Inhomogeneities in the freeze-out of relativistic heavy-ion collisions

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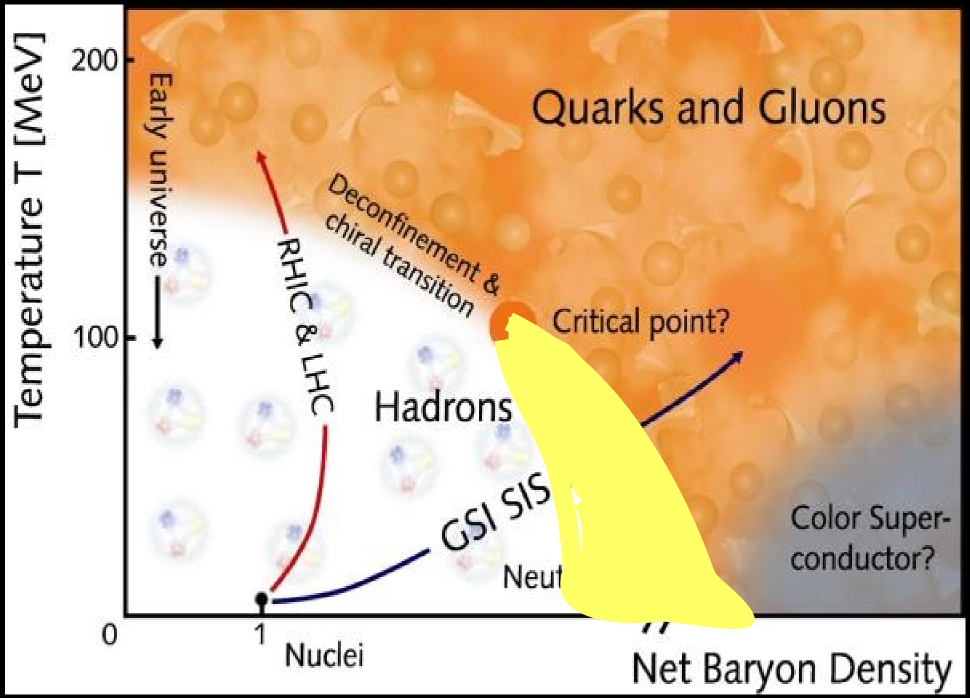
- Introduction
- Inhomogeneities?
- From homogeneous to inhomogeneous freeze-out models
- Results for CERN-SPS and BNL-RHIC
- Summary

Phys Rev C, 73 (2006)

Phase diagram & Heavy Ion Collisions



- expected that phase border is crossed during rel. heavy ion coll.

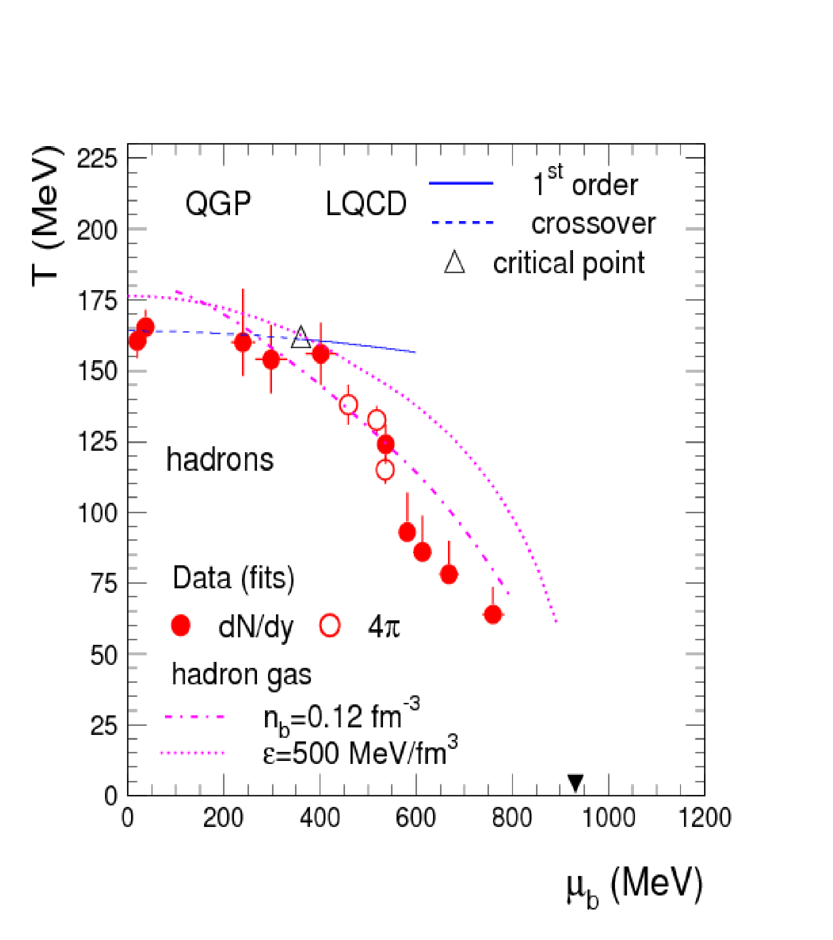
  different paths in the T-ρ plane for different energies

  "switching" between 1st order p.t. and crossover

  Maybe visible already in particle yields/ratios ?

Single, global freeze-out

Ideal Gas freeze-out



Andronic, Braun-Munzinger and Stachel, nucl-th 0511071
Becattini, Manninen, Gazdzicki, PRC 73 (2006)

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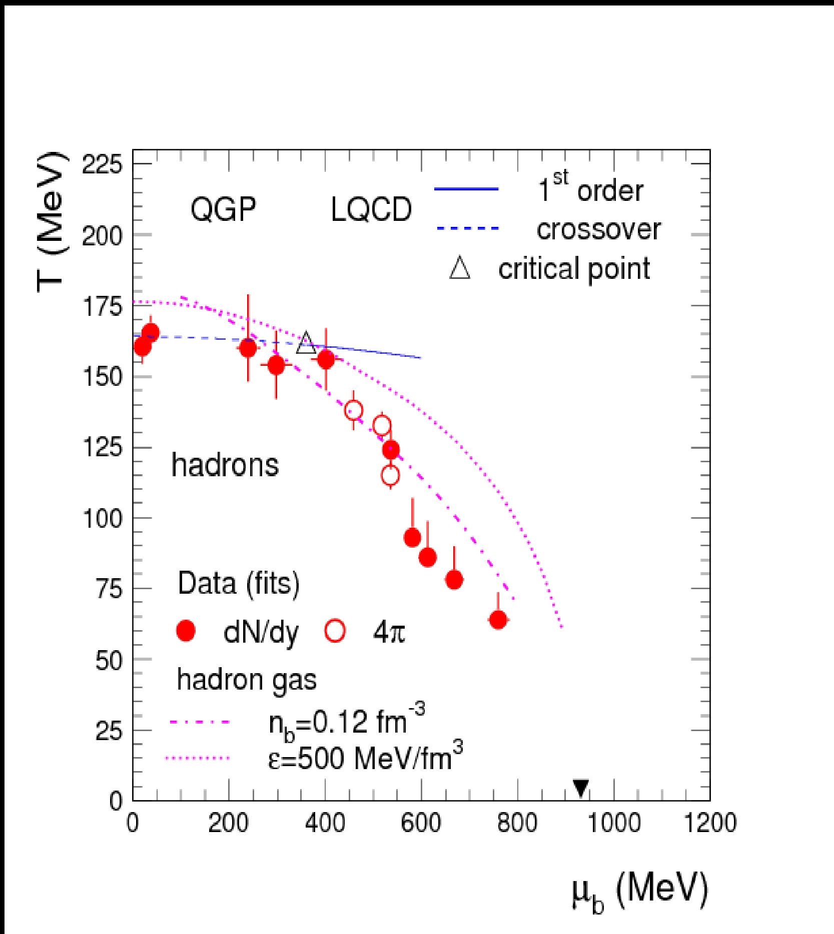
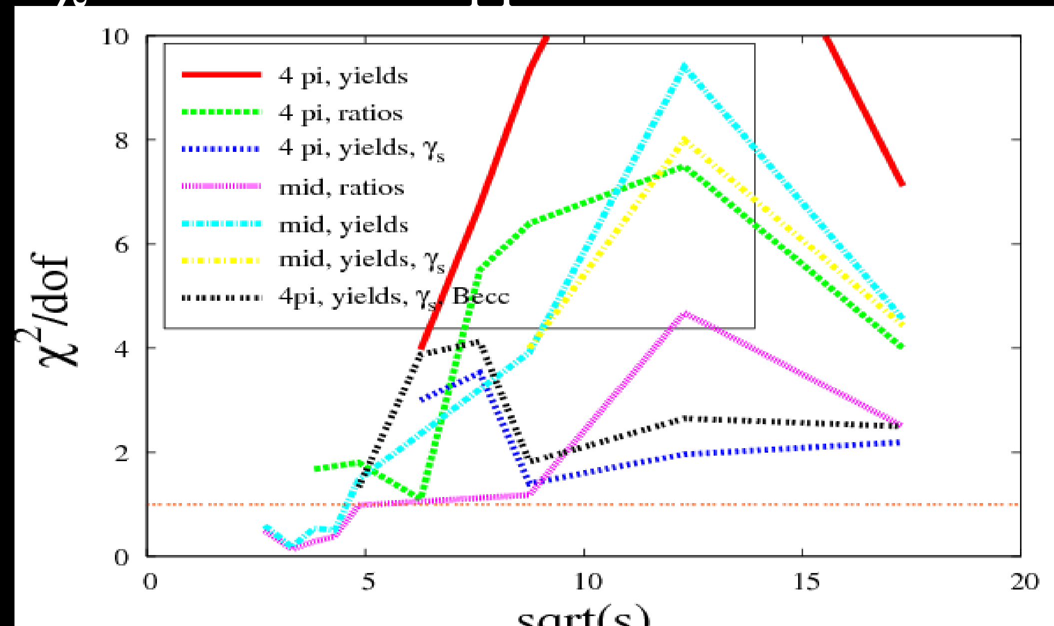
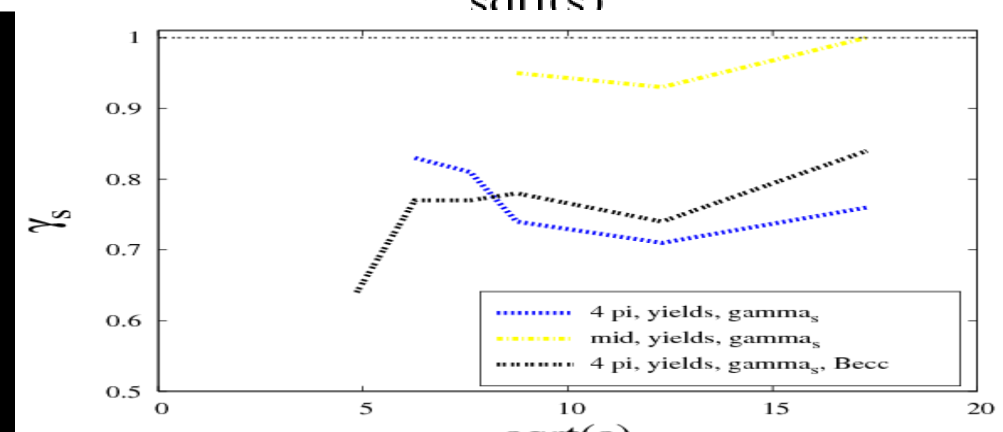


χ^2 for different approaches and data





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Becattini, Manninen, Gazdzicki, PRC 73 (2006)

Single freeze-out with interactions

chiral SU(3) σ-ω-model

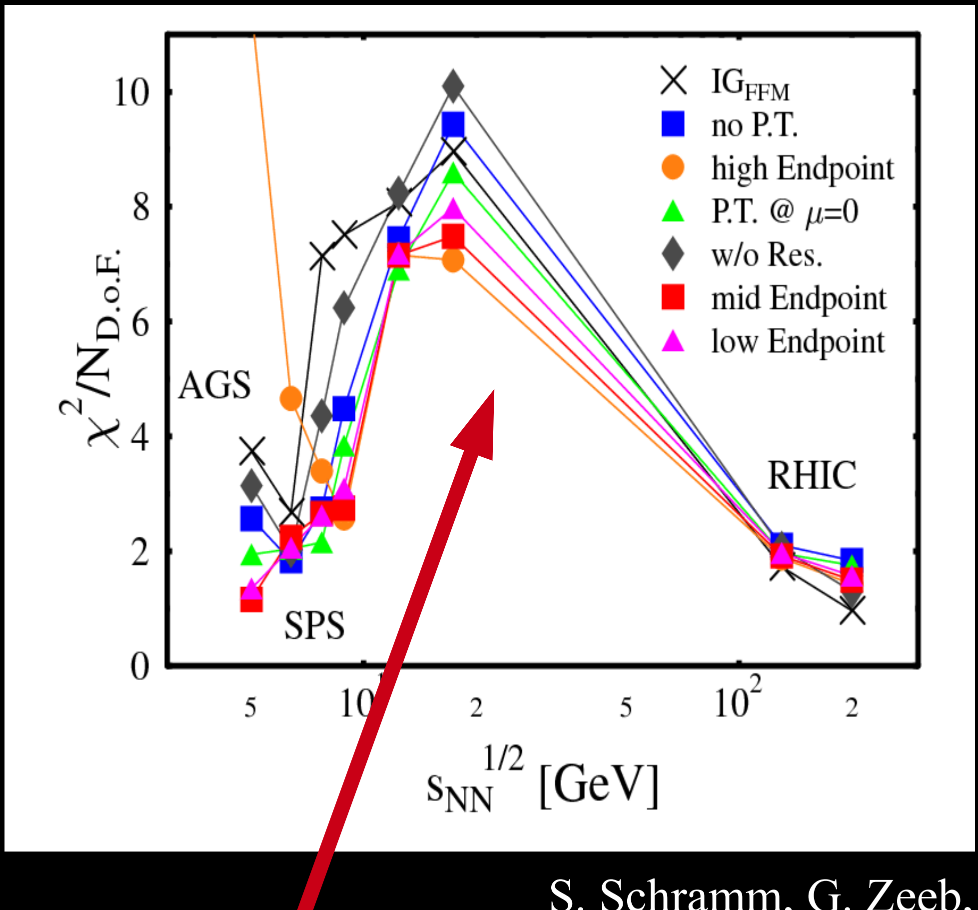
$$m_N \sim g_{N\sigma}\sigma + g_{N\zeta}\zeta$$

$$m_\pi \sim m_\pi^{vac}\sqrt{\frac{\sigma_0}{\sigma}}$$

$$\mu_i^* = \mu_i - g_{i\omega}\omega$$

investigate different possible phase structures, resulting from different Baryon-Meson couplings

Ideal and interacting hadron gas χ^2



S. Schramm, G. Zeeb, D.Z.

large χ^2/dof at mid/high SPS !

Why does single, global freeze-out have problems/fail?
Can this be connected to crossing the phase boundary?

Possibility: *Inhomogeneities on the freeze-out surface*

NOT
EbyE fluctuations with one/very few high density bubbles
BUT
many small (1-2 fm) hot
spots in every event,

i.e., in each single event
something
like this:

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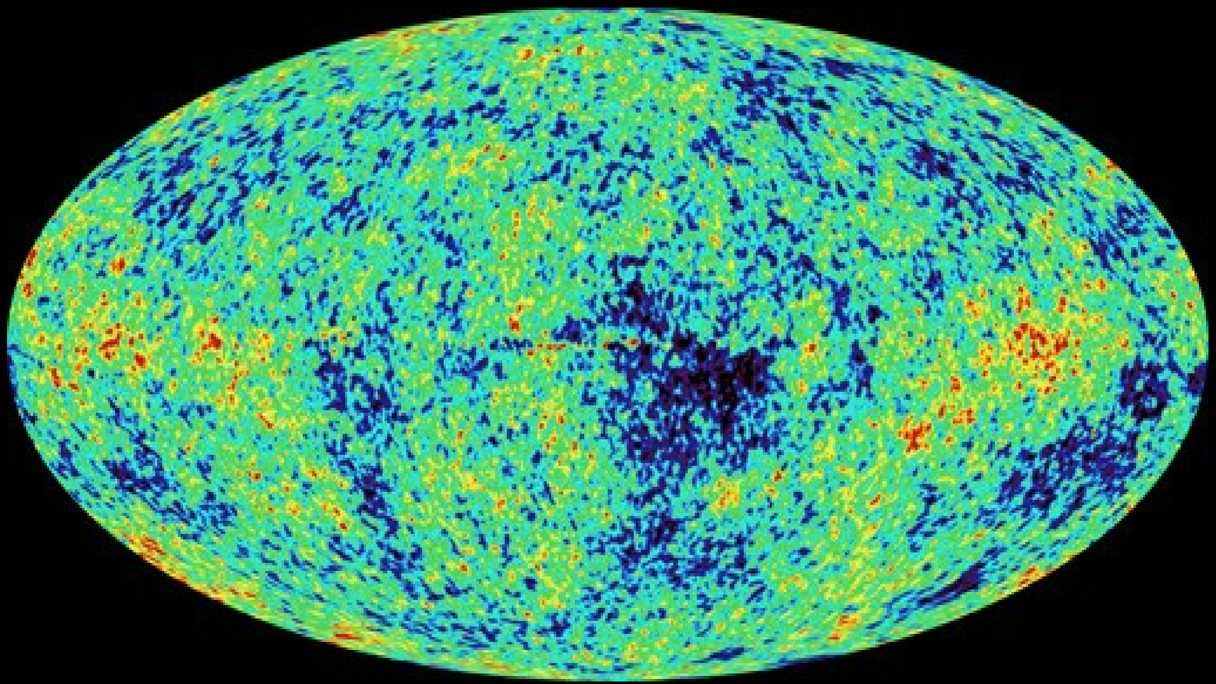


WMAP: http://lambda_gsfc.nasa.gov/product/map/m_images.cfm

Sources of Inhomogeneities

- large inhomog. from primary collisions predicted:

Bleicher et al (UrQMD): NPA 638 ('98) 391
Gyulassy, Rischke, Zhang (HIJING): NPA 613 ('97) 397
Socolowski, Grassi, Hama, Kodama (NEXUS): hep-ph/0405181

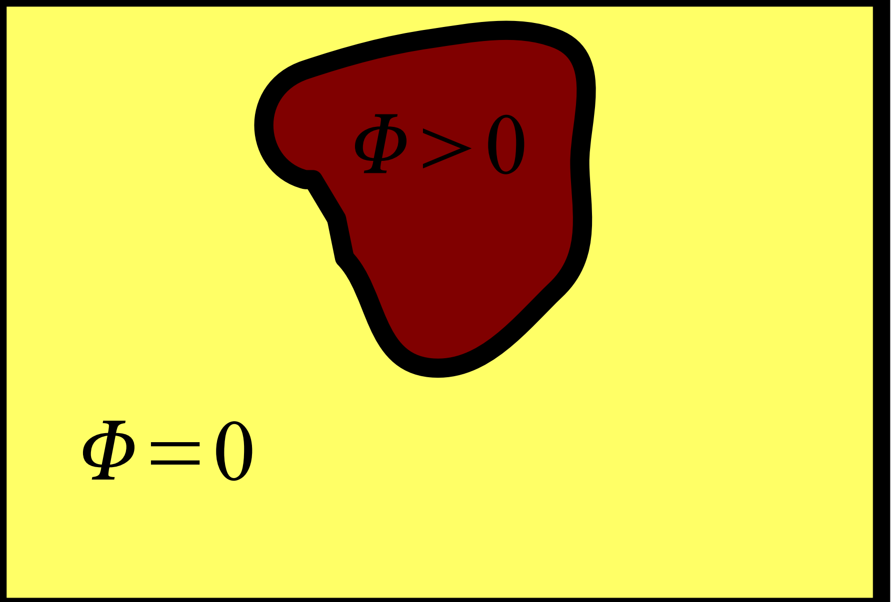
BUT:

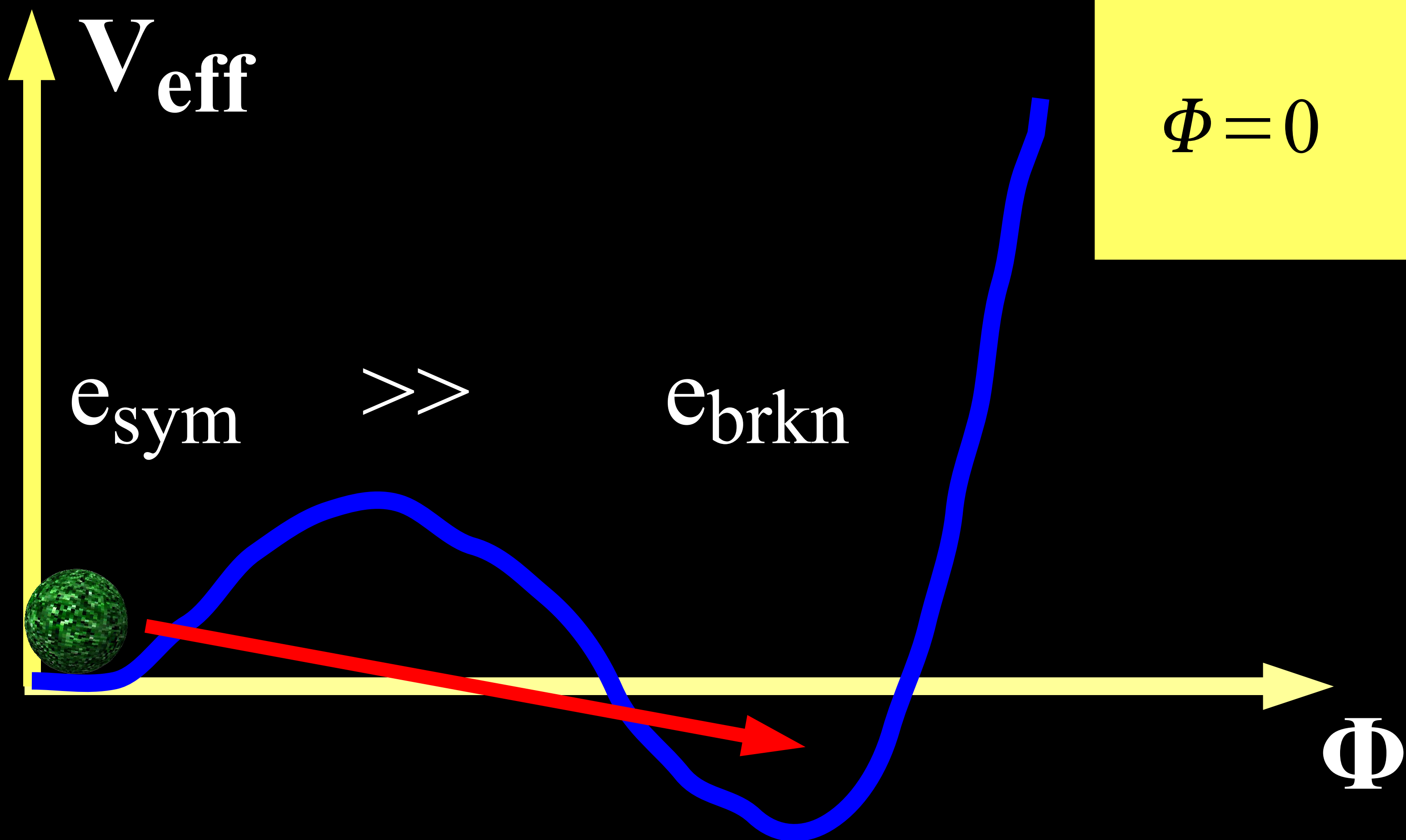
for expansion in 3D, density contrast decreases like $\Delta\rho \sim 1/t^3$
so for $t_{fo} \sim 10\ t_0$ they are washed out to perhaps ~ 1 %

However

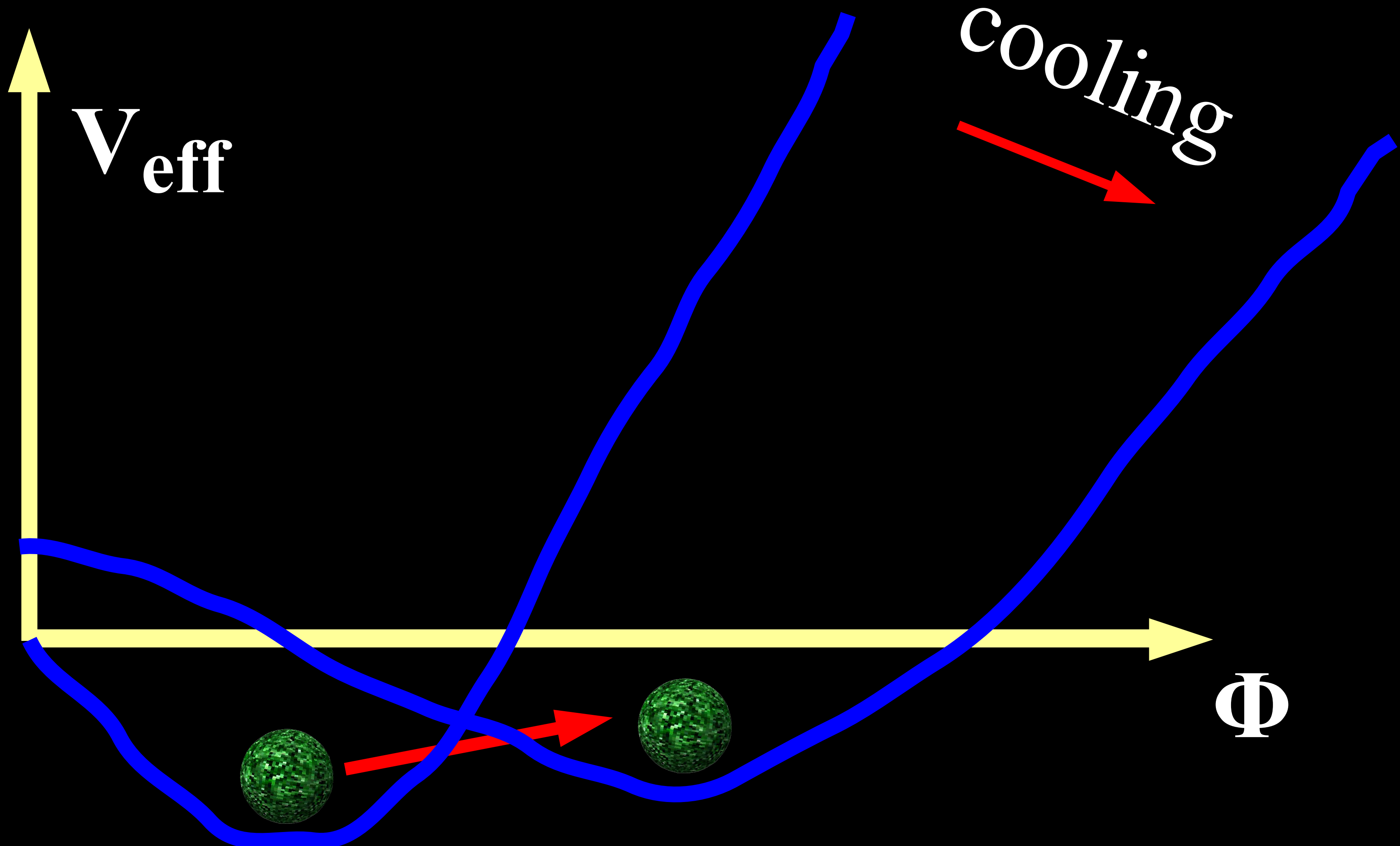
- If the system crosses a first order phase transition, this may lead to inhomogeneities in order parameter, energy density, baryon density,...

Thermal 1st-O transition





Cross over

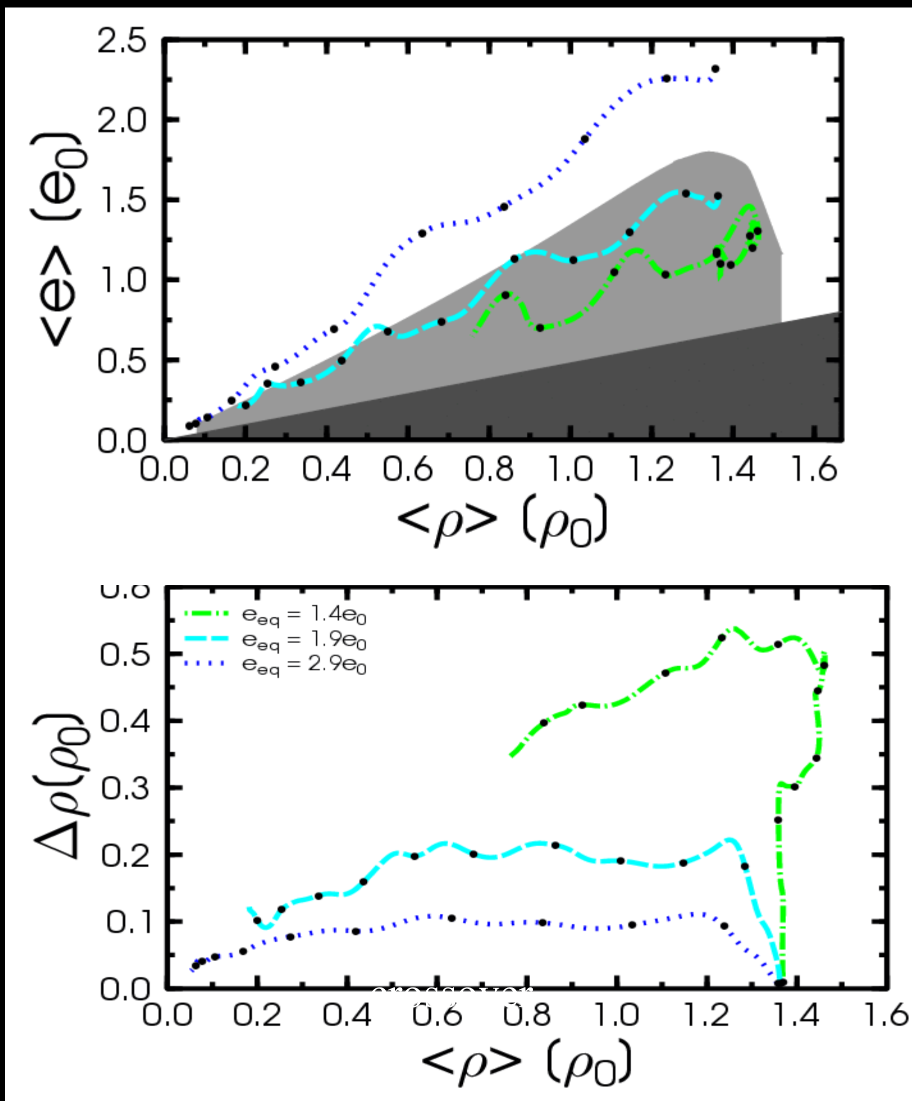


- e varies smoothly with Φ

→ expect more homogeneous system

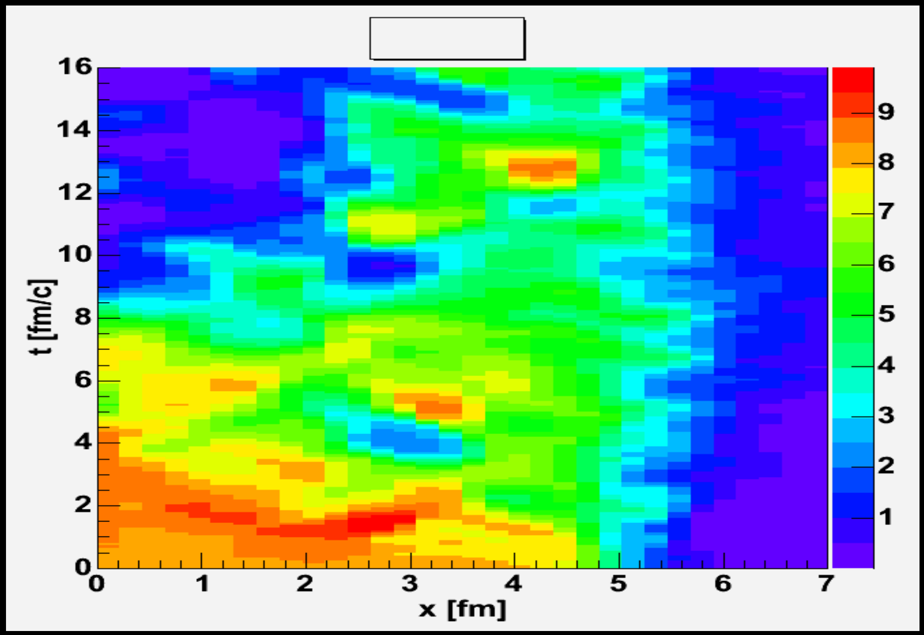
Non-equilibrium Hydro Simulation

different paths, depending on initial conditions



K. Paech & A. Dumitru, PLB 623, 200-207 (2005)
K.P., H. Stöcker, A.D., PRC 68 (2003)

energy density for 1st order



Inhomogeneities are generated in the course of non-equilibrium 1st order transition

Observables ?

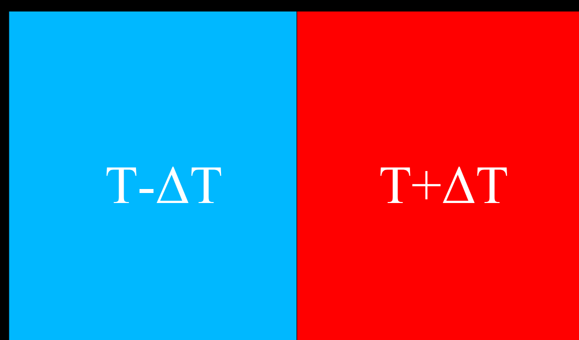
Freeze-out shortly after phase transition

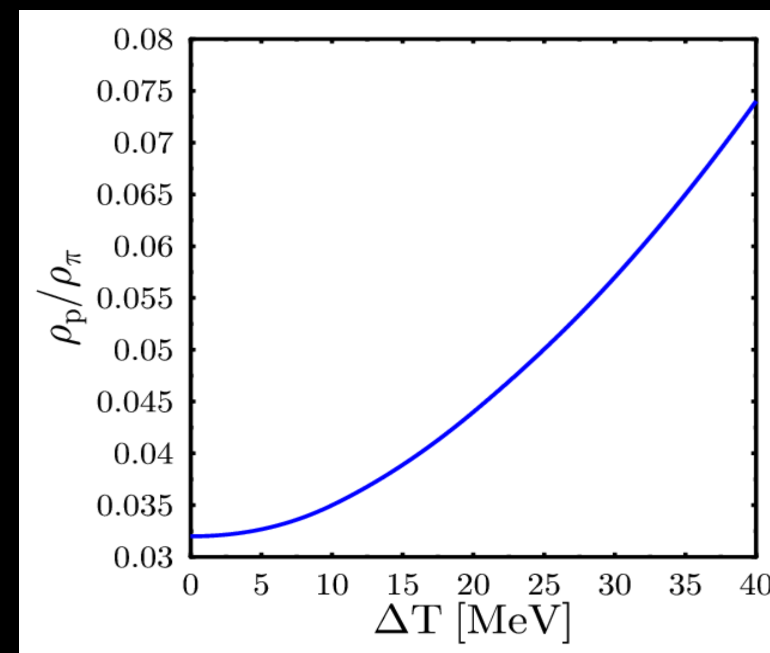
→ inhomogeneities on the freeze-out surface

Bulk/event averaged hadron densities depend non-linearly on density/temperature perturbations at freeze-out

Simple example: Two regions

T=150 MeV
μ = 0





Inhomogeneities might reflect in hadron "chemistry" !
similar to Inhomogeneous Big Bang Nucleosynthesis (IBBN)

Inhomogeneous baryon density during nucleosynthesis [e.g. Applegate & Hogan, PRD31 (1985)]
generated e.g. in QCD phase transition [e.g Witten, PRD30 (1984)]

Hadron Multiplicity Ratios

- standard homog. thermal model

$$N_i = \int d\sigma_\mu (u^\mu \rho_i) \; = \; \rho_i (T_{fo}, \mu_{fo}) \; \times \; Vol_3$$

include decays j→i with corresponding branching ratio

$$R_{i/n} = \frac{\sum_j B_{j \to i} \rho_j}{\sum_j B_{j \to n} \rho_j}$$

T_{fo}, μ_{fo} are determined as (T, μ) pair minimizing χ^2

Simple model for inhomogeneous freeze-out surface:

take T,μ as Gaussian random variables,

$$P[T] \sim \exp -\frac{(T-\bar{T})^2}{2\,\delta T^2} \qquad P[\mu] \sim \exp -\frac{(\mu-\bar{\mu})^2}{2\,\delta\mu^2}$$

This is the distribution on the f.o. surface in each event!
Do not confuse with EbyE fluctuations !

$$N_i = Vol_3 \times \bar{\rho}_i(\bar{T},\bar{\mu},\delta T,\delta\mu)$$

$$\bar{\rho}_i(\bar{T},\bar{\mu},\delta T,\delta\mu) = \int dT\, P[T] \int d\mu\, P[\mu]\; \rho_i(T,\mu)$$

$$\neq \rho_i(\bar{T},\bar{\mu}) \; !$$

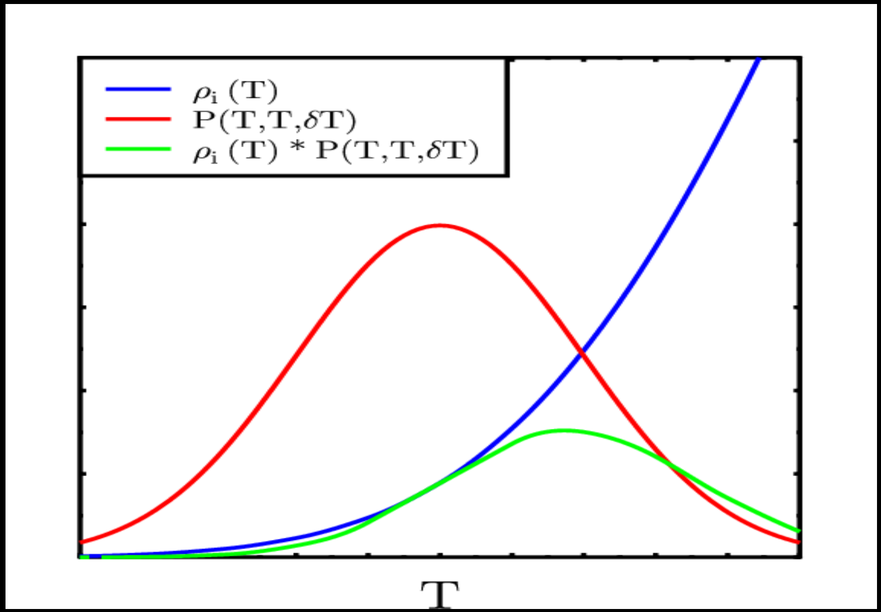
:

Probability distributions

fold Gaussian with ideal gas density:

$$D_i(T, \bar{T}, \bar{\mu}_B, \delta T, \delta\mu_B) = P(T; \bar{T}, \delta T) \frac{\int_{-\infty}^{\infty} d\mu_B P(\mu_B; \bar{\mu}_B, \delta\mu_B) \rho_i(T, \mu_B)}{\rho_i(\bar{T}, \bar{\mu}_B, \delta\mu_B, \delta T)}$$

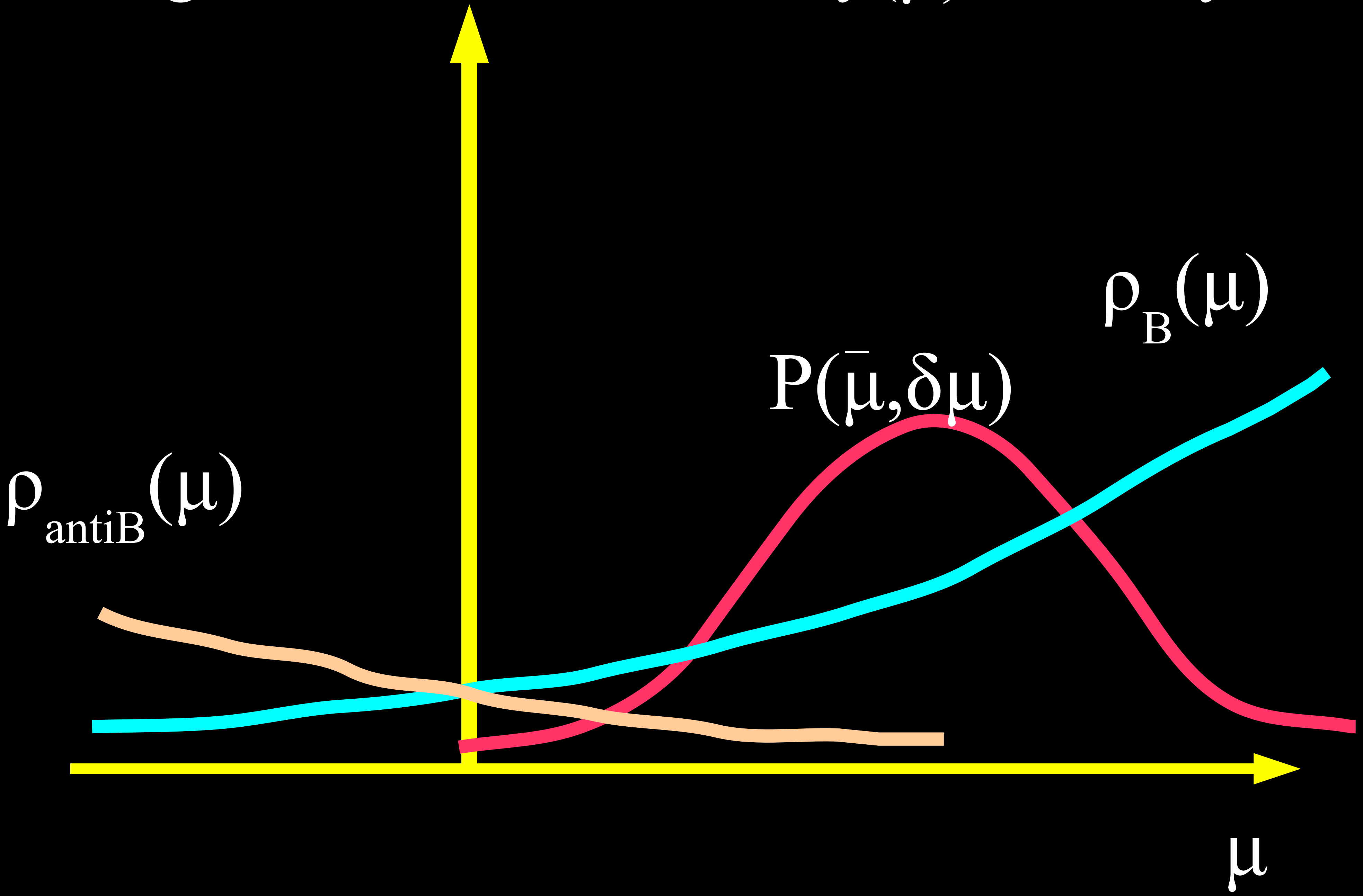
$$D_i(\mu_B, \bar{T}, \bar{\mu}_B, \delta T, \delta\mu_B) = P(\mu_B; \bar{\mu}_B, \delta\mu_B) \frac{\int_0^{\infty} dT\, P(T; \bar{T}_B, \delta T) \rho_i(T, \mu_B)}{\rho_i(\bar{T}, \bar{\mu}_B, \delta\mu_B, \delta T)}$$



$$\rho_i(T, \mu_B) \sim \int d^3k \frac{1}{e^{\frac{E_i - \mu_i}{T}} \pm 1}$$

yields different distribution for each particle species !

Folding Gaussian with density(μ) for Baryons



Mean emission temperatures/chemical potentials

now different for different particle species, depending on Gaussian widths

$$\langle T \rangle_i = \int dT\, T\, D_i(T, \bar{T}, \bar{\mu}_B, \delta T, \delta \mu_B)$$

$$\langle \mu_B \rangle_i = \int d\mu_B\, \mu_B\, D_i(\mu_B, \bar{T}, \bar{\mu}_B, \delta T, \delta \mu_B)$$

massles particles:

$$\frac{\langle T \rangle}{\overline{T}} = 1 + \frac{\delta T^2}{\overline{T}^2}\left(\frac{m}{\overline{T}} - \frac{\mu_B}{\overline{T}} + \frac{3}{2}\right) = 1 + \frac{\delta T^2}{\overline{T}^2}\left(\frac{m}{\overline{T}} + O(1)\right) .$$

$$\frac{\langle T \rangle}{\overline{T}} = 1 + 3\frac{\delta T^2}{\overline{T}^2} + \cdots$$

very heavy particles:

$$D(T) \sim \overline{T}^{\frac{3}{2}} \exp\left(\frac{3}{2}\log(T/\overline{T}) + \frac{\mu_B - m}{T} + \frac{\delta\mu_B{}^2}{2\overline{T}^2} - \frac{(T-\overline{T})^2}{2\,\delta T^2}\right) .$$

stat.point

$$\frac{\langle T \rangle}{\bar{T}} = 1 + \frac{\delta T^2}{\bar{T}^2}\left|\frac{m}{\bar{T}} - \frac{\mu}{\bar{T}} + \frac{3}{2}\right|$$

Data and analysis

- SPS: Na49 data for central Pb-Pb @ 20,30,40,80 and 158 AGeV

- RHIC: STAR data for central Au+Au collisions @ 130/200 AGeV

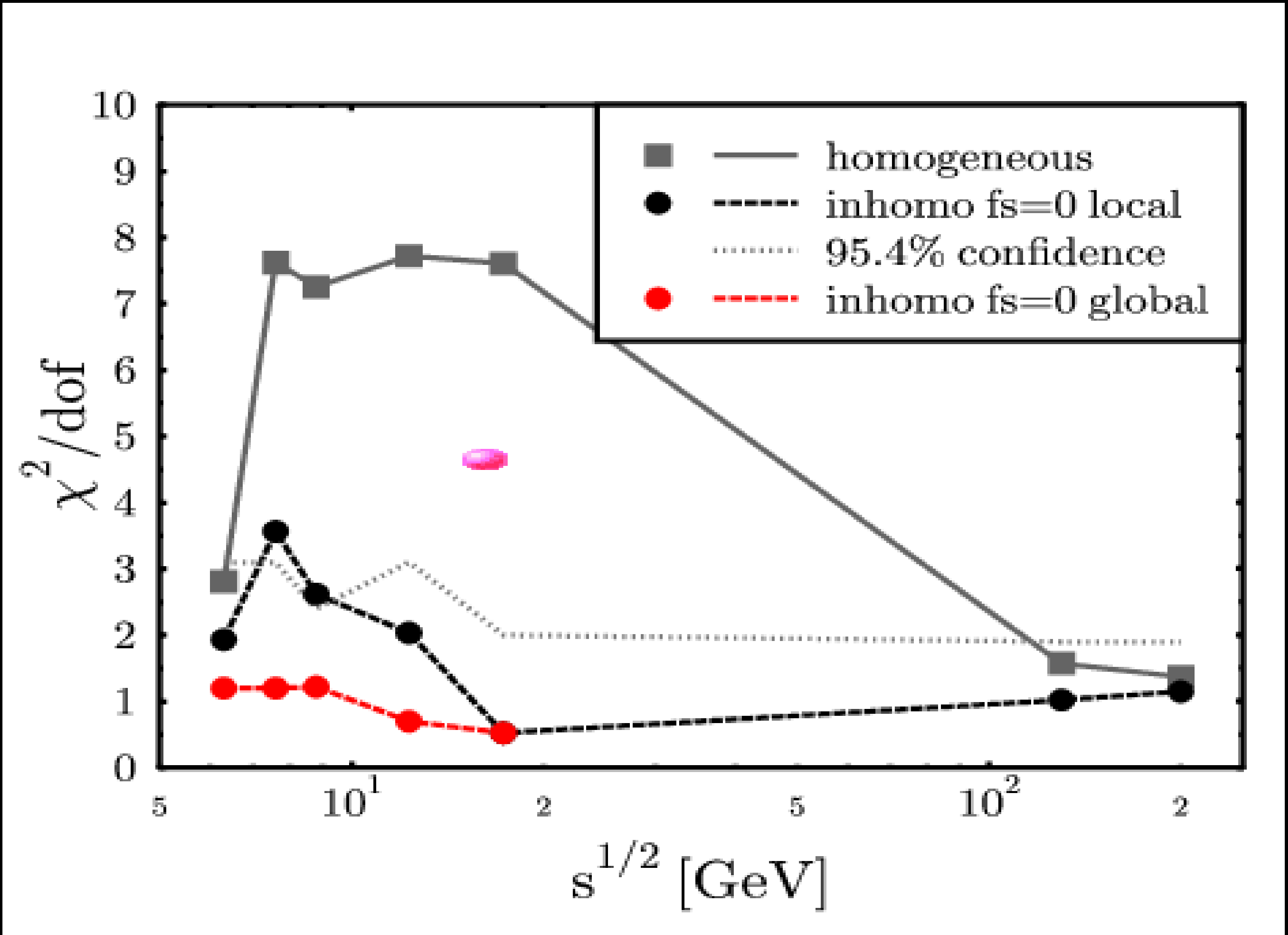
- Determination of minima of $$\chi^2 = \sum_i \left(\frac{r_i^{\mathrm{exp}} - r_i^{\mathrm{model}}}{\sigma_i^{\mathrm{exp}}} \right)^2$$

- Compare homogeneous ansatz ($\delta T = \delta\mu = 0$) and inhomogeneous ansatz (T,μ Gaussian distributed with finite widths δT, $\delta\mu$)

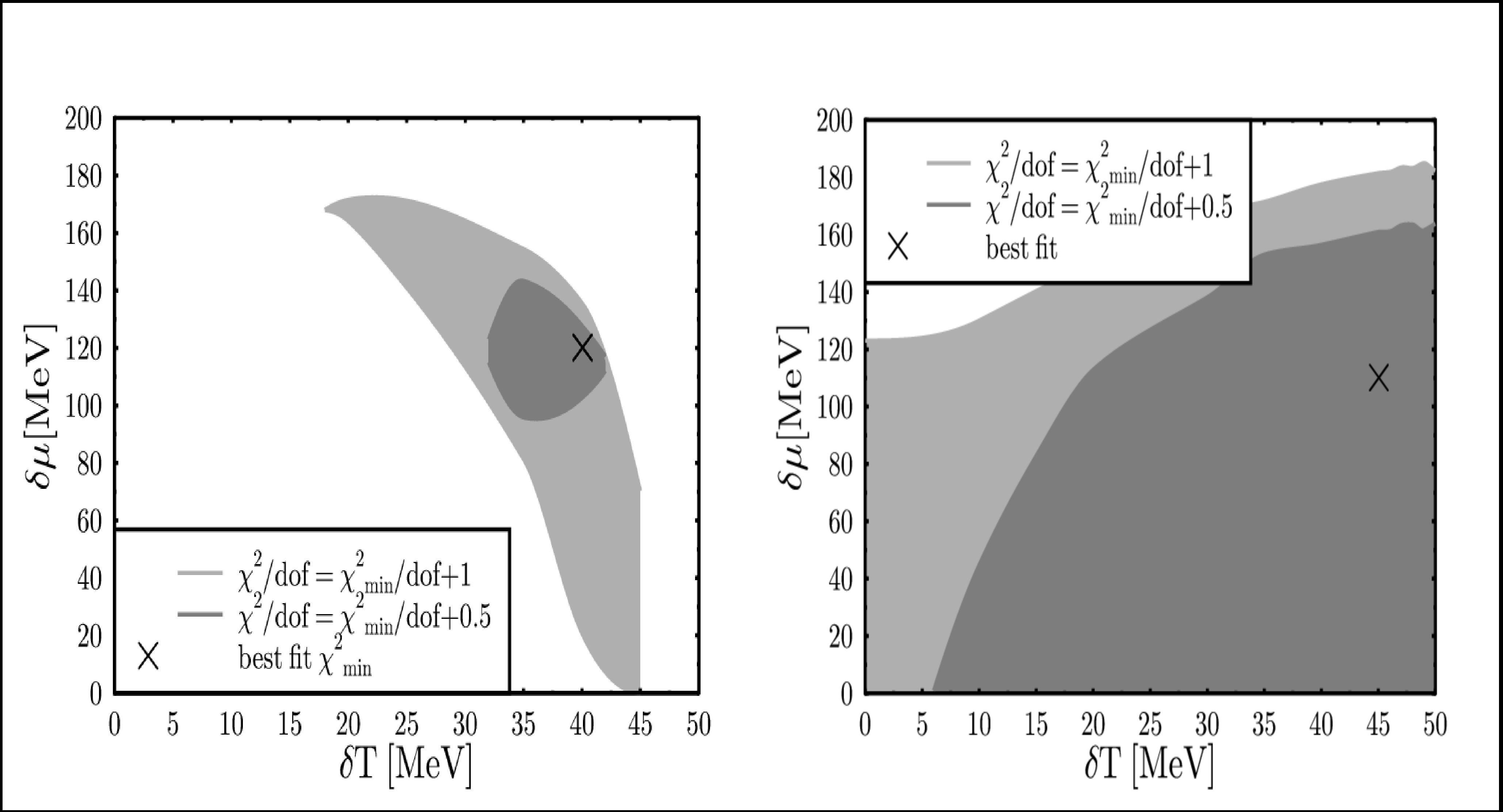
- Does the inhomogeneous ansatz improve the description considerably ? I.e., is χ^2/dof significantly lowered?

consider local and global strangeness conservation

Excitation function of χ^2



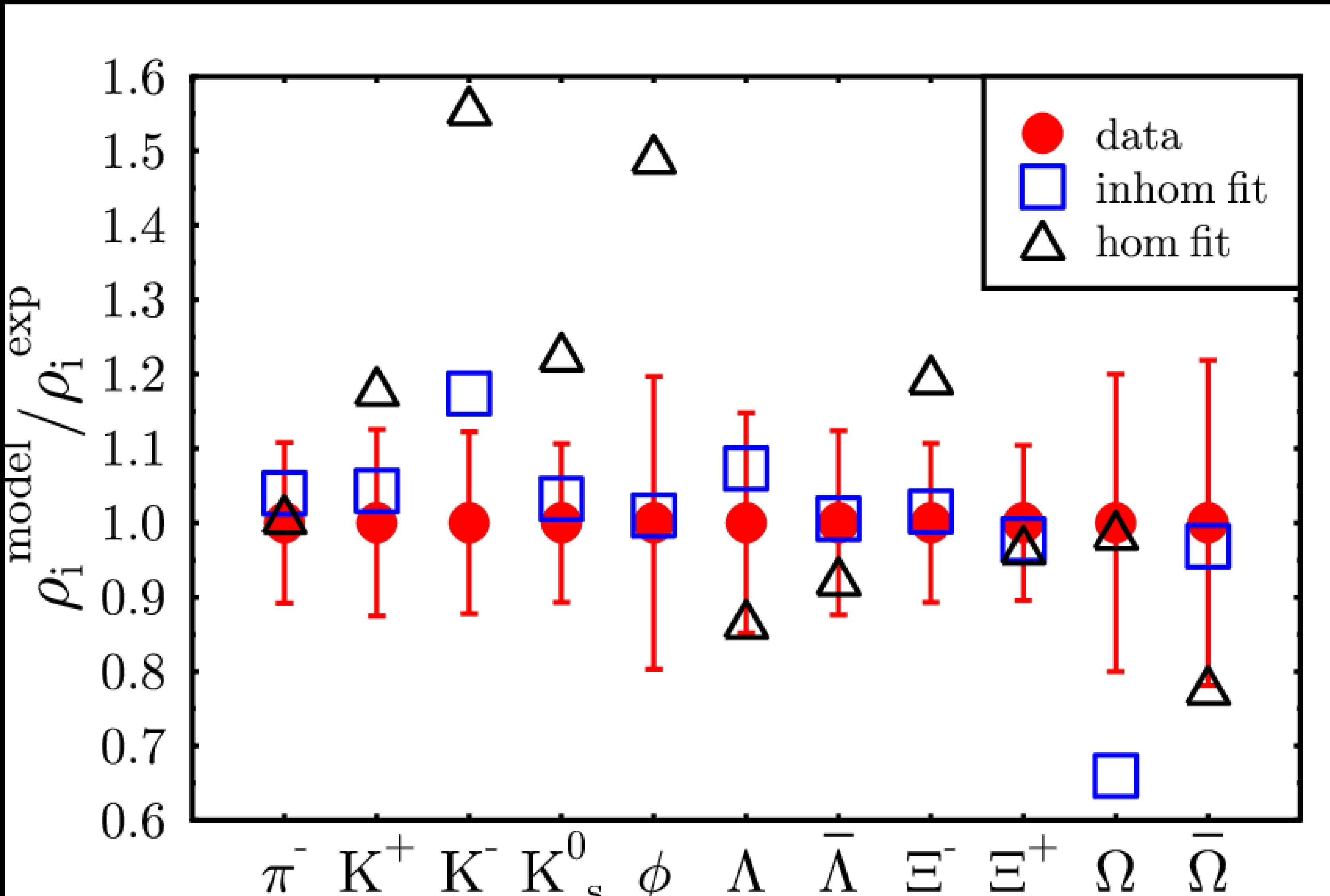
χ^2/dof contours



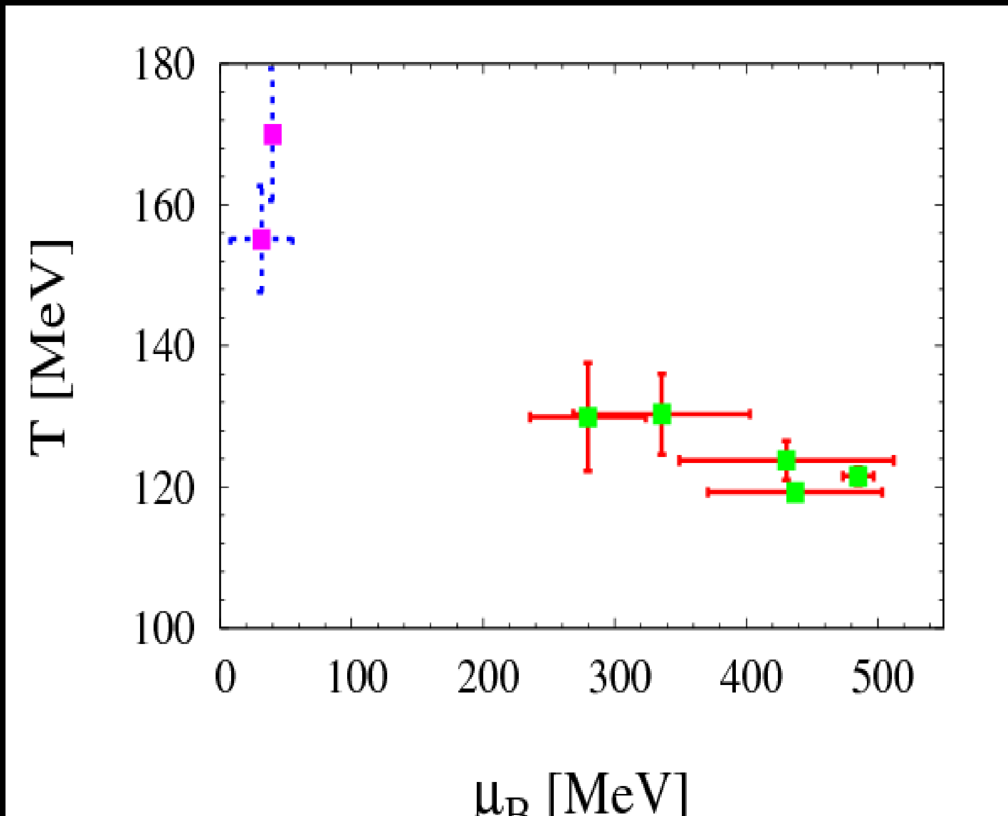
stat. significance for large finite widths at SPS

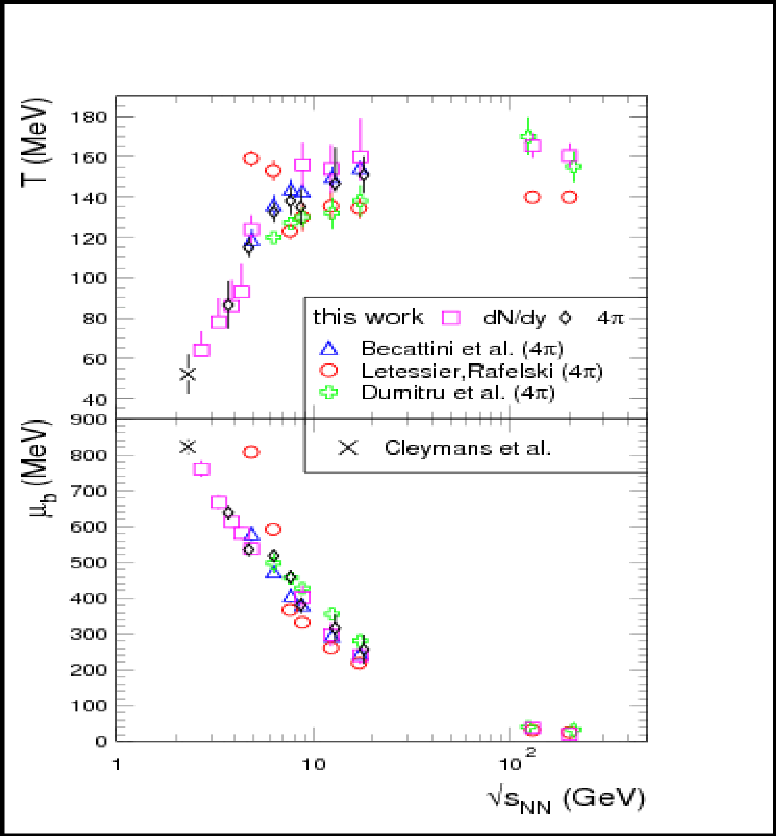
@RHIC: no stat. significance for finite width

Best Fits for SPS @ 158 GeV/A



Physical particle emission values





$$\langle T\rangle = \frac{\sum_i \langle T_i\rangle \bar{\rho}_i}{\sum_i \bar{\rho}_i}$$

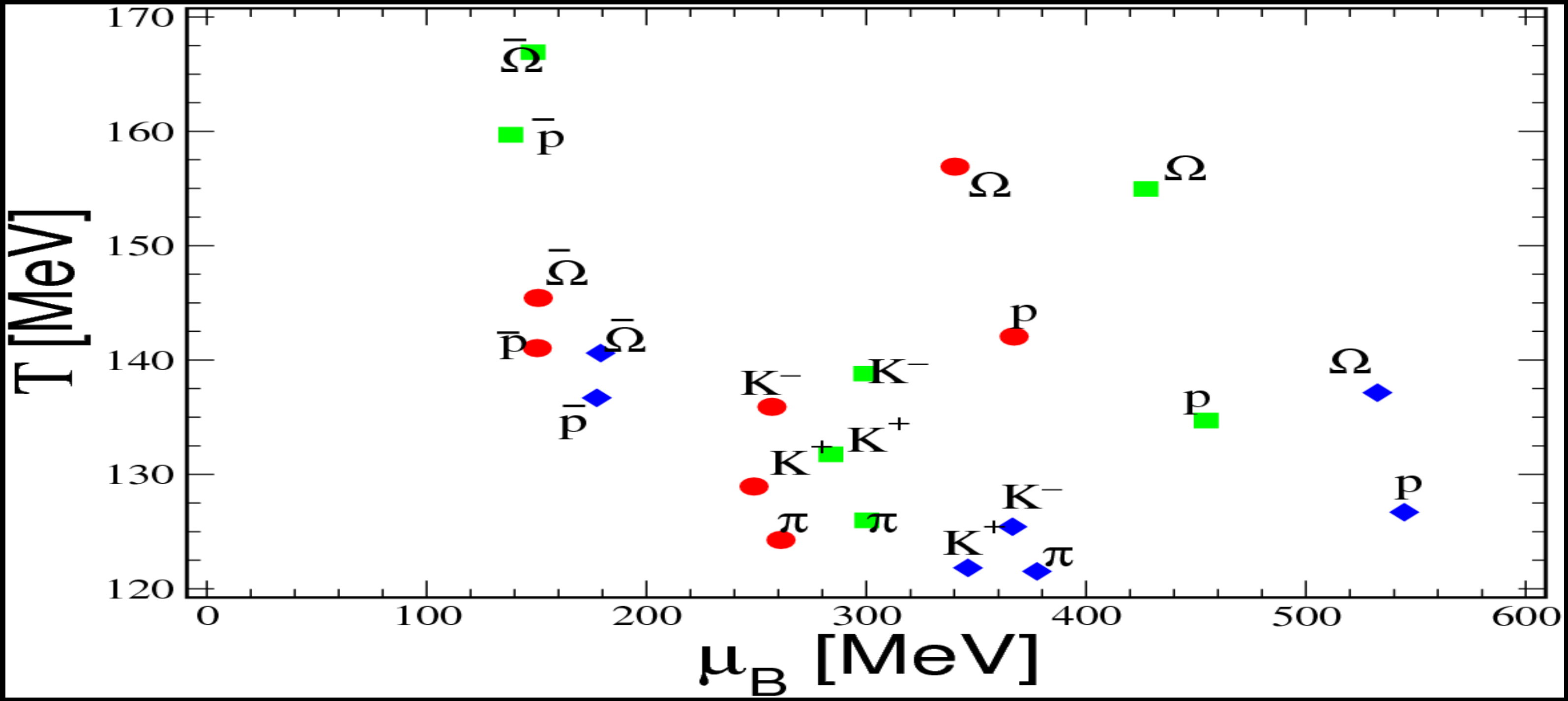
$$\delta\langle T\rangle = \sqrt{\frac{\sum_i (\langle T_i\rangle - \langle T\rangle)^2 \bar{\rho}_i}{\sum_i \bar{\rho}_i}}$$

Andronic, Braun-Munzinger and Stachel, nucl-th/0511071

"Error Bars" indicate RMS deviations over particle species

Be careful: Not stat. significant at RHIC!

Freeze-out at SPS – mean emission values



- individual freeze-out values spread over T-μ plane – only due to the finite width in T- and μ-distribution- not individual fit for each particle

- Baryons in average result from high μ and antibaryons from low μ regions

- Baryons show in general larger T than Mesons, especially than Pions

Summary

- Particle ratios are not completely understood in single freeze-out scenario

- Inhomogeneities on the freeze-out surface can strongly influence event-averaged abundances, i.e. possible link between rather easily measurable bulk observable and phase diagram

- Taking into account inhomogeneous freeze-out with global strangeness conservation yields χ^2/dof ~ 1 over all energies

- Data at intermediate SPS energies show statistically significant inhomogeneities ($\delta T, \delta\mu > 0$) . At RHIC and low SPS energies no stat. significance for inhomogeneities, i.e nearly homogeneous decoupling surface

- If inhomogeneities are present, then individual freeze-out values are spread over T-μ plane

OUTLOOK

EbyE flucs -> information about # of cells

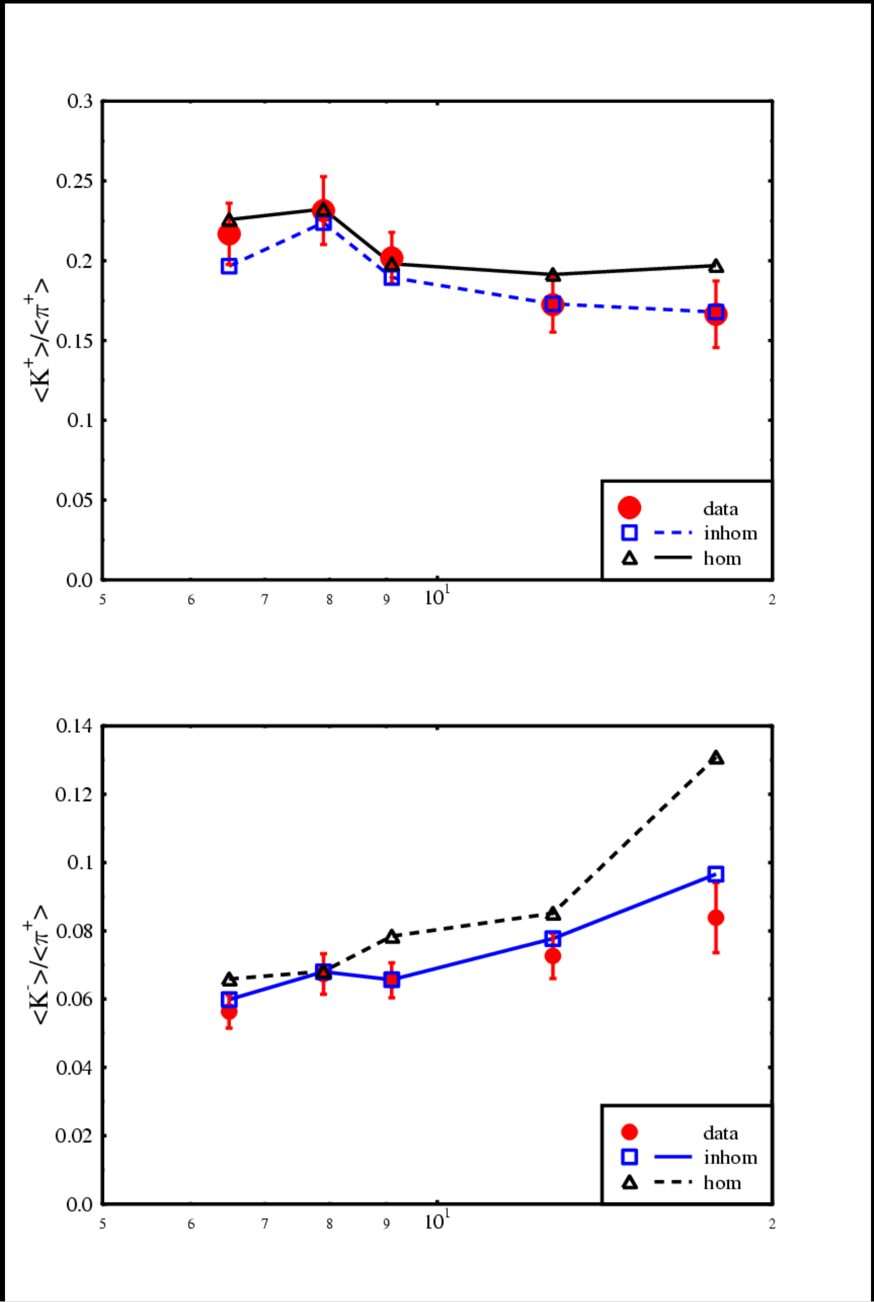
Observable in Interferometry?

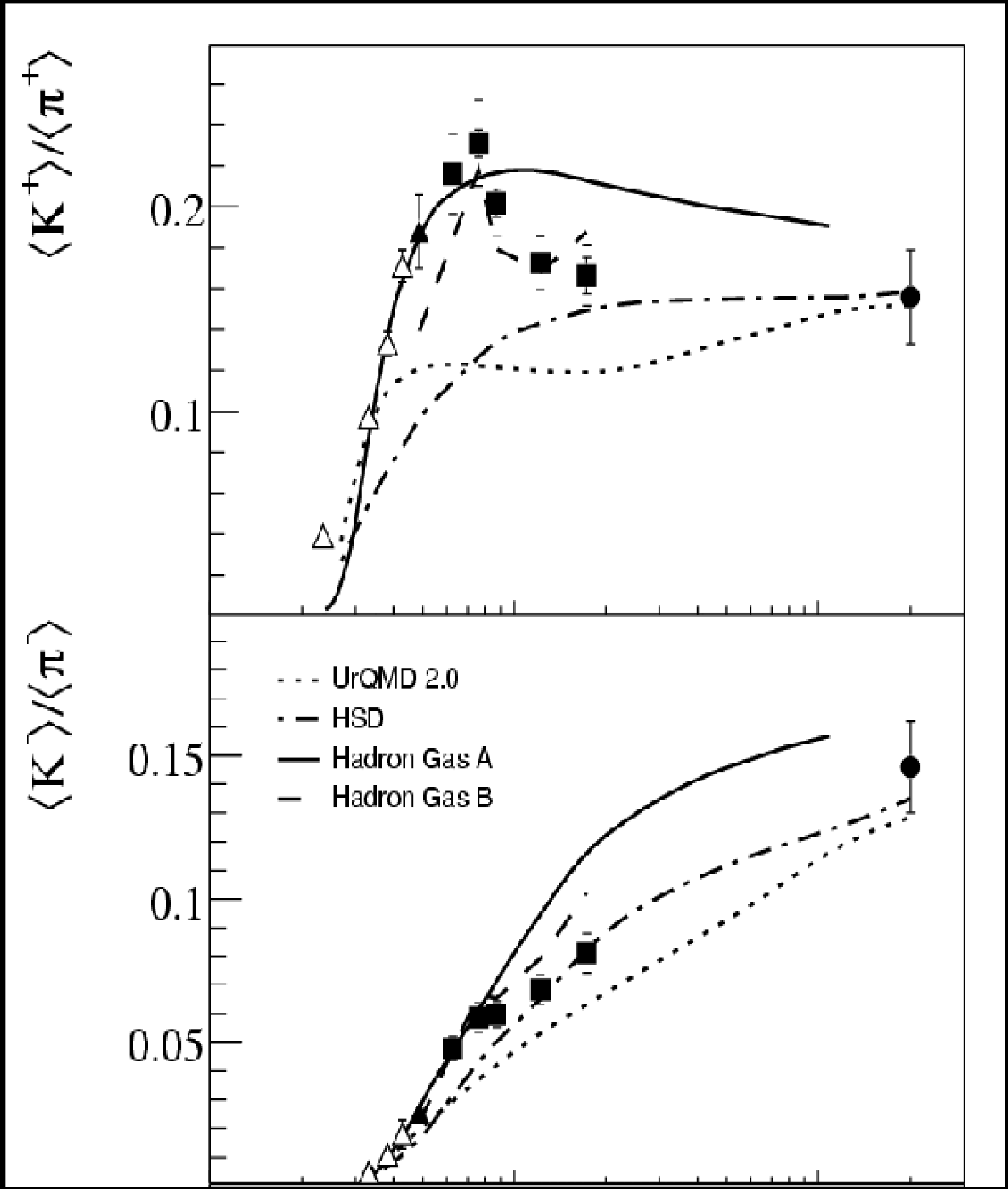
More observables? Reduced v2 predicted, what else?

Further work on consistent approach which generates Inhomogeneities – Study real time dynamics of PT probably also important for HBT!

Disentangle different possible contributions like e.g. continuous emission, 4π, different cross sections

Excitation function of Kaons



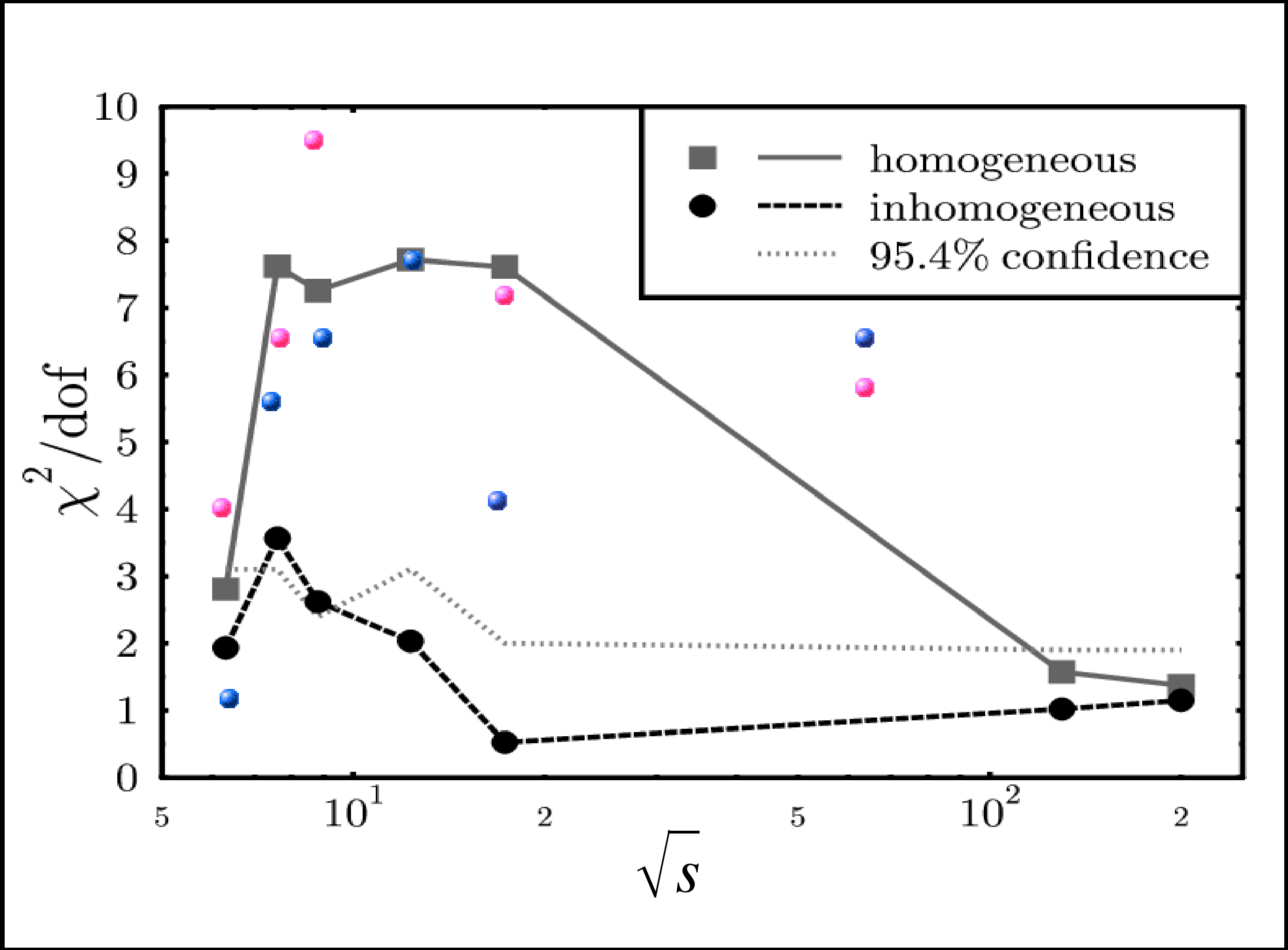


√s

Excitation function of χ^2/dof

intermediate energies:
χ^2/dof much lower for
inhomogeneous case
$\delta T, \delta\mu > 0$
stat. significant

No statistical significance
for inhomogeneities



Excitation function of Lambdas