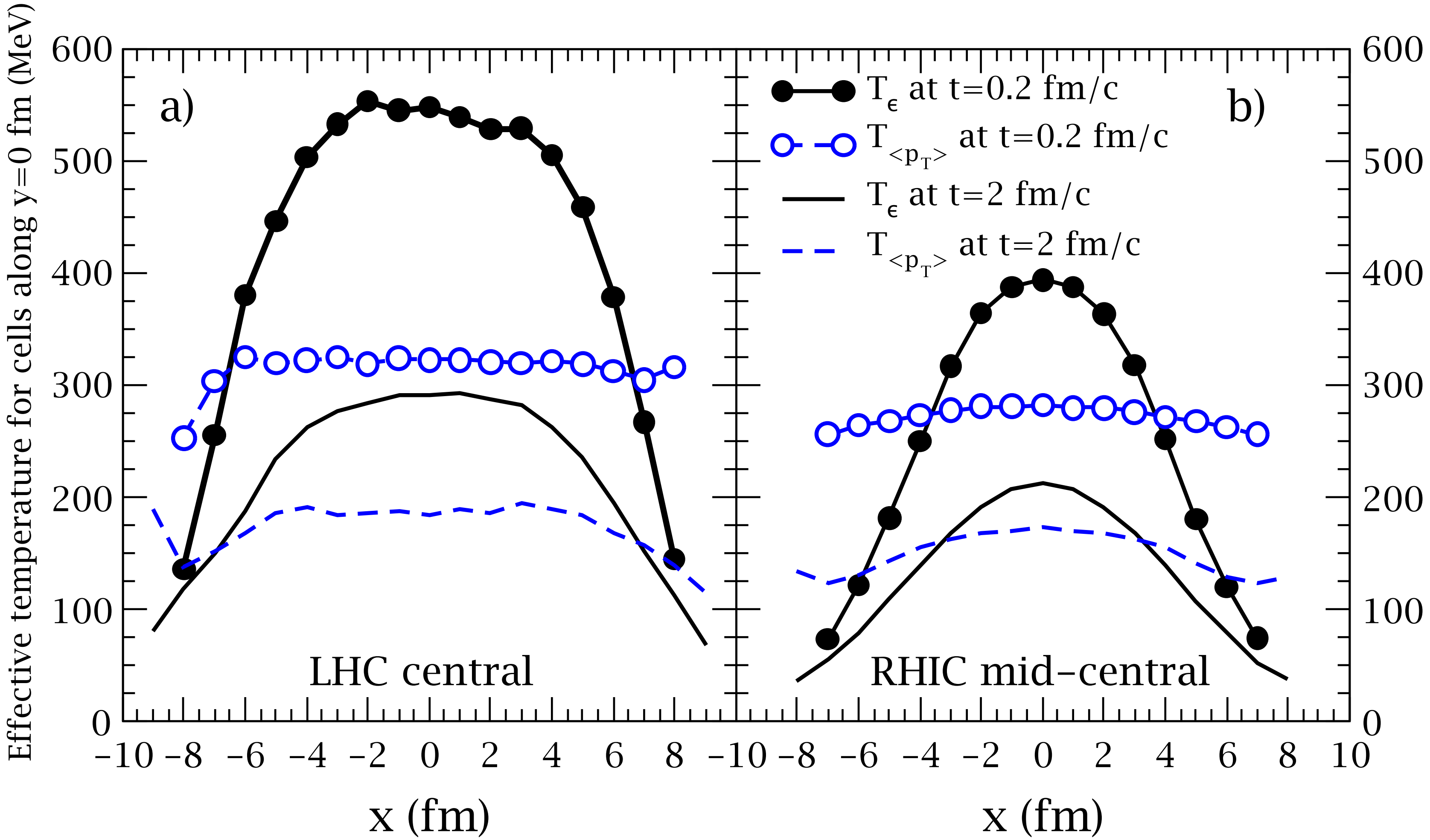
Evolution of extracted effective temperatures

$T_\varepsilon >> T_{<p_T>}$ is true for the center cell of all 4 collision systems:



Evolution of extracted effective temperatures

How about other locations?

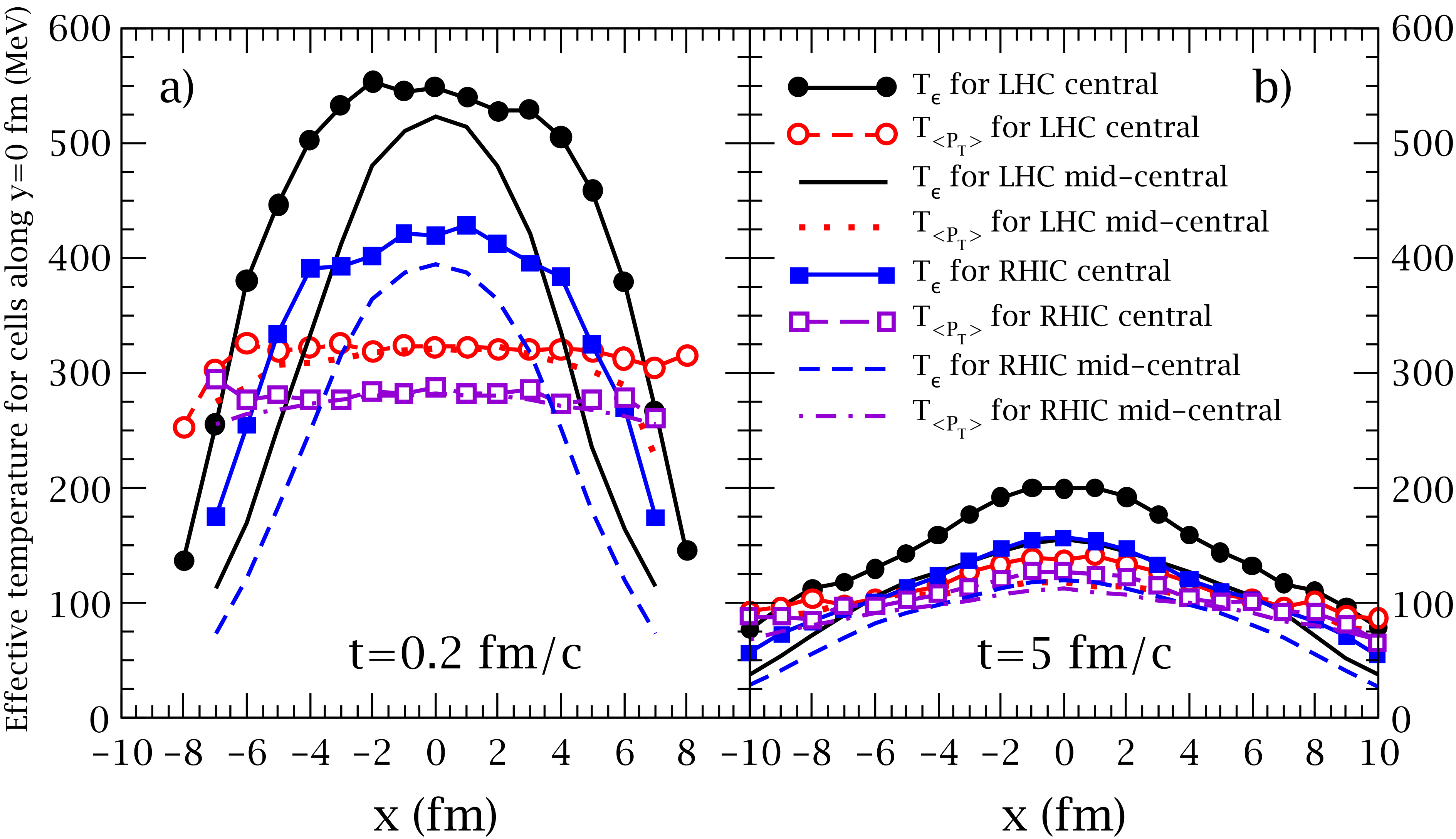


➔ $T_\varepsilon > T_{<p_T>}$ over the inner part of the overlap volume;

the opposite over the outer part.

Evolution of extracted effective temperatures

This is the case in all 4 collision systems:

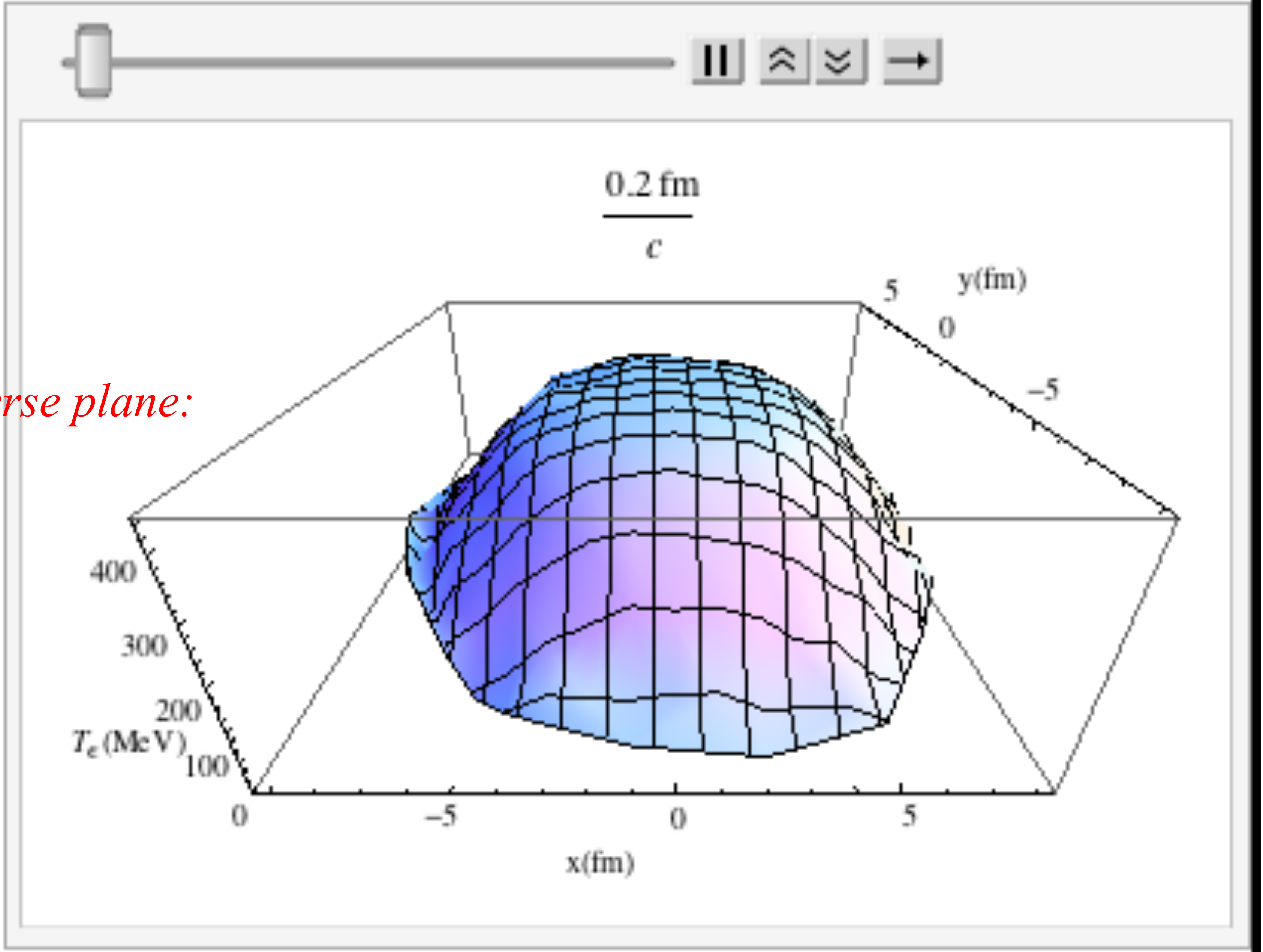


Evolution of extracted effective temperatures

T_ε

in RHIC central

over the transverse plane:

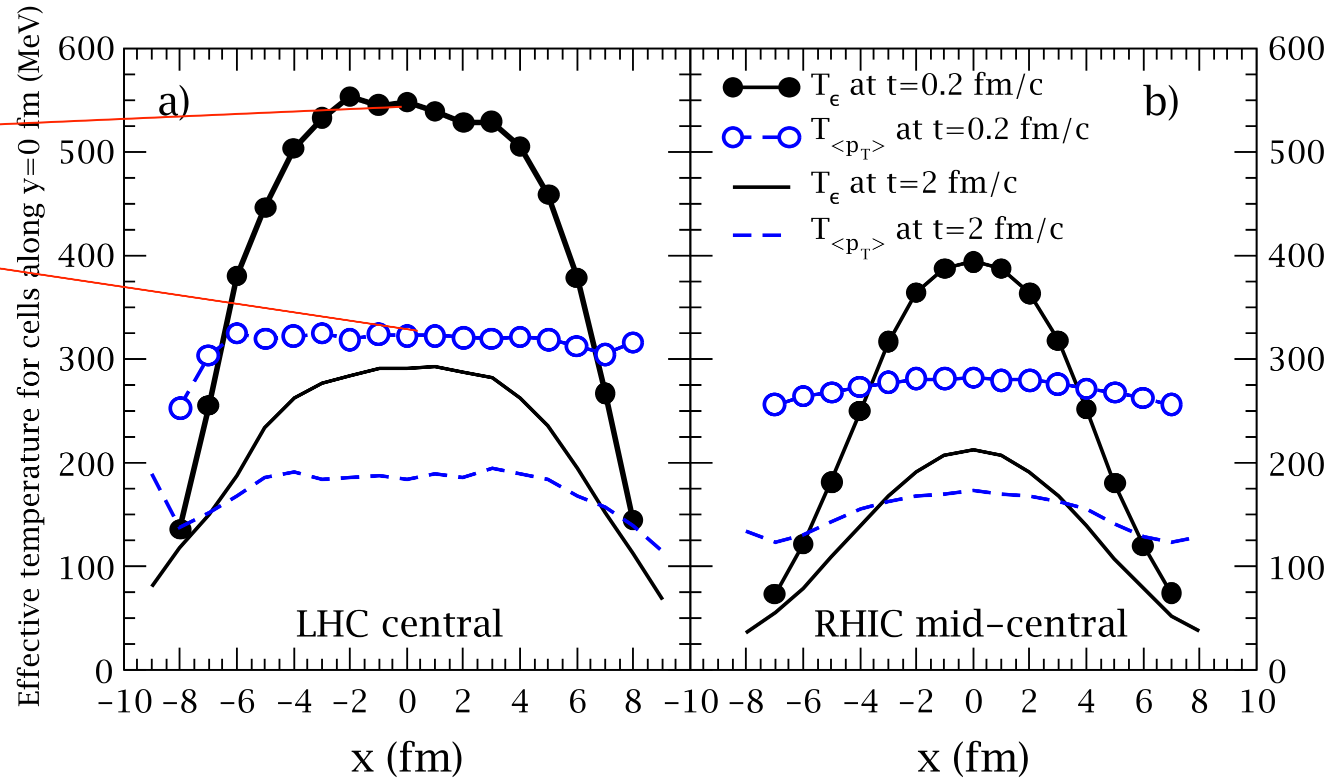


Note again:
for partons
within |η|<1/2

Over-population of partons

For the center cell:

$$\frac{T_{\varepsilon}}{T_{<p_T>}} = \frac{548MeV}{322MeV} \approx 1.7$$



$$\varepsilon_T = \langle E_T \rangle n$$

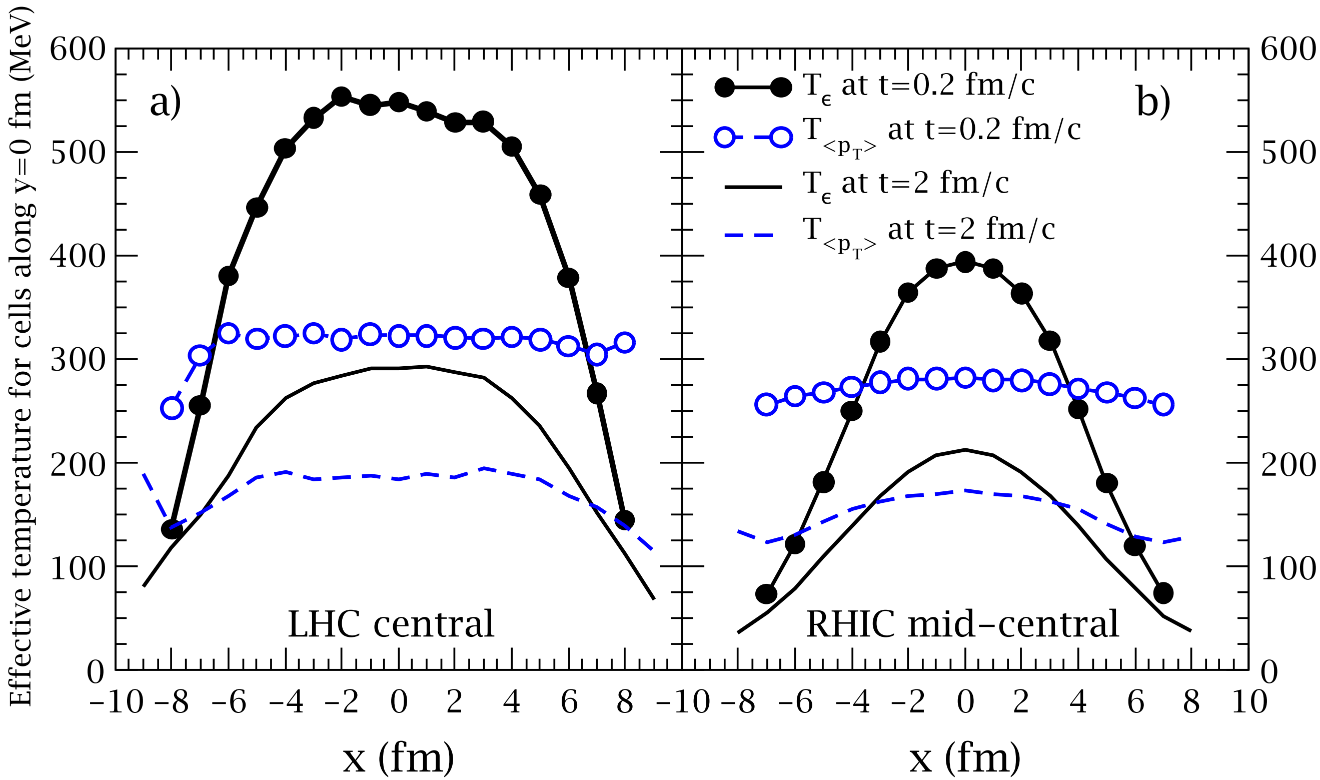
$$\Rightarrow T^4_{<\varepsilon_T>} = T_{<E_T>} T^3_n$$

$$\Rightarrow T^4_{\varepsilon} \approx T_{<p_T>} T^3_n$$

$$\Rightarrow \frac{n}{n\left(T_{<p_T>}\right)} = \left(\frac{T_n}{T_{<p_T>}}\right)^3 \approx \left(\frac{T_\varepsilon}{T_{<p_T>}}\right)^4 = 1.7^4 \approx 8.4$$

The actual parton density n >>
expected density for an ideal QGP at temperature $T_{<p_T>}$

Over-population of partons



$T_\varepsilon > T_{<p_T>}$ for each cell in the inner part of the overlap volume

➔ Energy and number densities ε, *n* are too high, relative to the expected values for an ideal QGP at $T_{<p_T>}$ (that has the same $<p_T>$ as partons in the cell)

➔ The local parton system is over-populated.

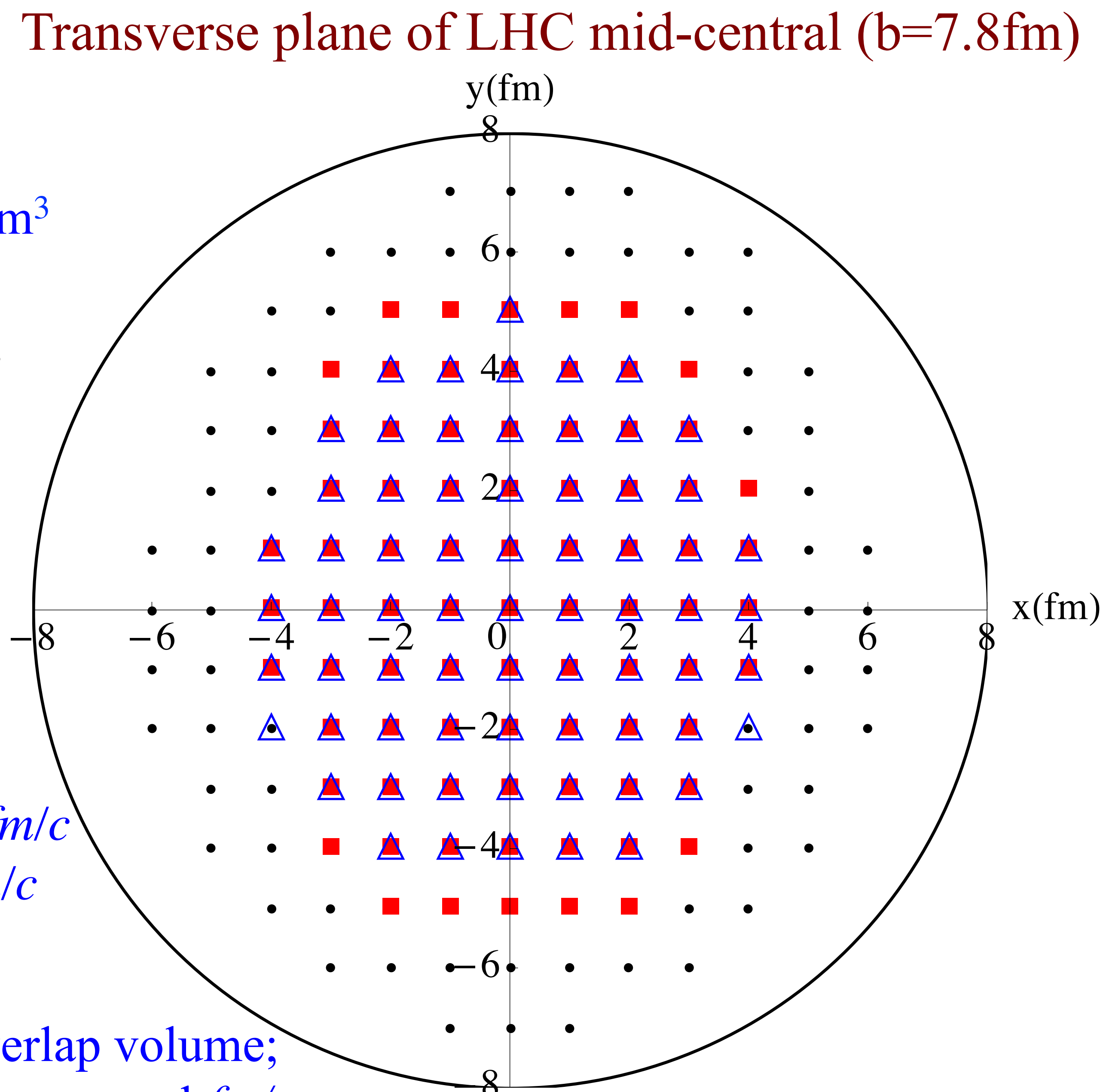
Over-population of partons

Let us define 2 terms:

QGP cell: cell with ε >1.05 GeV/fm^3

Over-populated cell:

QGP cell with $T_\varepsilon > T_{<p_T>}$



- • QGP cells at *t=0.2 fm/c*
- ■ Over-populated cells at *t=0.2 fm/c*
- Δ Over-populated cells at *t=3 fm/c*

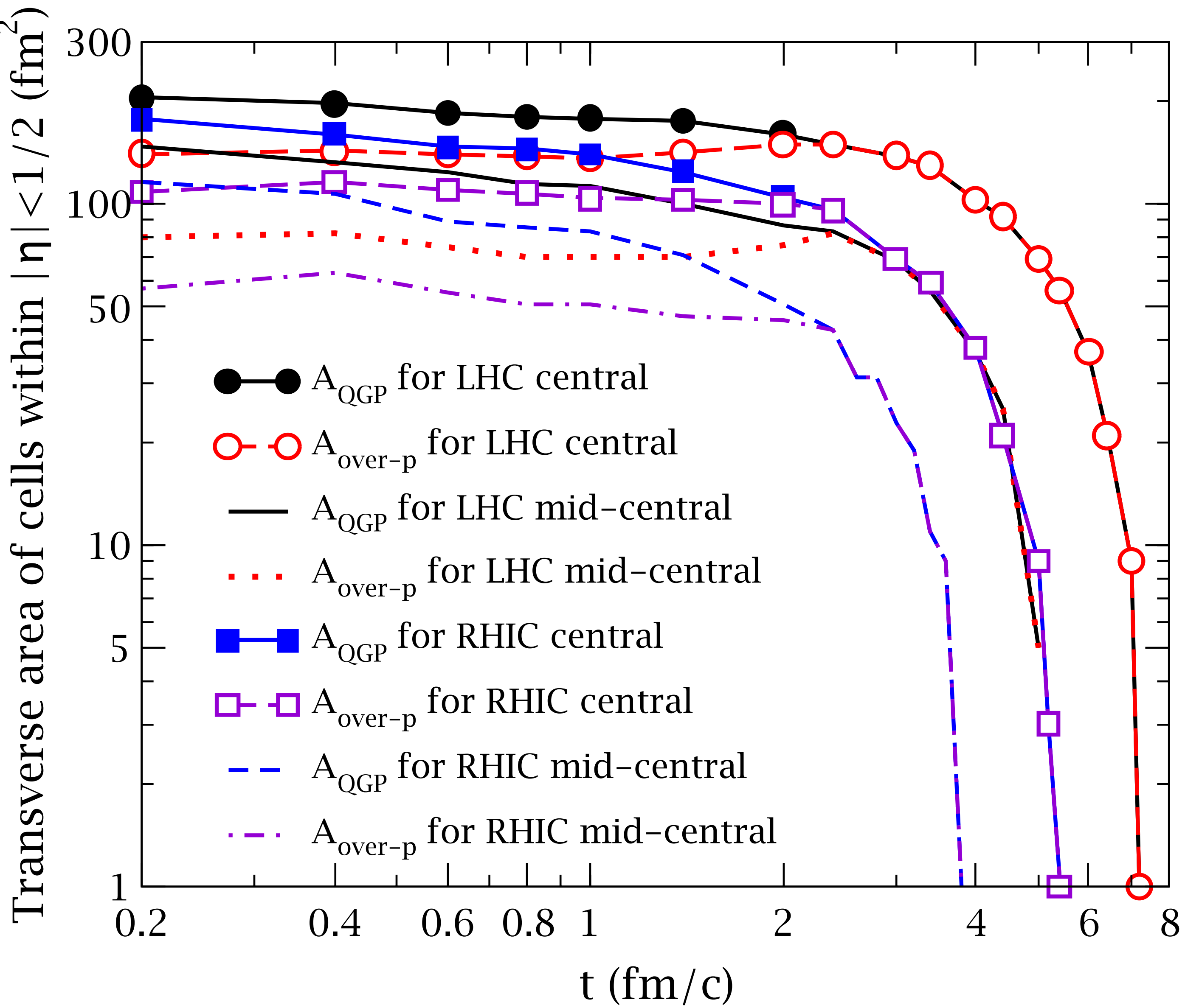
Over-population in inner part of overlap volume;
many over-populated cells even after several *fm/c*

Over-population of partons

Transverse area:

50-70% of initial QGP cells are over-populated.

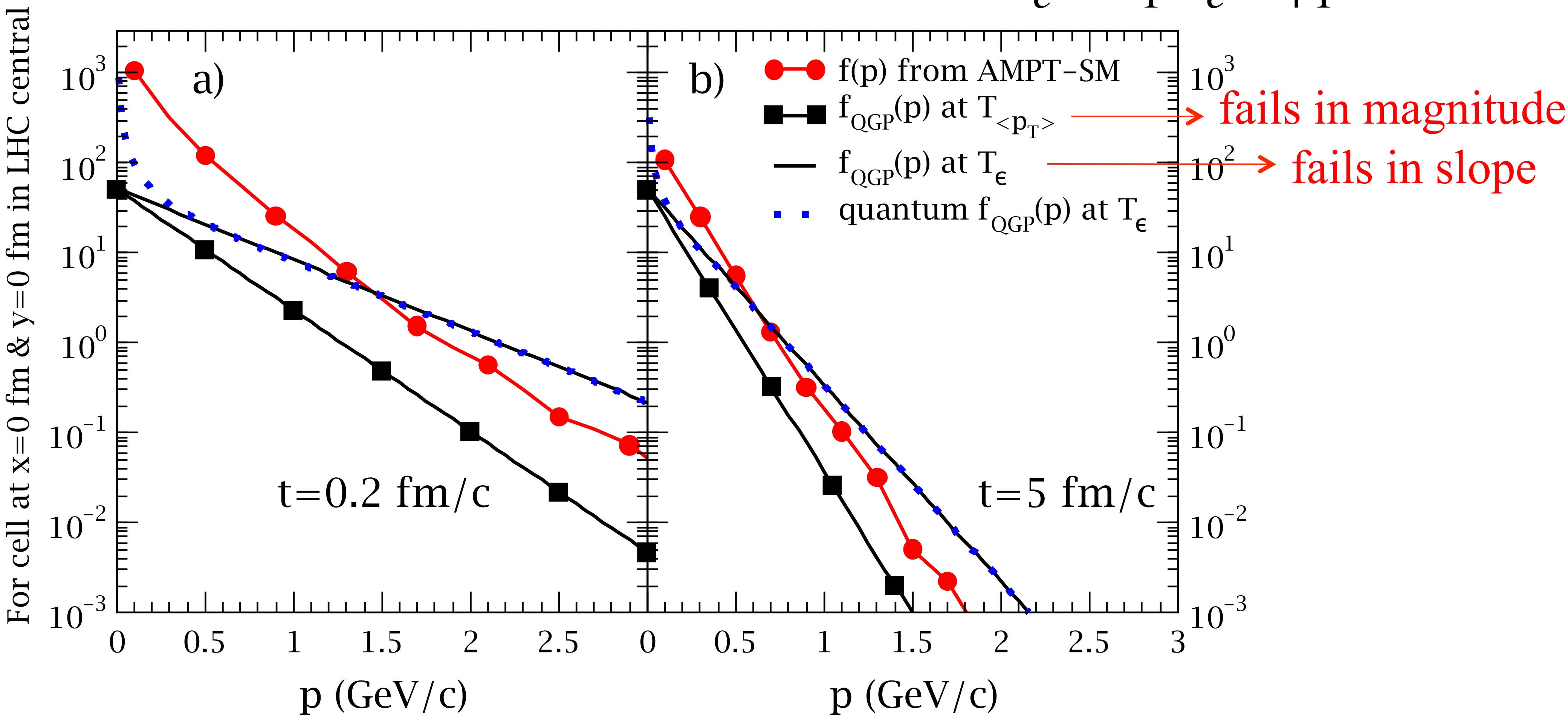
After 2-3 fm/c, all QGP cells are over-p.



Over-population of partons

Evaluate parton phase-space density function *f(p)* in center cell of LHC central: then compare with **equilibrium** functions

$$f_{QGP}(p)=g_B e^{-p/T},\ \text{or quantum}\ f_{QGP}(p)=\frac{16}{e^{p/T}-1}+\frac{12N_f}{e^{p/T}+1}.$$



If quarks/antiquark densities are limited by the Pauli principle

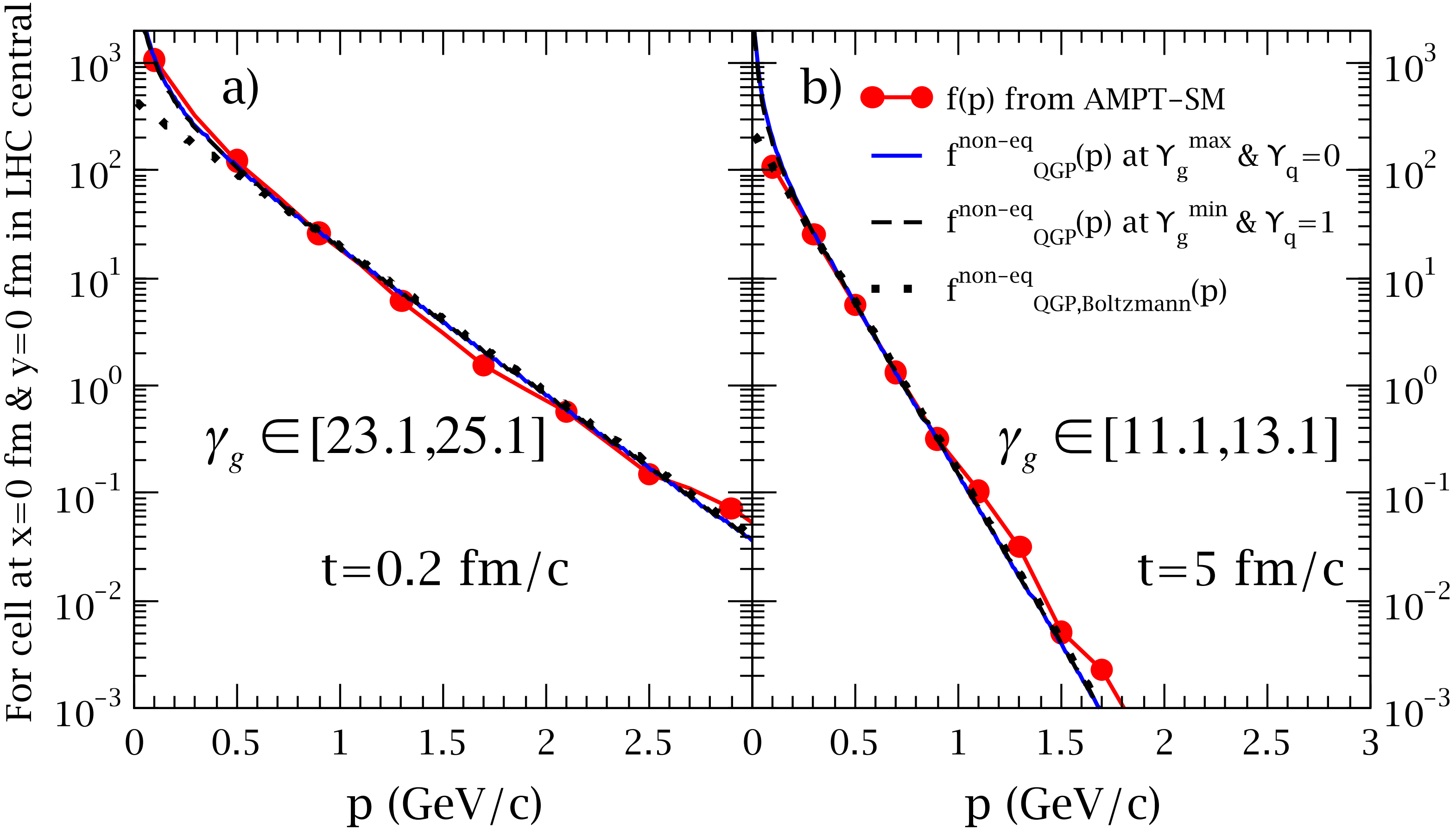
➔ Gluons must be over-populated.

Over-population of partons

Compare *f(p)* in center cell of LHC central with **non-equilibrium** functions:

$$f_{QGP,Boltzmann}(p) = \left(16\gamma_g + 12N_f\gamma_q\right)e^{-p/T}, \text{ or } f_{QGP}^{non-eq}(p) = \frac{16\gamma_g}{e^{p/T}-1} + \frac{12N_f\gamma_q}{e^{p/T}+1}.$$

γ_g & γ_q *are gluon & quark phase-space occupancy factors, respectively*



Set T as $T_{<p_T>}$, then match ε of the cell

➔ an equation for γ_g and γ_q

Pauli principle

$\gamma_q \in [0,1]$

$\Rightarrow \gamma_g^{max}$ & γ_g^{min}:

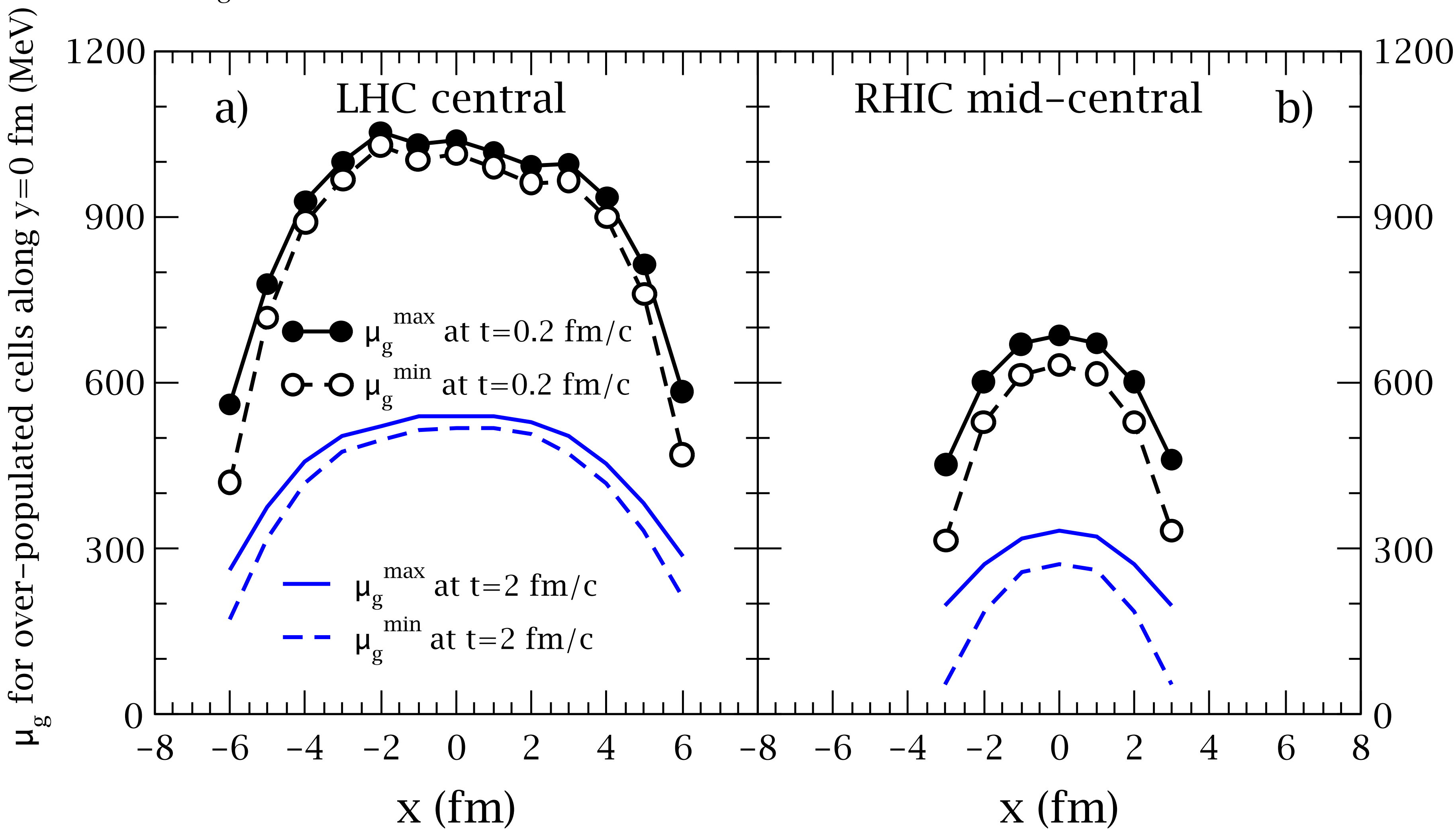
range of γ_g

f(p) can be described well by **non-equilibrium** functions, with $\gamma_g >> 1$

Over-population of partons

Can also use **gluon "chemical potential"** μ_g to represent gluon over-population:

$$\gamma_g \equiv e^{\left(\frac{\mu_g}{T_{<p_T>}}\right)}, \qquad \text{range of } \gamma_g \Rightarrow \text{range of } \mu_g$$



Summary

Effective temperatures extracted from different variables

(ε, n, <E>, <p_T>, … in the rest frame of each cell)

can be quite different

➔ the parton matter from AMPT-SM is not in full equilibrium

$T_\varepsilon > T_{<p_T>}$ is seen over the inner part of the overlap volume

➔The parton system (at least the gluons) is over-populated there, often by a large factor.

Parton phase-space distributions from the constrained AMPT-SM model

- cannot be described by QGP in full equilibrium (Boltzmann or quantum)
- can be described well by non-equilibrium QGP (with phase-space occupancy factors γ_g & γ_q)

A large gluon over-population gives $\gamma_g >> 1$, or $\mu_g >> T_{<p_T>}$