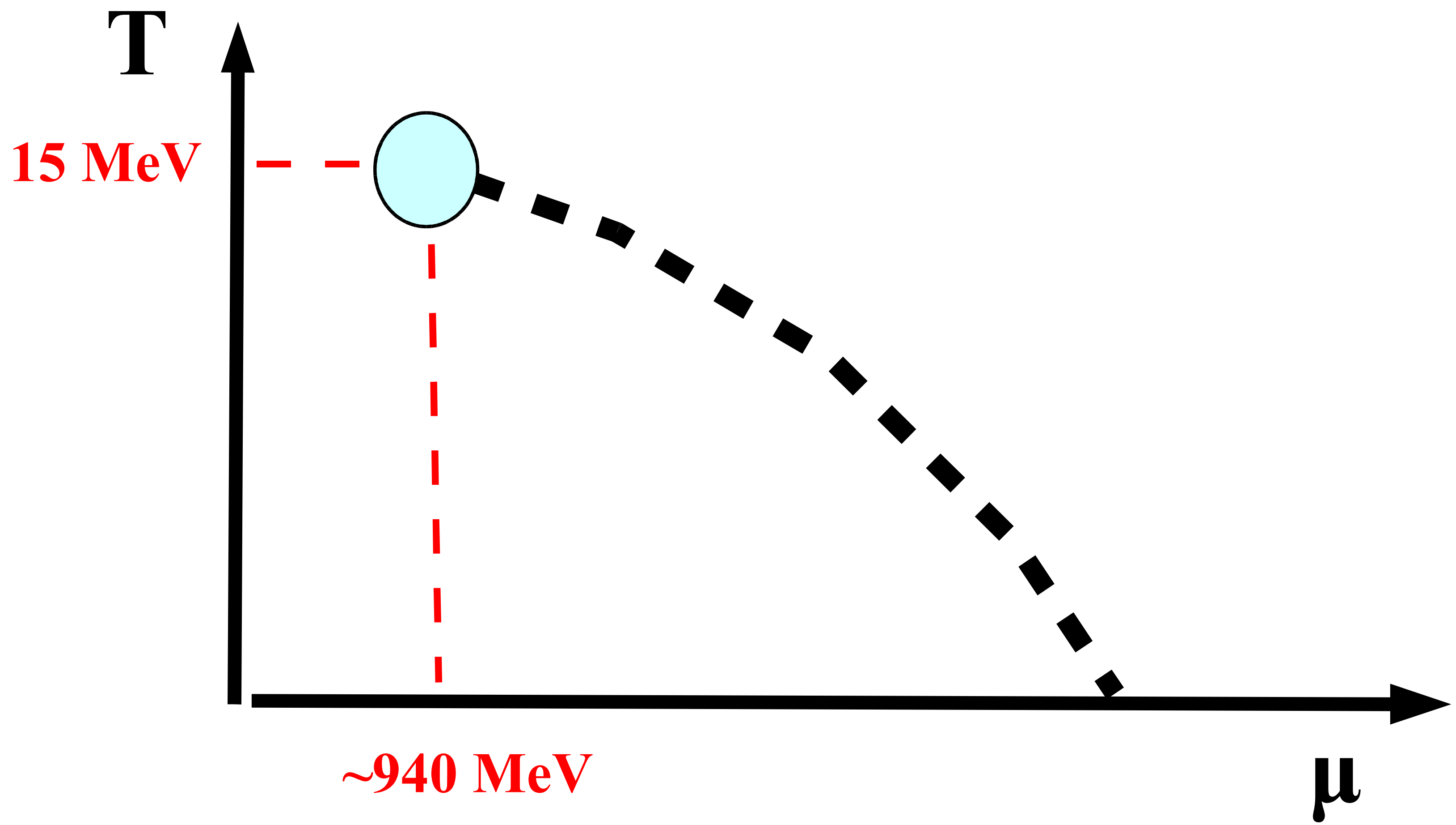
Fluctuations and Correlations

Everything has been said!

But not by everybody.....

The QCD Phase Diagram from experiment



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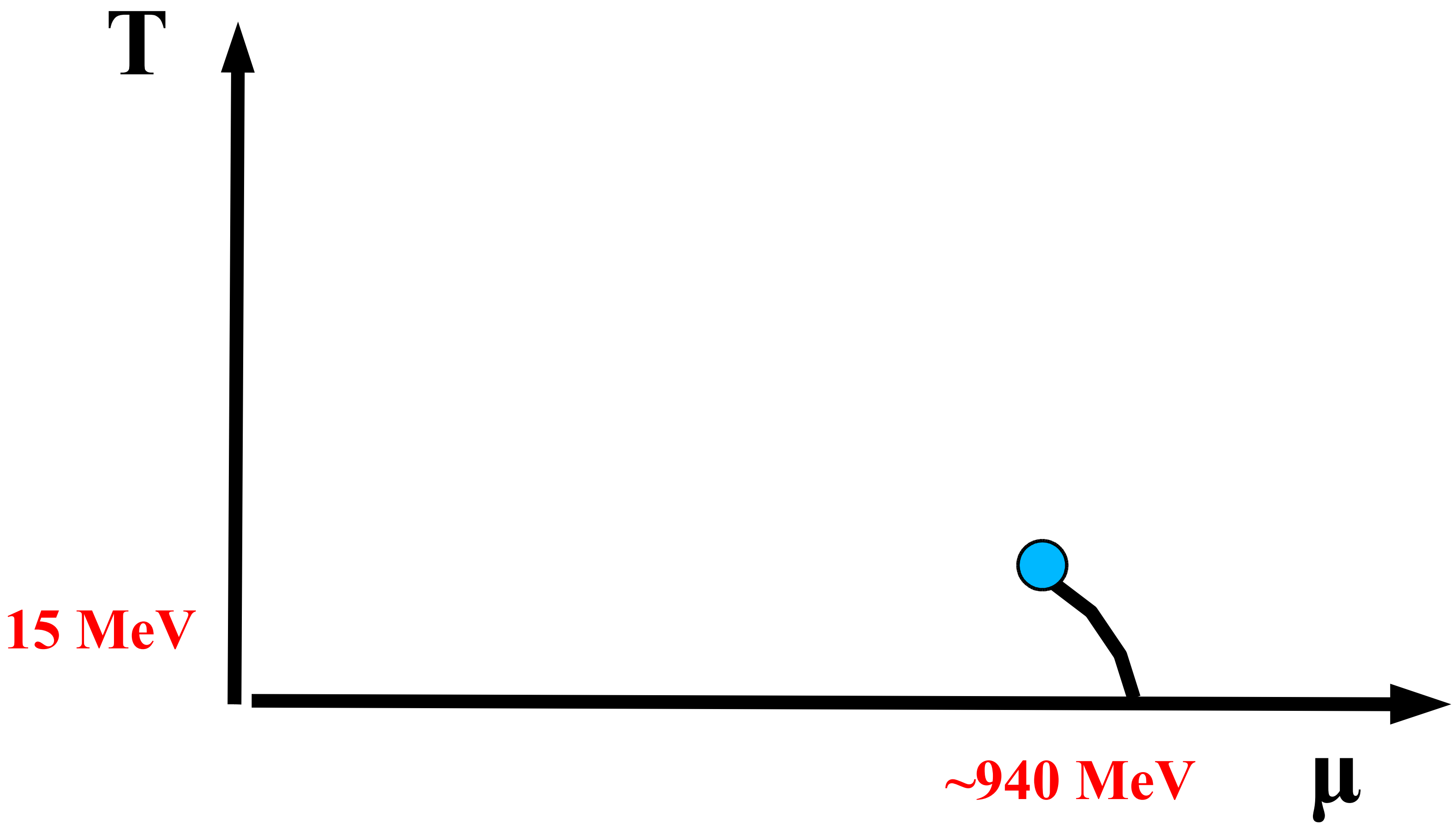
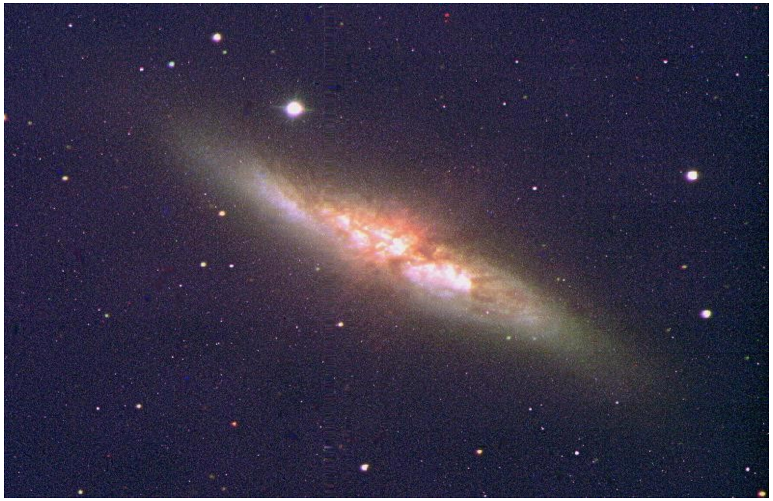
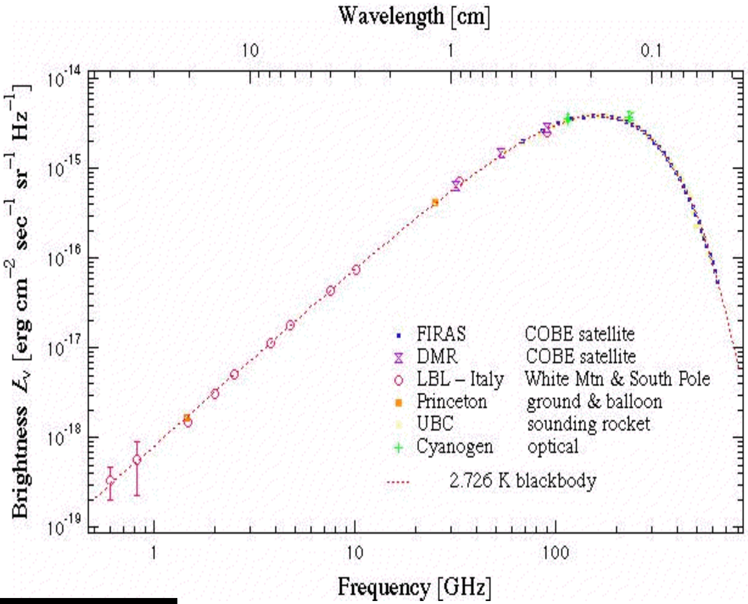
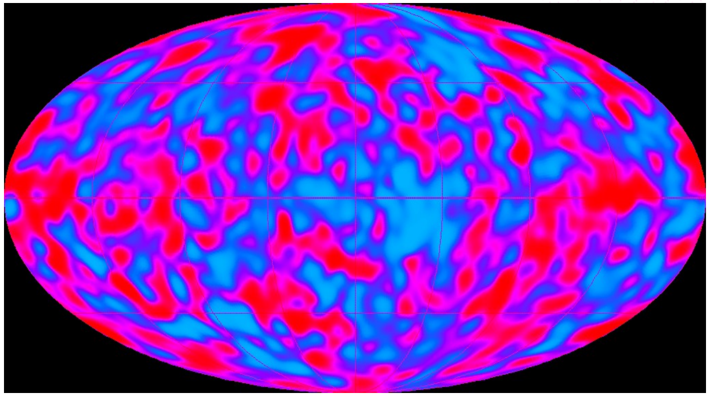


The mother of all thermal spectra and fluctuations







Fluctuations at the level of 10^{-5} !!!

Fluctuations in thermal system

e.g. Lattice QCD

$$Z = Tr\left[\exp\left(-\beta\left(H - \mu_Q Q - \mu_B B - \mu_S S\right)\right)\right]$$

Mean : $\langle X \rangle = T \frac{\partial}{\partial \mu_X} \log(Z) = -\frac{\partial}{\partial \mu_X} F$ $\qquad X = Q, B, S$

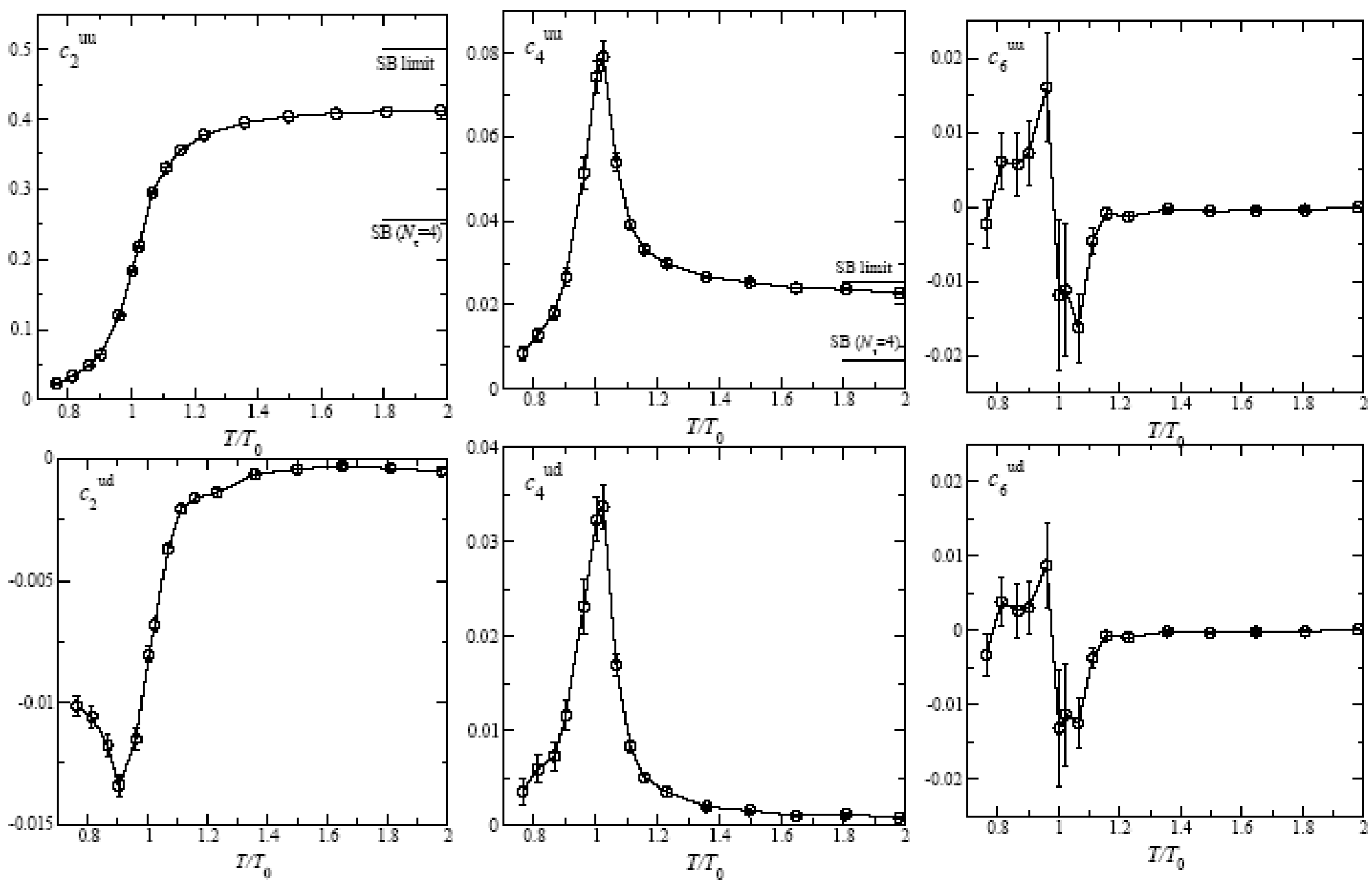
Variance: $\langle (\delta X)^2 \rangle = T^2 \frac{\partial^2}{\partial \mu_X^2} \log(Z) = -T \frac{\partial^2}{\partial \mu_X^2} F$

Co-Variance: $\langle (\delta X)(\delta Y) \rangle = T^2 \frac{\partial^2}{\partial \mu_X \partial \mu_Y} \log(Z) = -T \frac{\partial^2}{\partial \mu_X \partial \mu_Y} F$

Susceptibility: $\chi_{XY} = -\frac{1}{V} \frac{\partial^2}{\partial \mu_X \partial \mu_Y} F = -\frac{1}{V} \frac{\partial}{\partial \mu_X} \langle Y \rangle$

Lattice-QCD susceptibilities

$$\frac{\chi(T,\mu_q)}{T^2} = 2c_2 + 12\,c_4\left(\frac{\mu_q}{T}\right)^2 + 30\,c_6\left(\frac{\mu_q}{T}\right)^4 + \ldots$$



Rule of thumb:

$$c_n \sim \langle X^n \rangle$$
$$X = B, Q, S, \ldots$$

Alton et al, PRD 66 074507 (2002)

E-by-E observables

- Multiplicity fluctuations
  - interesting centrality dependence at top SPS energies

- Charge fluctuations
  - Resonance gas at RHIC
  - no sensitivity at SPS

- Transverse momentum fluctuations
  - some signal at SPS & RHIC (mostly “jets”)

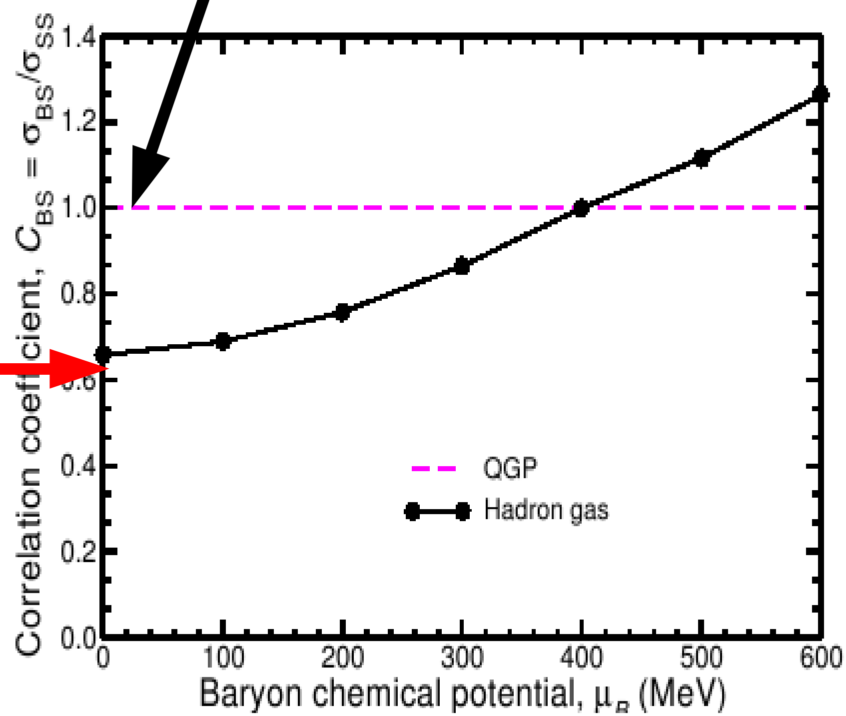
- Ratio (K/π) fluctuations
  - statistical at top SPS, possible signal at low SPS

Something new: <BS> , <QS>

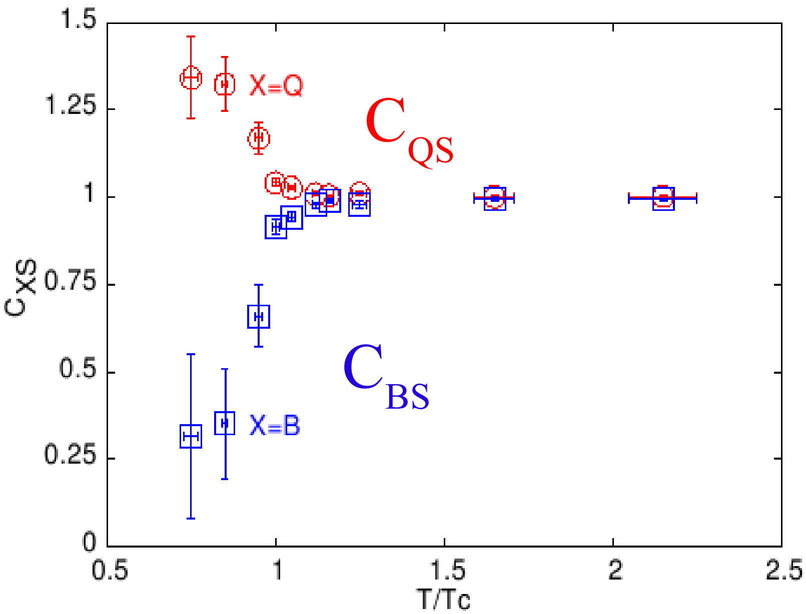
Independet quarks and
LATTICE QCD for T>1.1T_c

$$C_{BS} = -3\frac{\langle BS \rangle}{\langle S^2 \rangle} \qquad C_{QS} = -3\frac{\langle QS \rangle}{\langle S^2 \rangle}$$

Bound state QGP



V.K, Majumder, Randrup PRL95:182301,2005

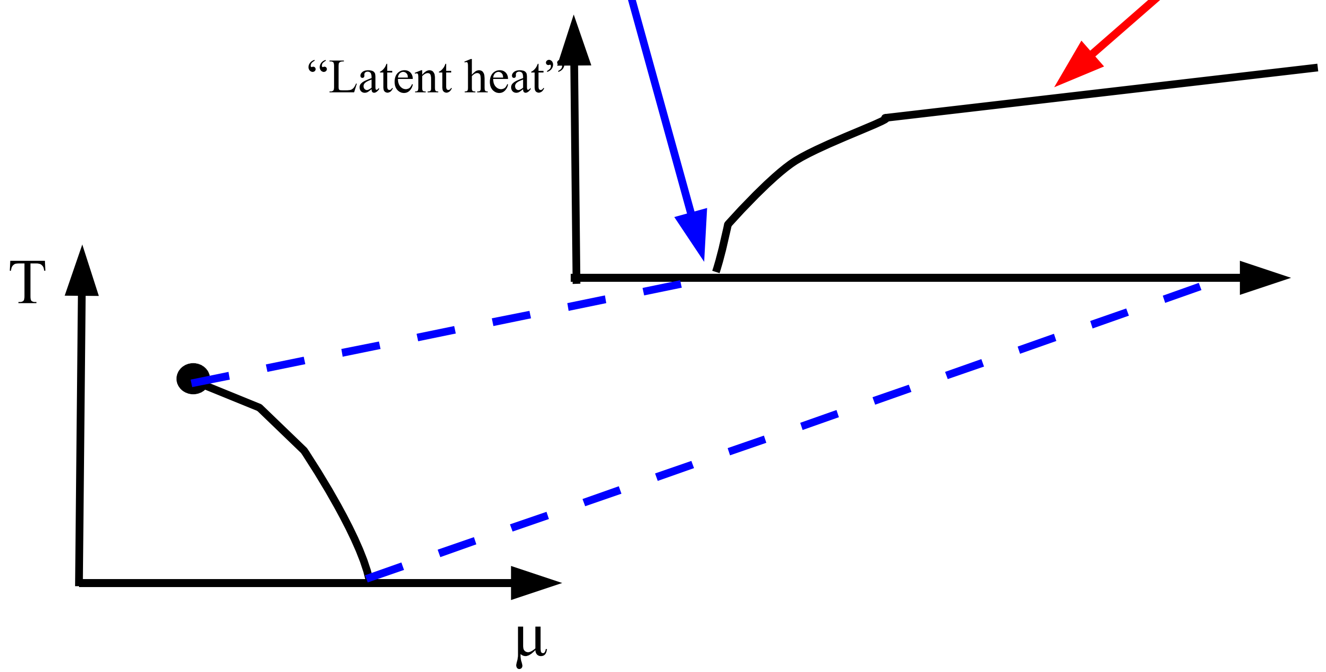


Gavai,Gupta, hep-lat/0510044

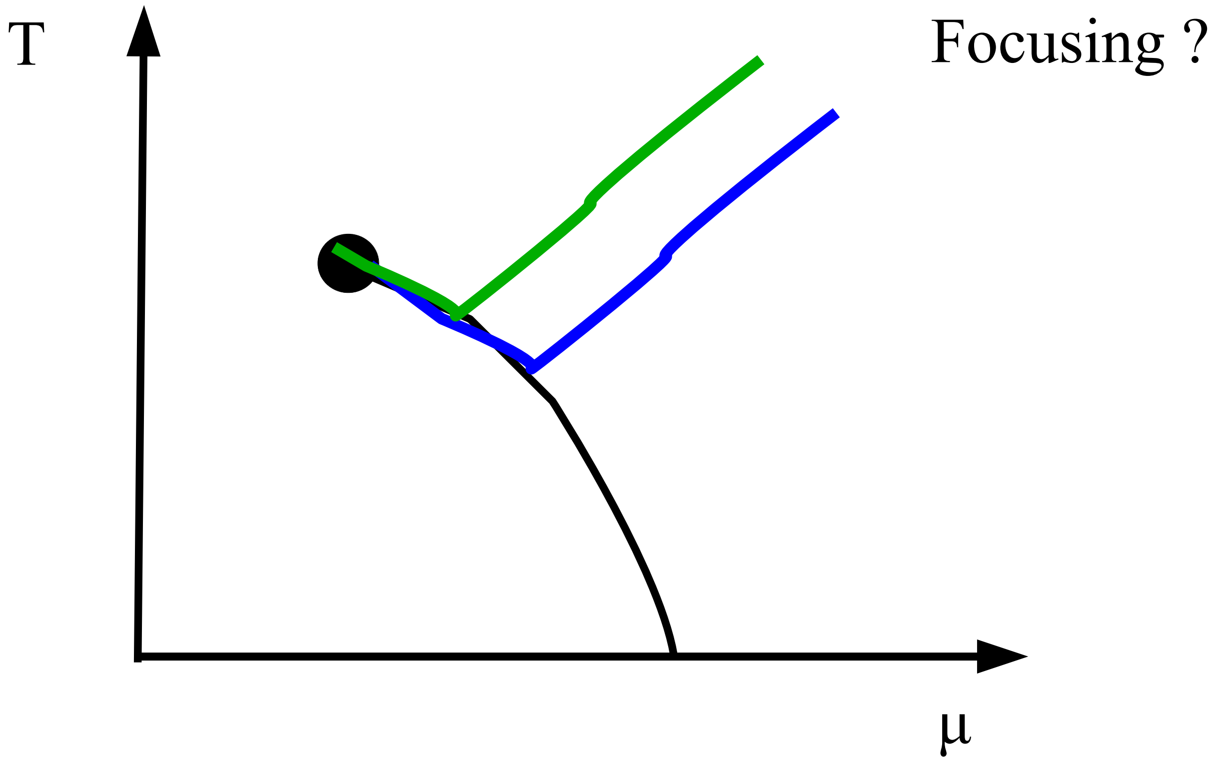
First order or second order?

Second order:
- Critical fluctuations
- Diverging Susceptibilities

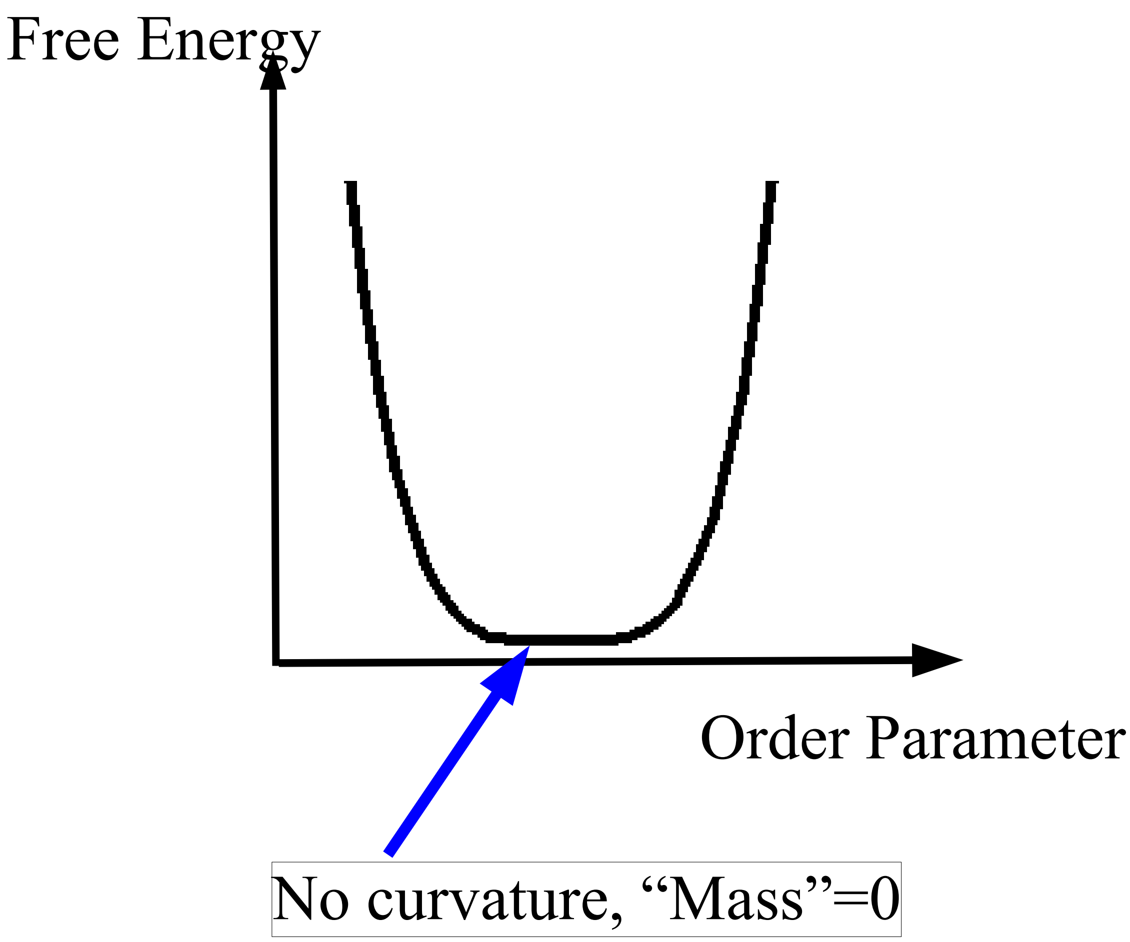
First order:
- Phase coexistence, bubbles
- Spinodal instabilities



First or second order?



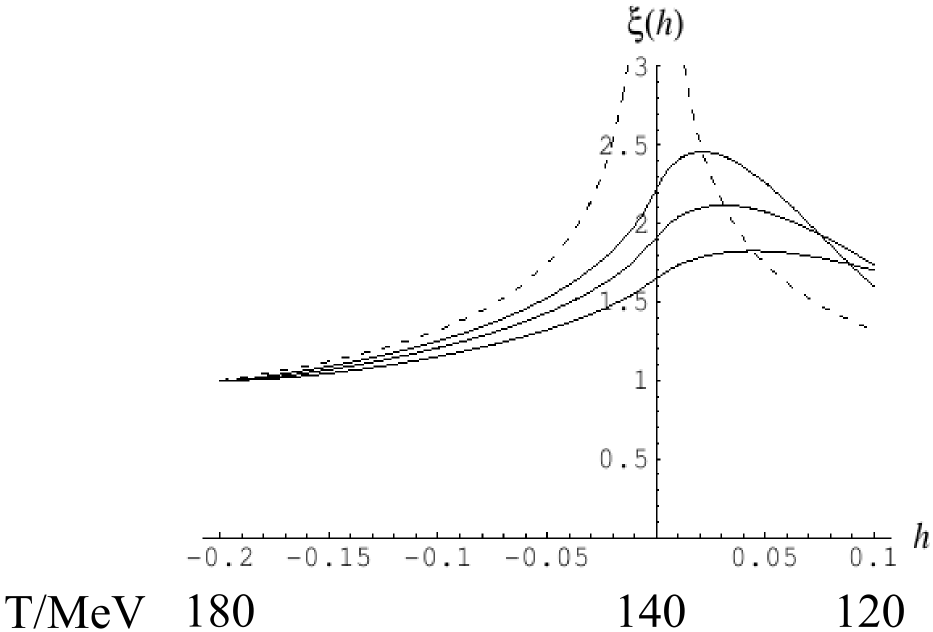
Second order



- Fluctuation of order parameter at all scales
- Diverging susceptibilities
  ~1/(”Mass”)^2
- Diverging correlation length
  ~1/(“Mass”)
- Universality
- Critical slowing down !

Second order

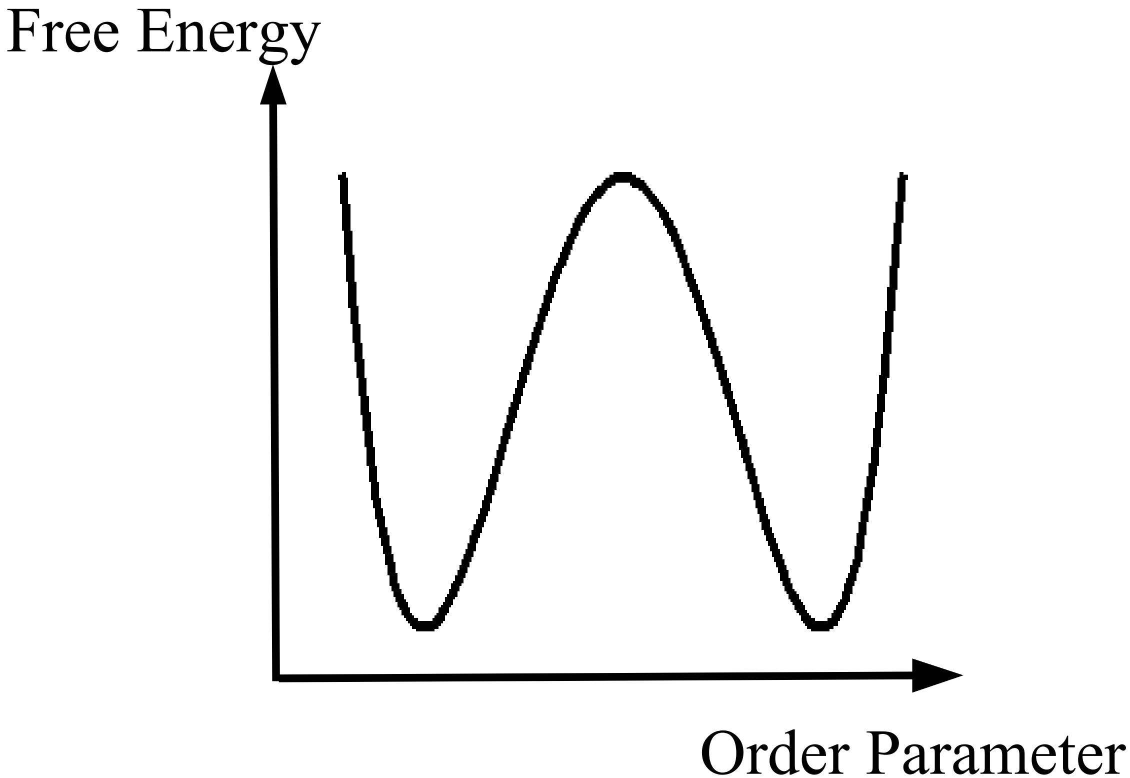
correlation length $\sim 1/m_\sigma$



Bernikov, Rajagopal, hep-ph/9912274

- Critical slowing down
- limited sensitivity on model parameters
- Max. correlation length 2-3 fm
- Translates in **3-5%** effect in p_t-fluctuations

First order

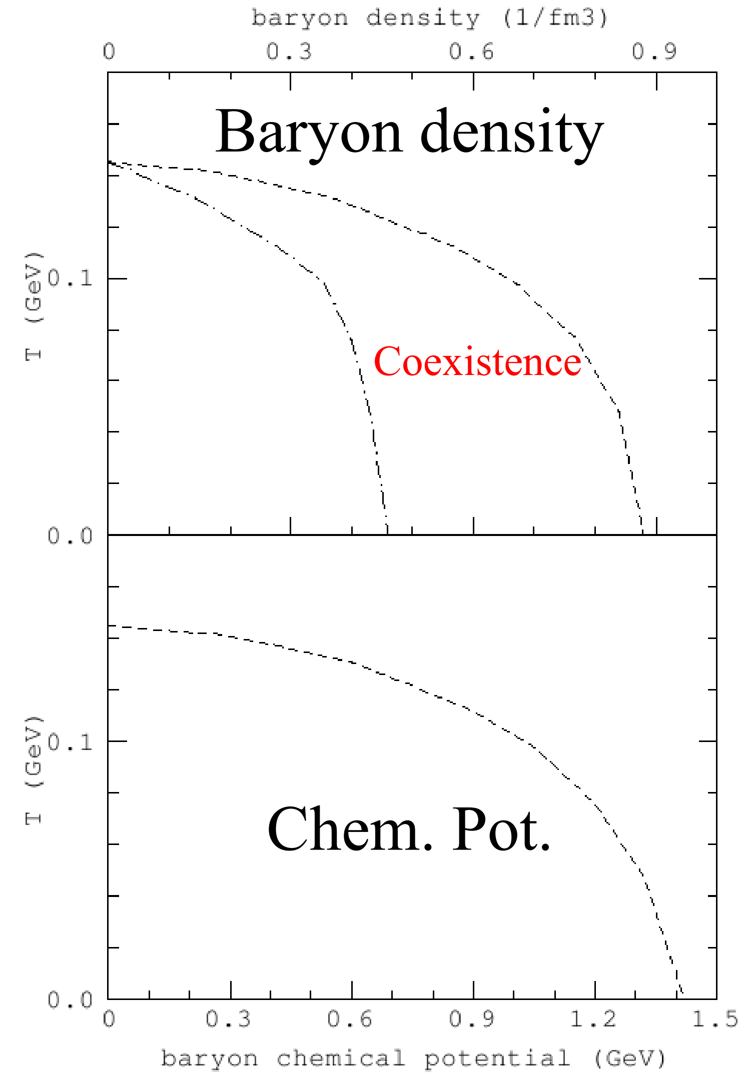


- Phase coexistence
- "Bubble" formation
  - Spatial fluctuations of order parameter
  - definite length scale
- Specific heat
- Dynamics: Spinodal instability

First order

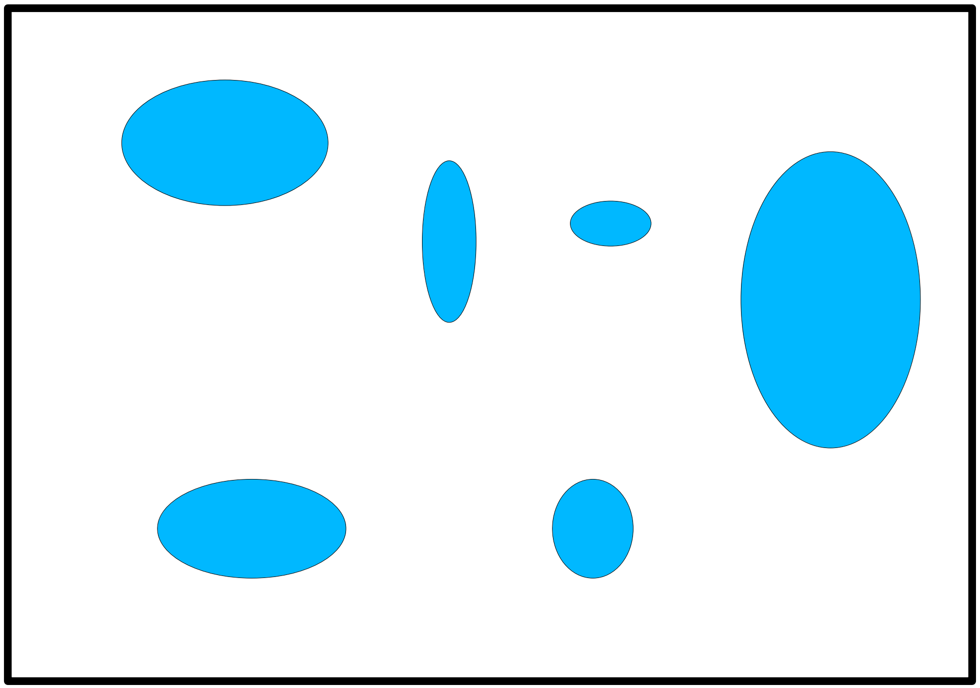
What are the phases?

“One” order parameter



P. Braun-Munzinger and J. Stachel,
Nucl.Phys.A606:320-328,1996

Baryon number fluctuations

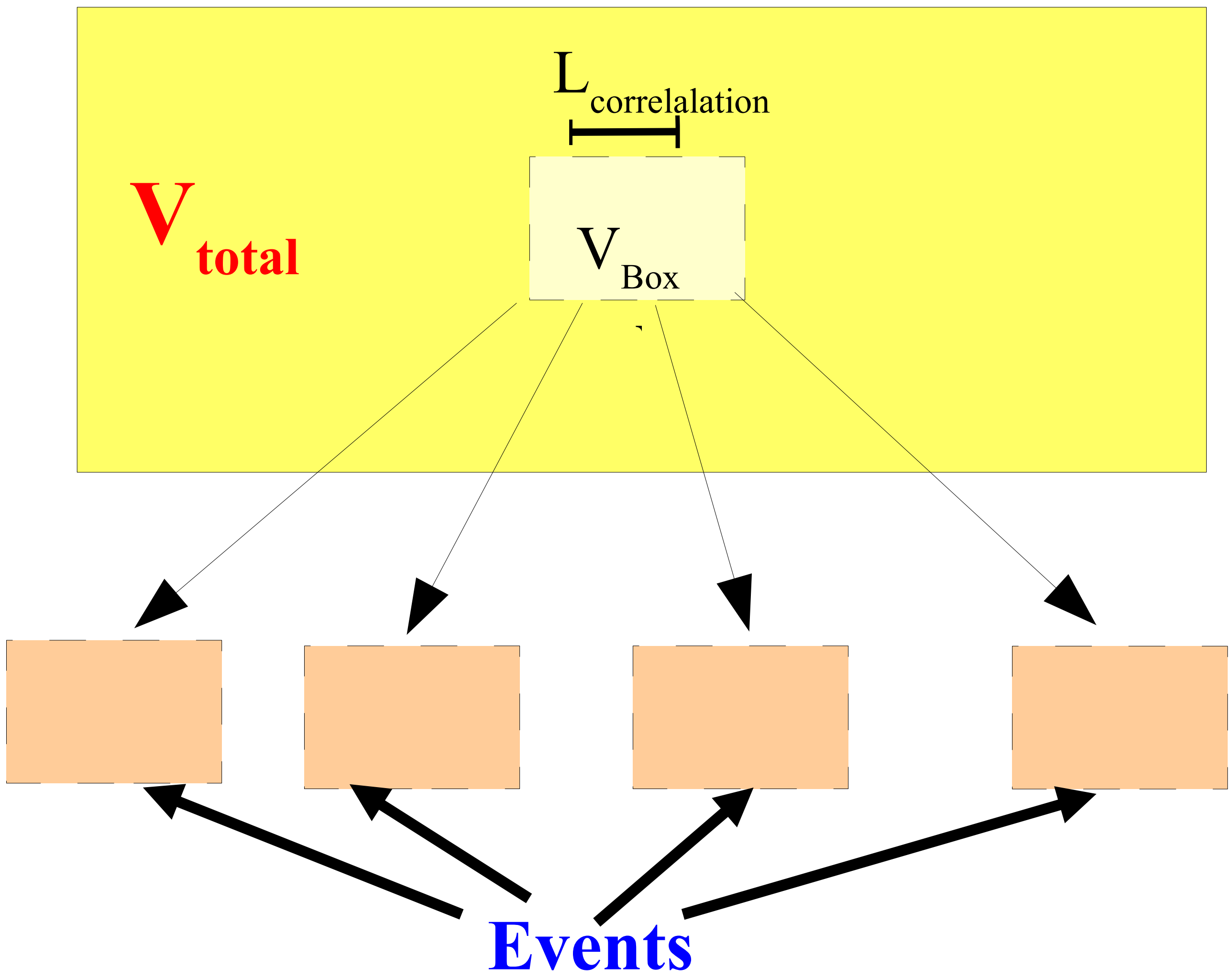


Strong spatial fluctuations

If $V_{domain} << V$, small effect on integrated Baryon Number fluctuations

$$\frac{\langle (\delta N)^2 \rangle}{\langle N \rangle} \approx \left(1 + \frac{(\Delta \rho)^2}{4 \bar{\rho}^2} \right)$$

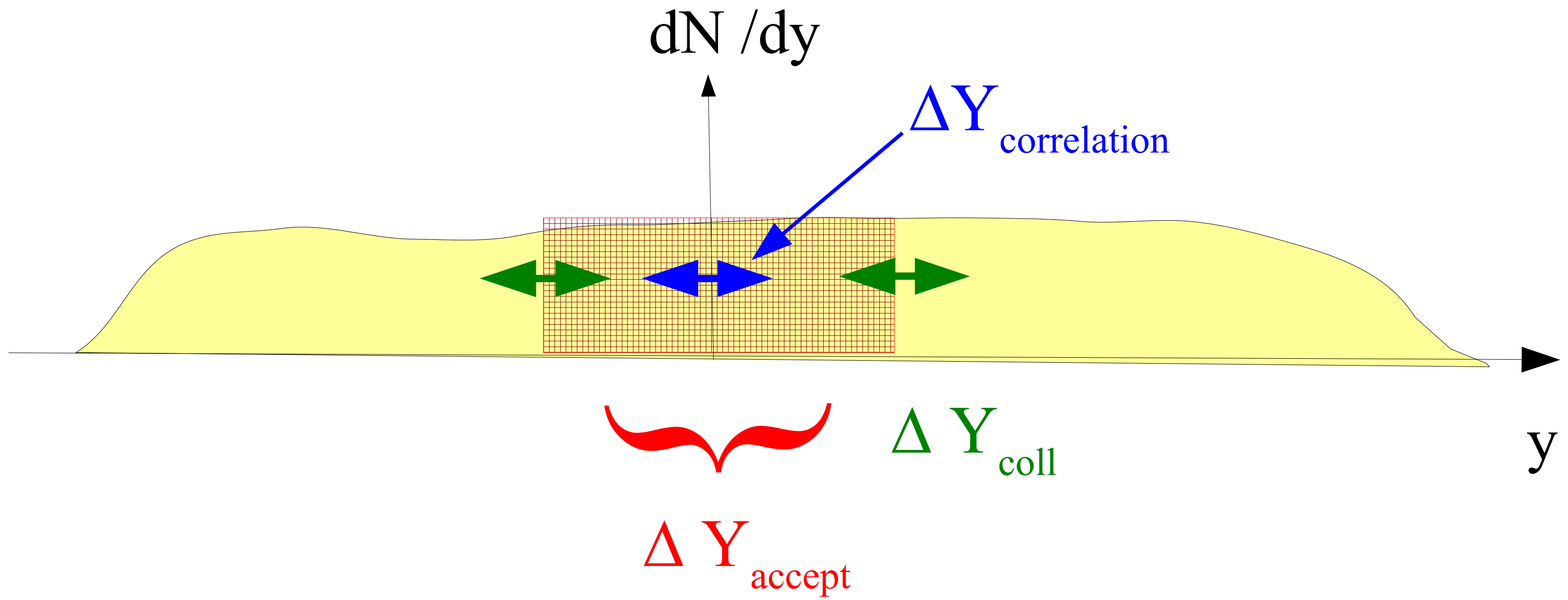
“Charge” Fluctuations



$V_{box} << V_{total}$

$L_{correlation} << V_{box}^{1/3}$

"Charge" fluctuations



Condition for "charge" fluctuations:

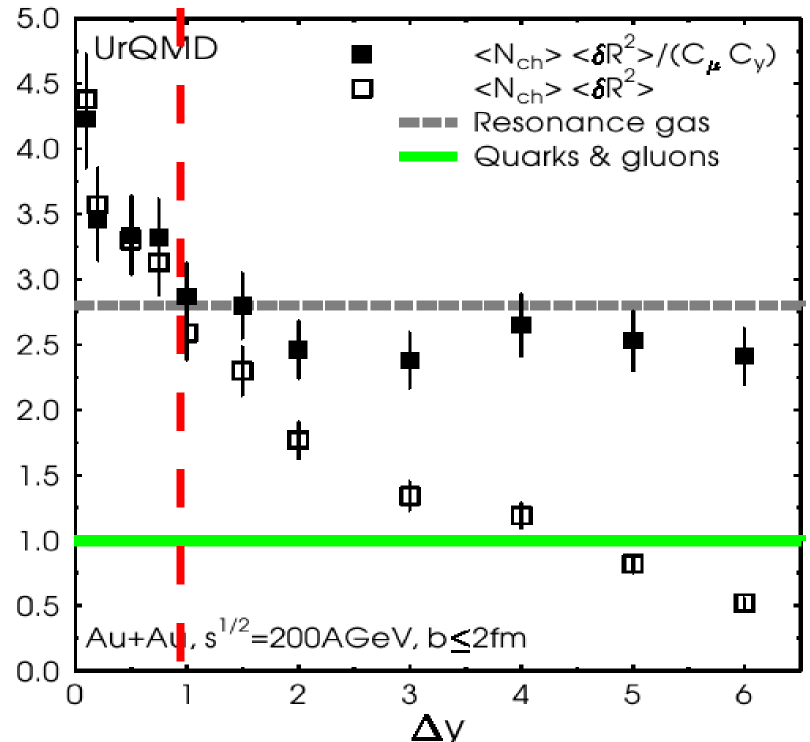
1) $\Delta Y_{corrrelation} << \Delta Y_{accept}$ **(catch the physics)**

3) $\Delta Y_{total} >> \Delta Y_{accept} >> \Delta Y_{coll}$ **(keep the physics)**

Charge conservation

$$C_\mu = \tilde{R}^2_{\Delta y} = \frac{\langle N_+ \rangle^2_{\Delta y}}{\langle N_- \rangle^2_{\Delta y}}$$

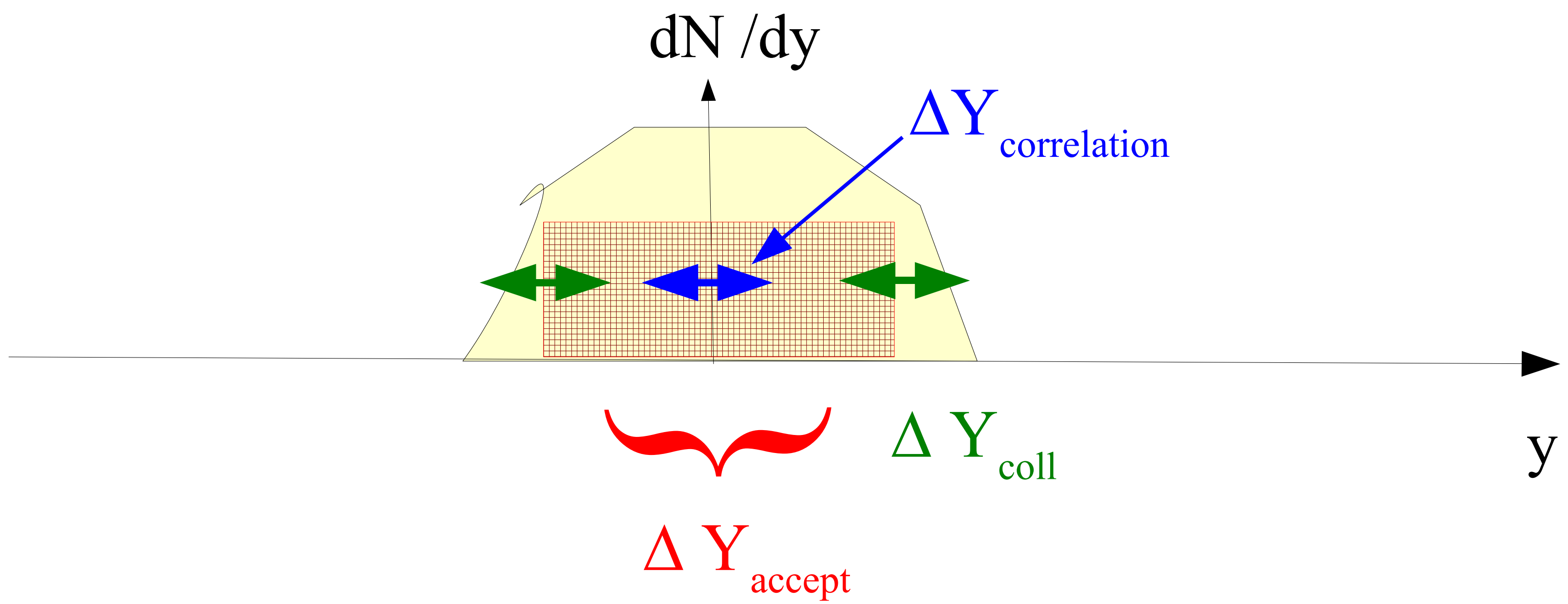
$$C_y = 1 - P = 1 - \frac{\langle N_{\rm ch} \rangle_{\Delta y}}{\langle N_{\rm ch} \rangle_{\rm total}}$$



Correlations (meson decay)

Bleicher et al.
Phys.Rev.C62:061902,2000

Charge fluctuations at SPS



Condition for “charge” fluctuations:

1)$\Delta Y_{corrrelation} << \Delta Y_{accept}$ **(catch the physics)**

3)$\Delta Y_{total} >> \Delta Y_{accept} >> \Delta Y_{coll}$ **(keep the physics)**

Correlation length?

Theory: $\langle \rho(x)\rho(y) \rangle$ Correlation in coordinate space

Experiment: $\frac{dN}{dp_1 dp_2} \sim \langle \tilde{\rho}(p_1)\tilde{\rho}(p_2) \rangle$ Correlation in momentum space

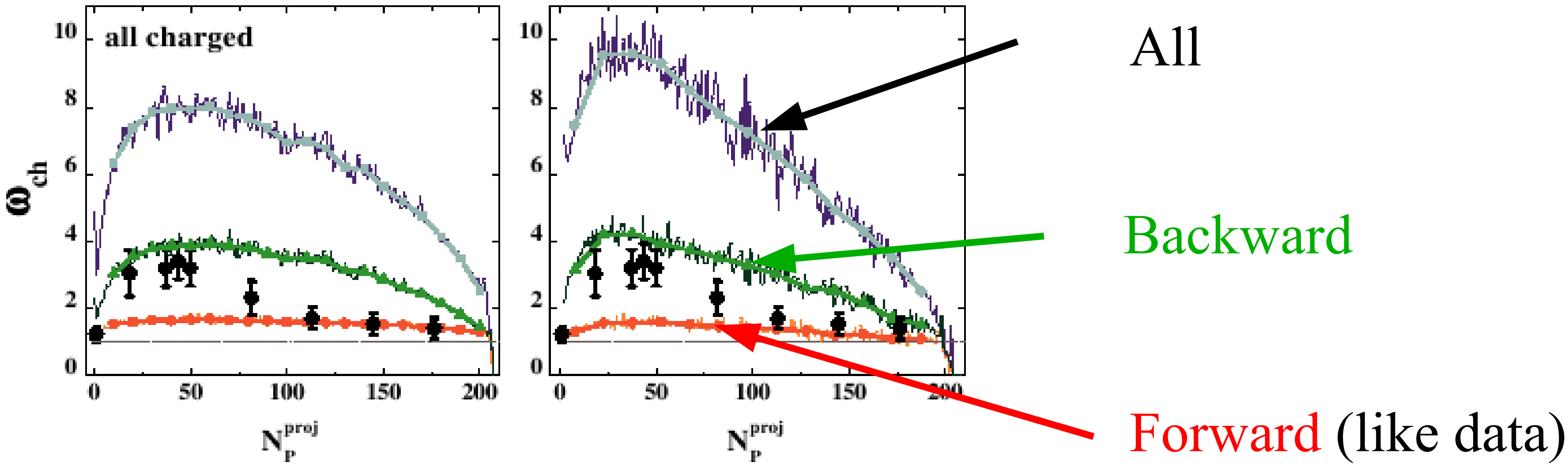
Flow helps maybe....

Better: Calculation of momentum space correlations

Dynamics, event selection ...

(or why a symmetric detectors are good)

Konchakovski et al, nucl-th/0511083



•Fluctuations are sensitive to dynamics (mixing of projectile and target material?)

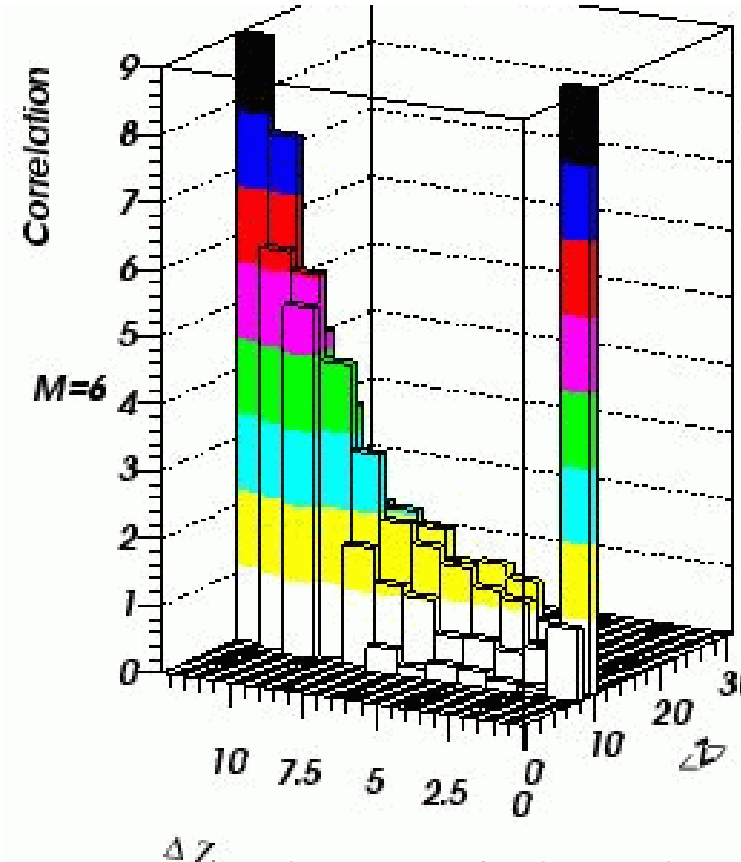
•Event selection/trigger affects fluctuations → large Acceptance!

Things to do!

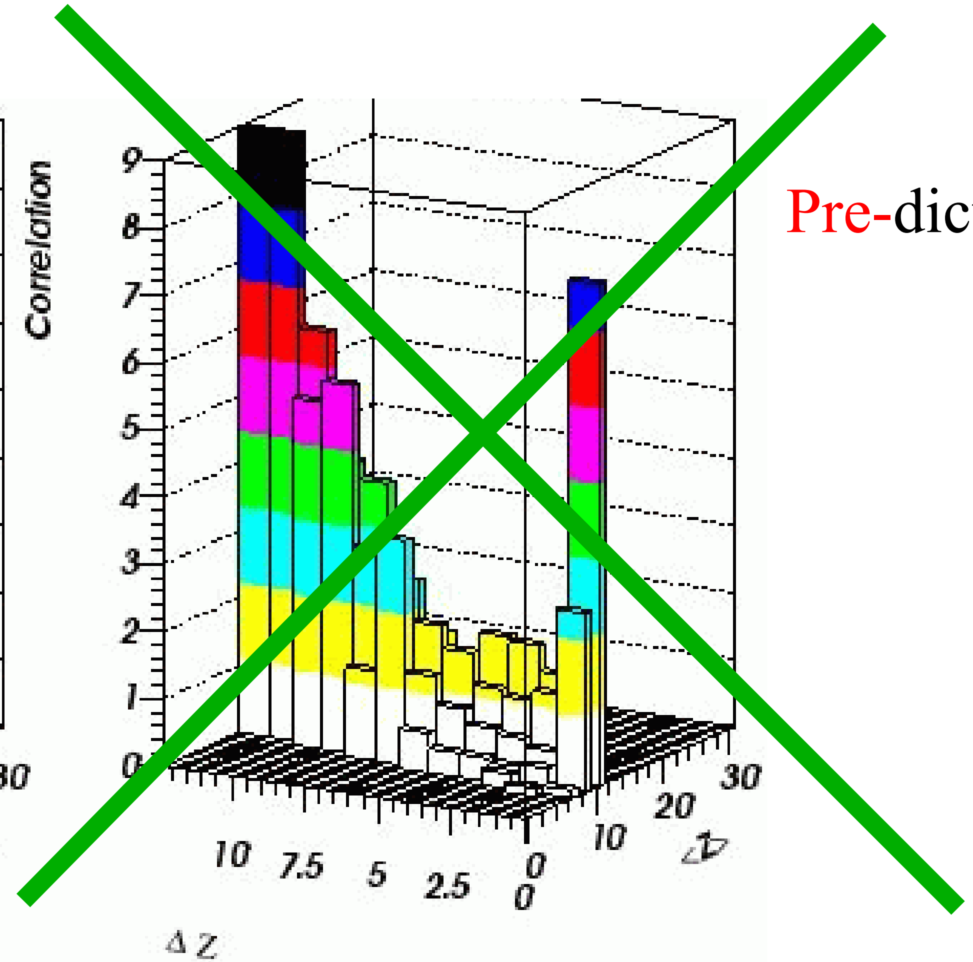
- Characterize the Phases
  - what are useful order parameters
- Test observables using static and dynamical models
  - Effects are small, comparable with 'trivial ones” such as quantum statistics, dynamics etc.
  - Only a well chosen observable / set of observables will prevent us from seeing Poisson
    - e.g. can we live without neutrons?
  - CONSERVATION LAWS

Spinodal decomposition in nuclear multifragmentation
occurs!

Data speak for themselves!



Experiment (*INDRA @ GANIL*)
Borderie *et al*, PRL 86 (2001) 3252

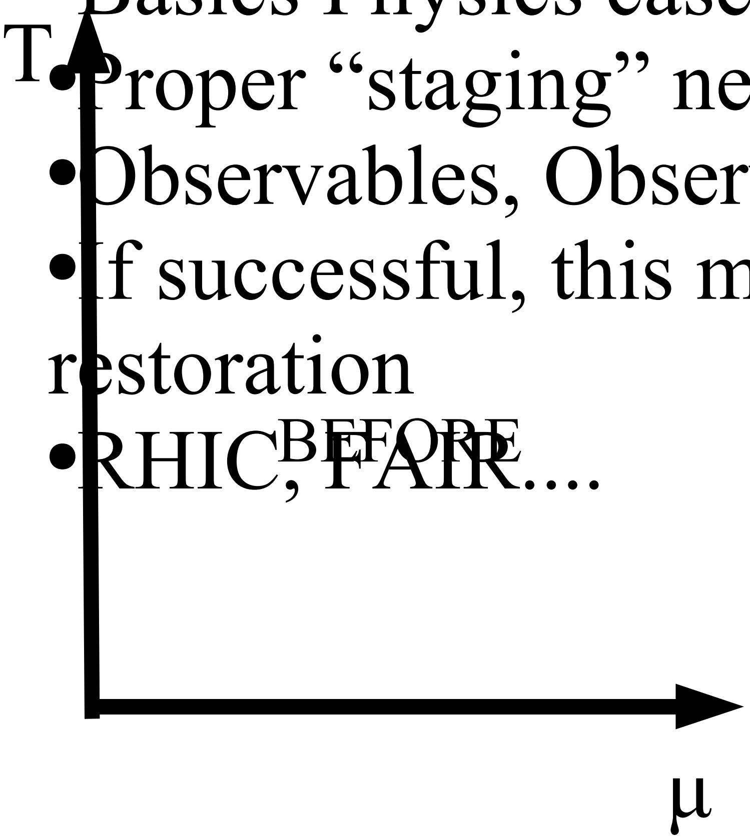


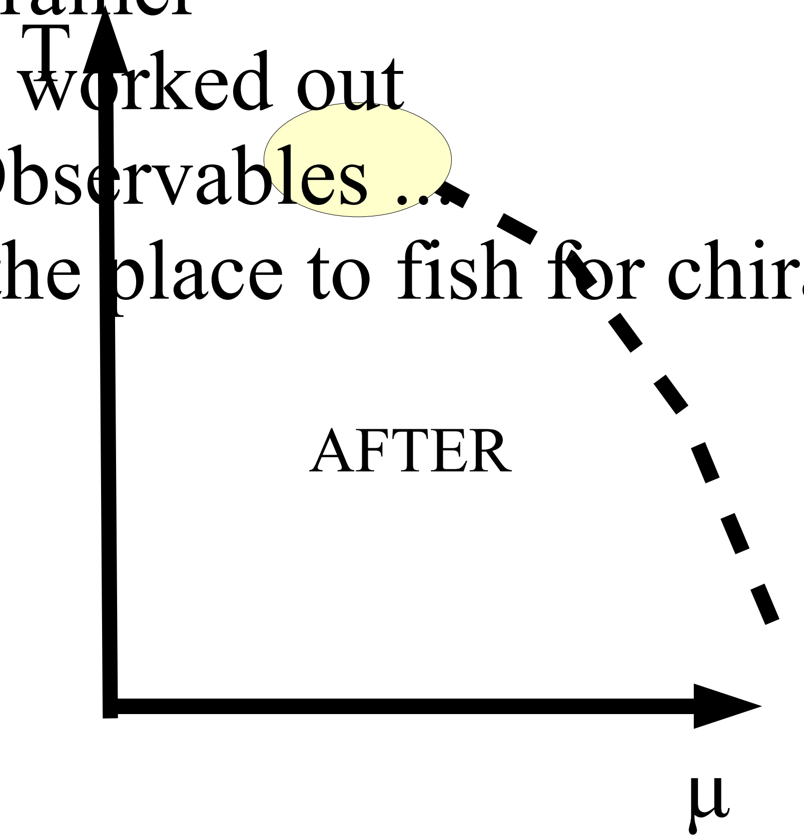
Pre-diction

Theory (*Boltzmann-Langevin*)
Chomaz, Colonna, Randrup, …

This is NOT a one shot deal!

- Basics Physics case is a no brainer
- Proper “staging” needs to be worked out
- Observables, Observables, Observables ...
- If successful, this might be the place to fish for chiral restoration
- RHIC, FAIR....





The End