Scientific challenges (and opportunities) for the next decade*

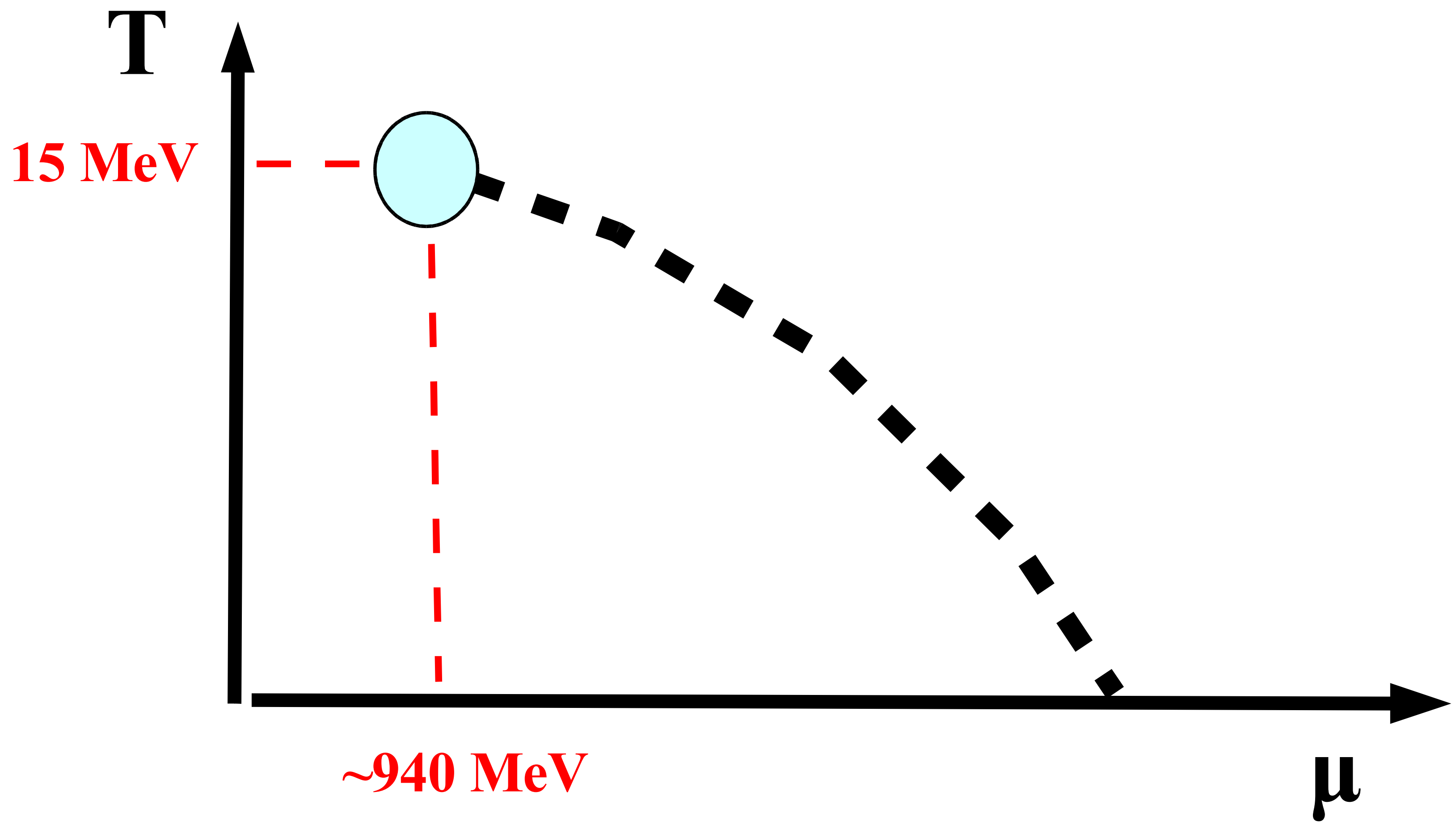
*Planning means replacing chance by error

Outline

- Phases of dense matter

- New form of matter: Can we quantify it?

The QCD Phase Diagram from experiment



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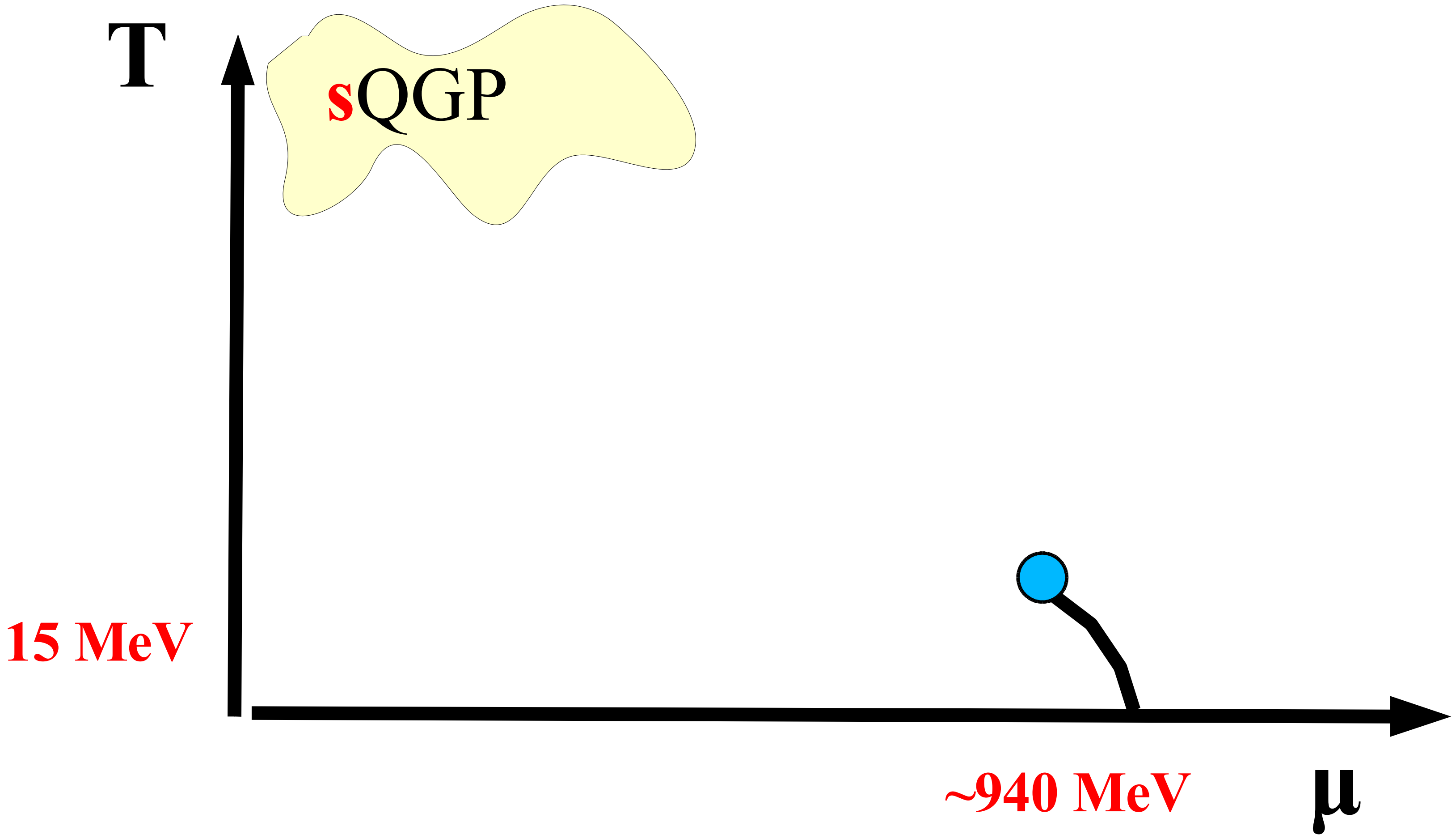
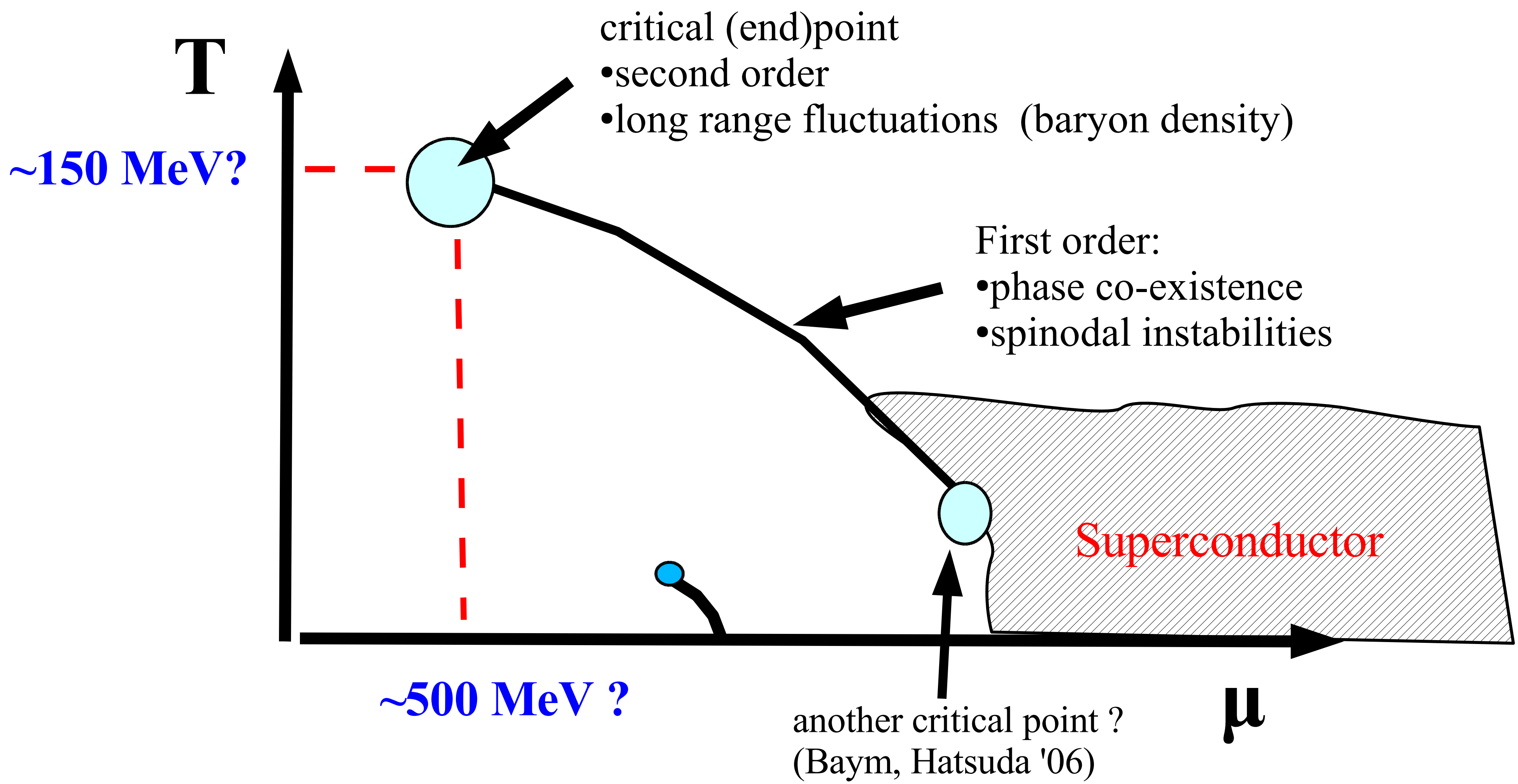
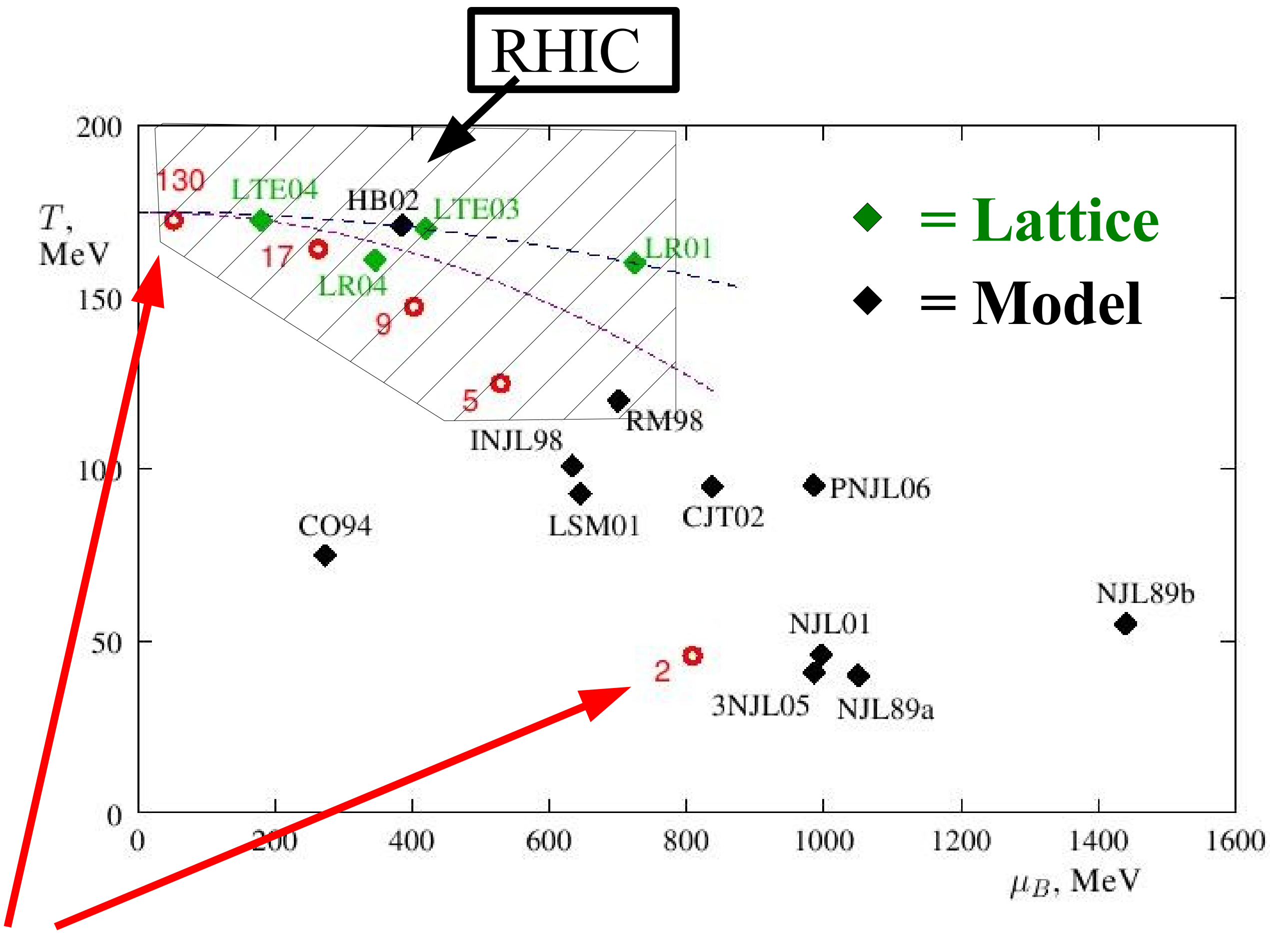


The QCD Phase Diagram



N.B.: Critical point of water: T_c=647.096 K, p_c = 22.064 MPa, ρ_c = 322 kg/m3

Location of Critical point



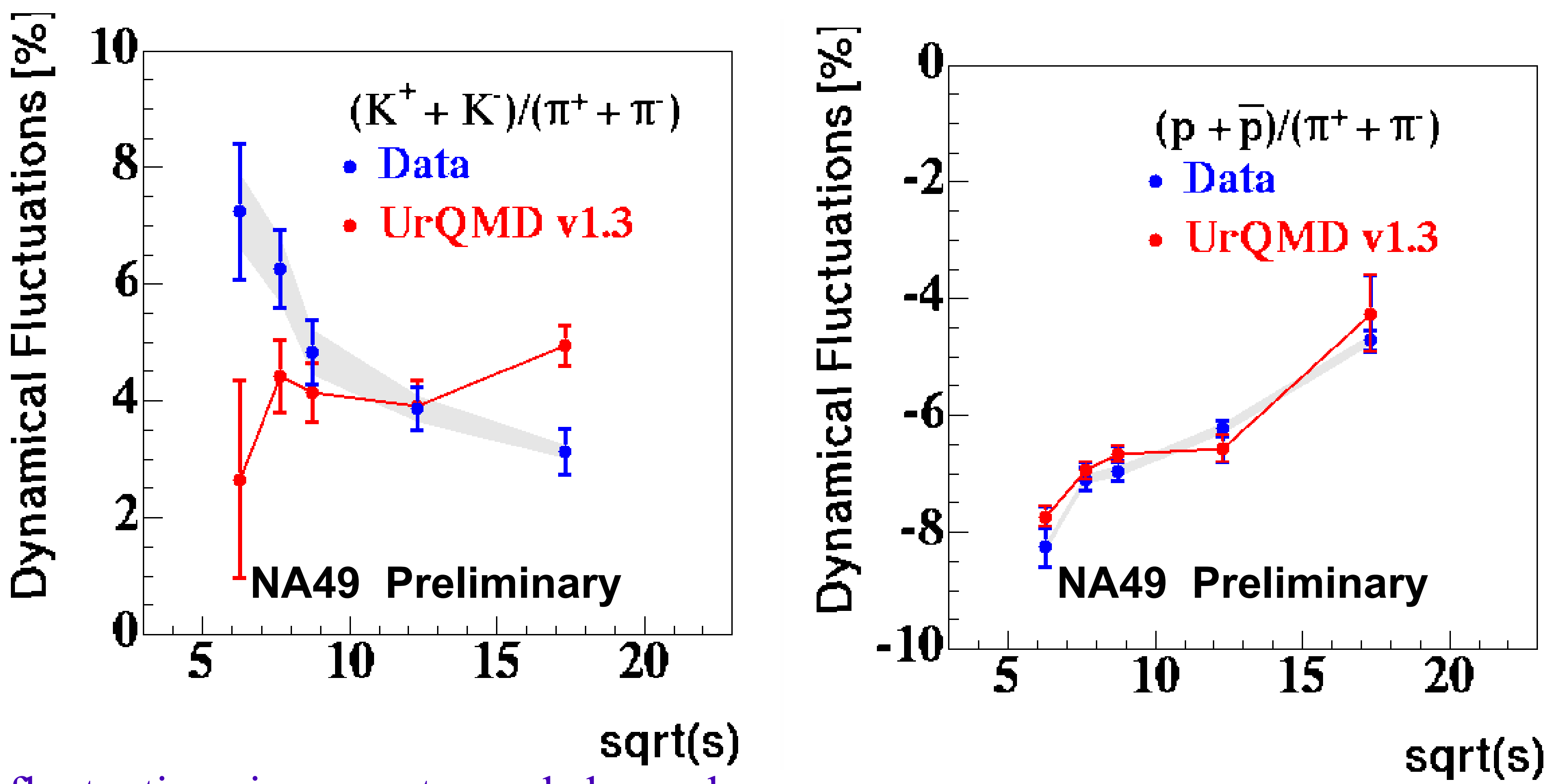
Freeze-out Temperatures

M. Stephanov

Observables

- Fluctuations in Baryon density
  - Proton number fluctuations? (Hatta, Stephanov)
- Fluctuations in isoscalar-scalar channel (Sigma)
  - P_t fluctuations (Stephanov, Rajagopal)
- Lumpiness ("blobs") due to first order transition (spinodal instabilities) (Randrup)
- Flow, K/π fluctuations, Dileptons, etc....
- Many issues to be clarified: Conservation laws, time/length scales, dynamics etc
  - Workshops: Trento 06, INT August 2008, ...

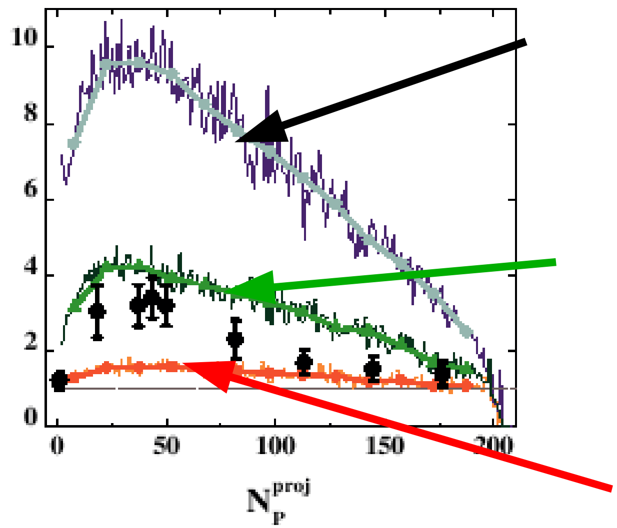
Fluctuations (NA49, QM2004)



- K/π fluctuations increase towards lower beam energy
  - Significant enhancement over hadronic cascade model
- p/π fluctuations are negative
  - indicates a strong contribution from resonance decays
  - **Where are the baryon number fluctuations????**

Acceptance, Acceptance ...

- K/π from NA 49:
  - different acceptance for K and π
- AGS experiments
  - Mostly small acceptance



All

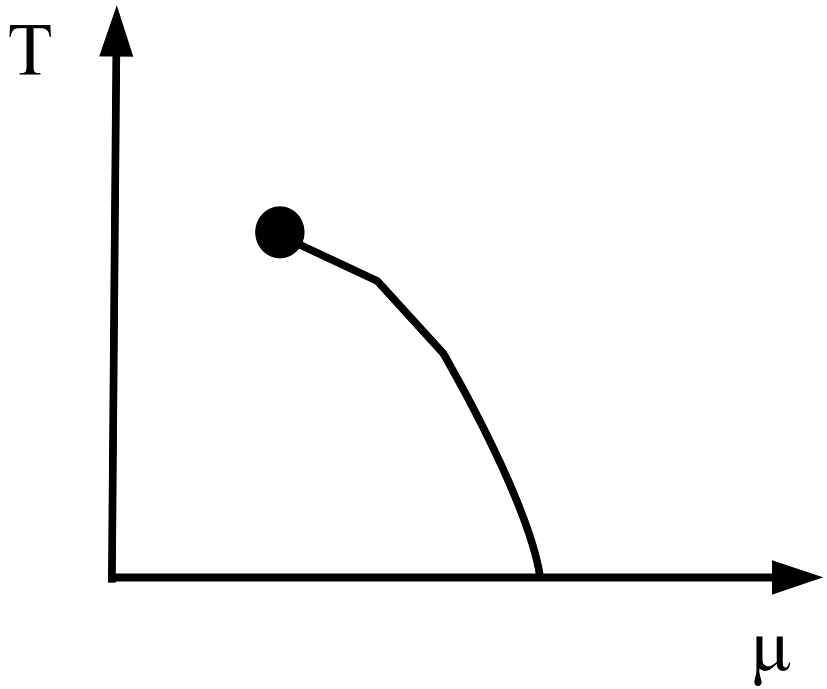
Backward

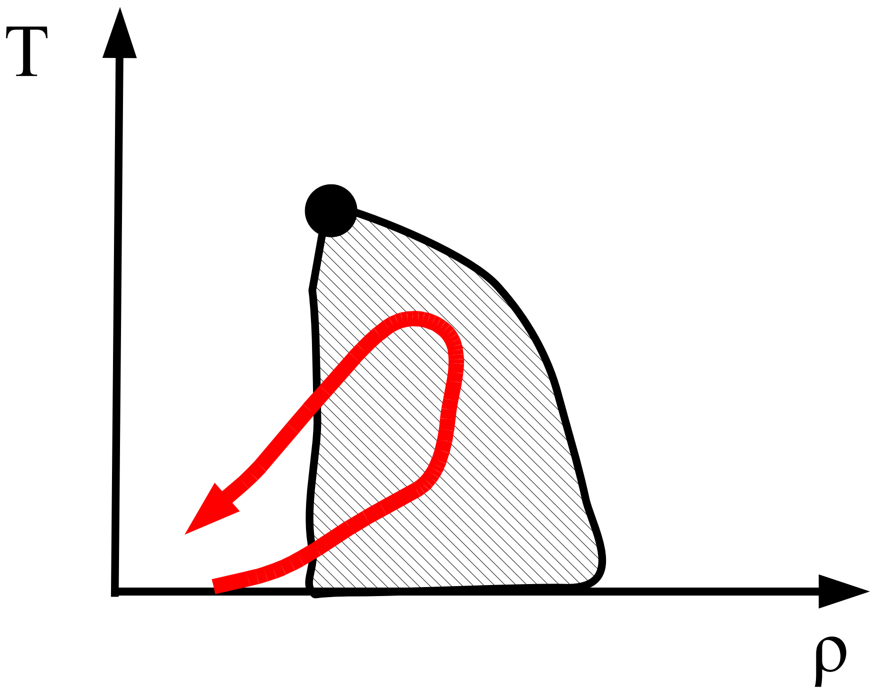
Forward
(like data)

- Large Acceptance
- Collider Geometry
  - need to vary beam energy

Event selection/trigger
affects fluctuations
→ large Acceptance!

Find right energy!



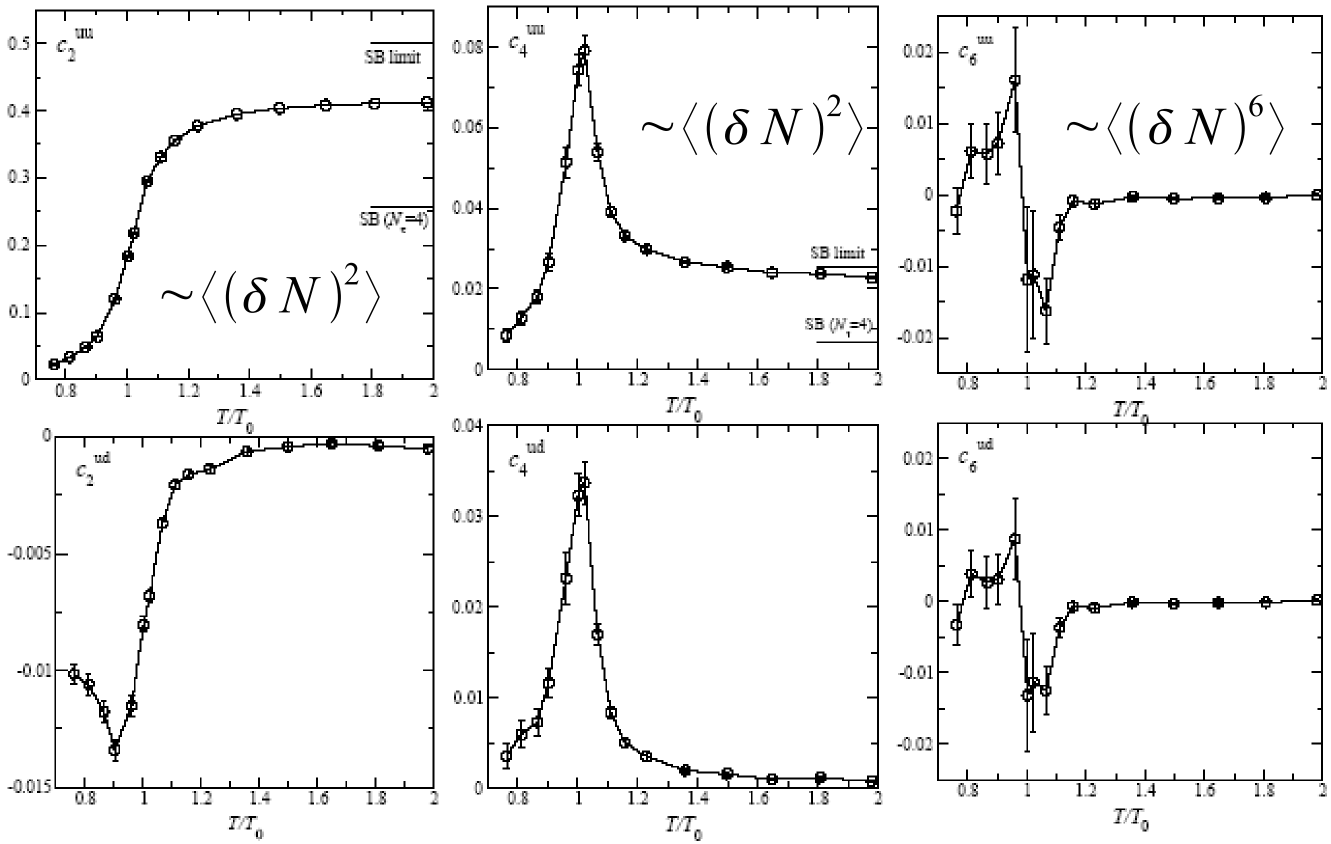


Energy Scan: 5 AGeV < Sqrt(s) < 20 AGeV

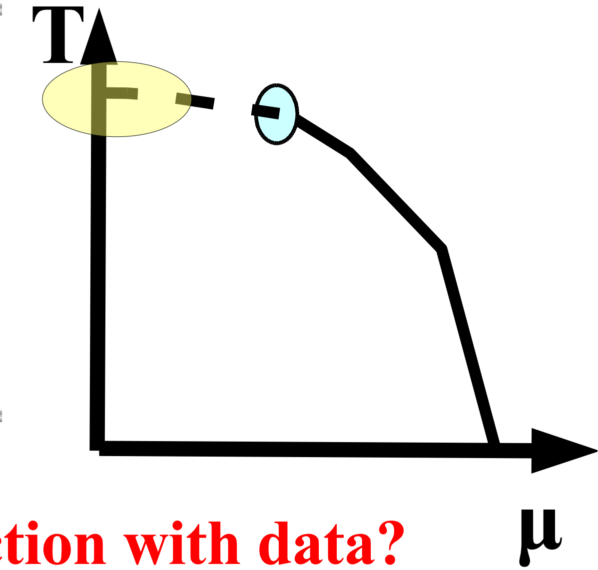
RHIC and CBM (FAIR)

Lattice-QCD susceptibilities

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



Rule of thumb:
$c_n \sim \langle X^n \rangle$
$X = B, Q, S$



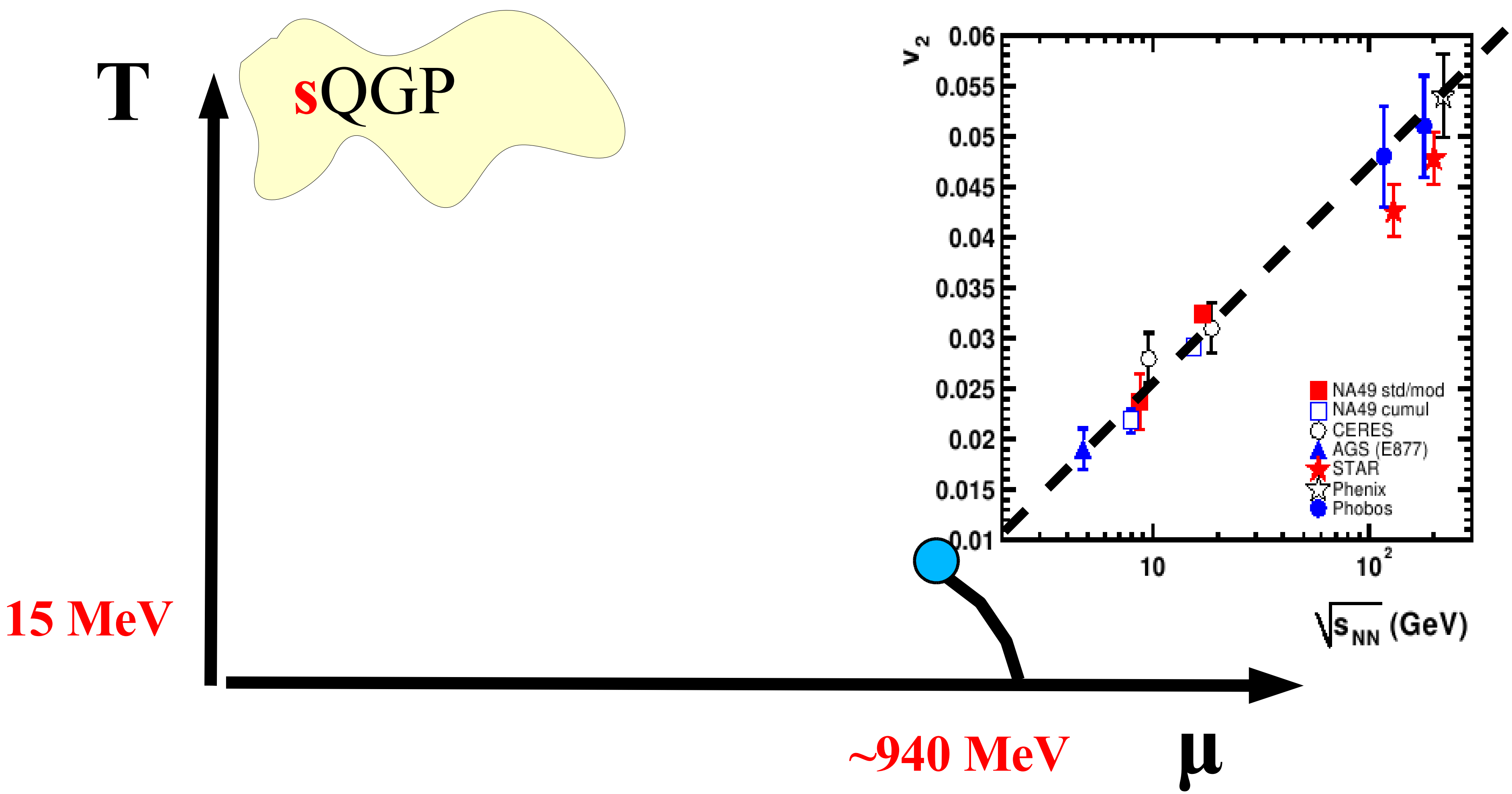
Alton et al, PRD 66 074507 (2002)

Can we make a connection with data?

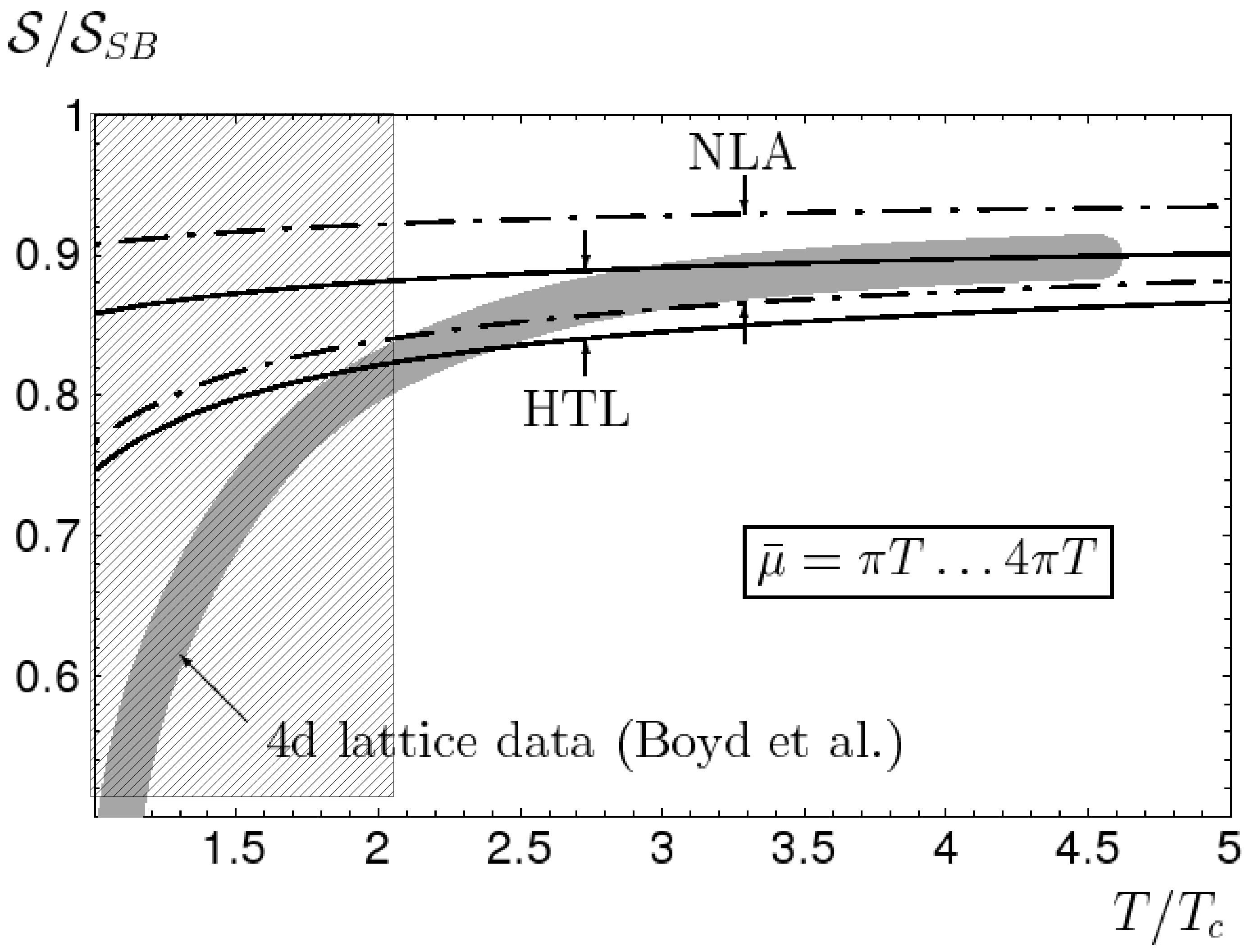
Phase Structure

- Search requires:
  - detailed energy scan, possibly as low as Sqrt(s) ~ 4 -5 GeV
    - luminosity !
  - upgraded detectors (Collider is ideal for this)
  - robust Observables

New Form of Matter



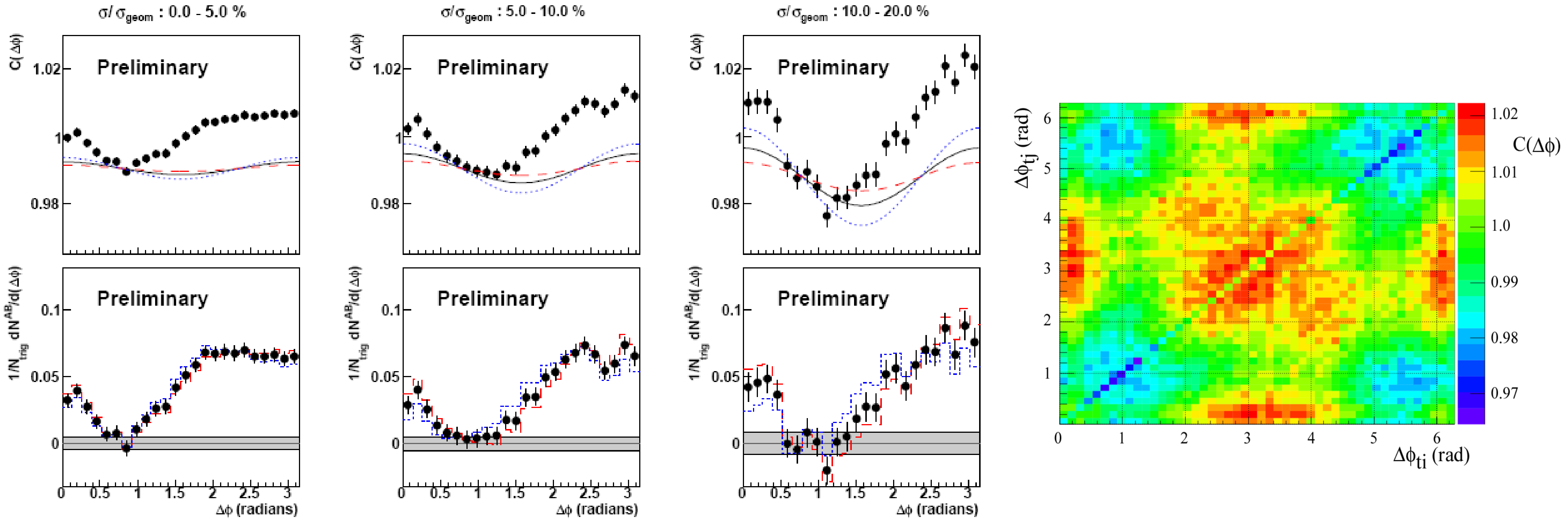
RHIC is where the action is
(should be...)



“New form of matter”

- Many new phenomena found at RHIC
  - cones, ridges, v_2, disappearing jets....
  - However: most “re-discovered” at SPS
- What defines new form of matter?
  - NEW COMPARED TO WHAT? To SPS?
  - What is different:
    - EOS ?
    - Transport Coefficients ?
    - Mean free paths ?
    - degrees of freedom ?
    - Chiral condensate ?
    - ......

Cones at SPS ? (CERES)



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Towards numbers

- Has the time of precision HI- physics arrived
  - Can we do it?
  - Is it worthwhile?
- Quantitative vs qualitative
  - Can we develop limits ? Credible error-bars on these numbers?
  - Can we (should we) calculate everything from first principles
    - properties of water from QED???
  - Is there a consistent theoretical framework. What needs to be done? (Example: "Stiff EOS at Bevalac prior to momentum dependence")

It is time to turn HI physics into a quantitative science!

Matter....

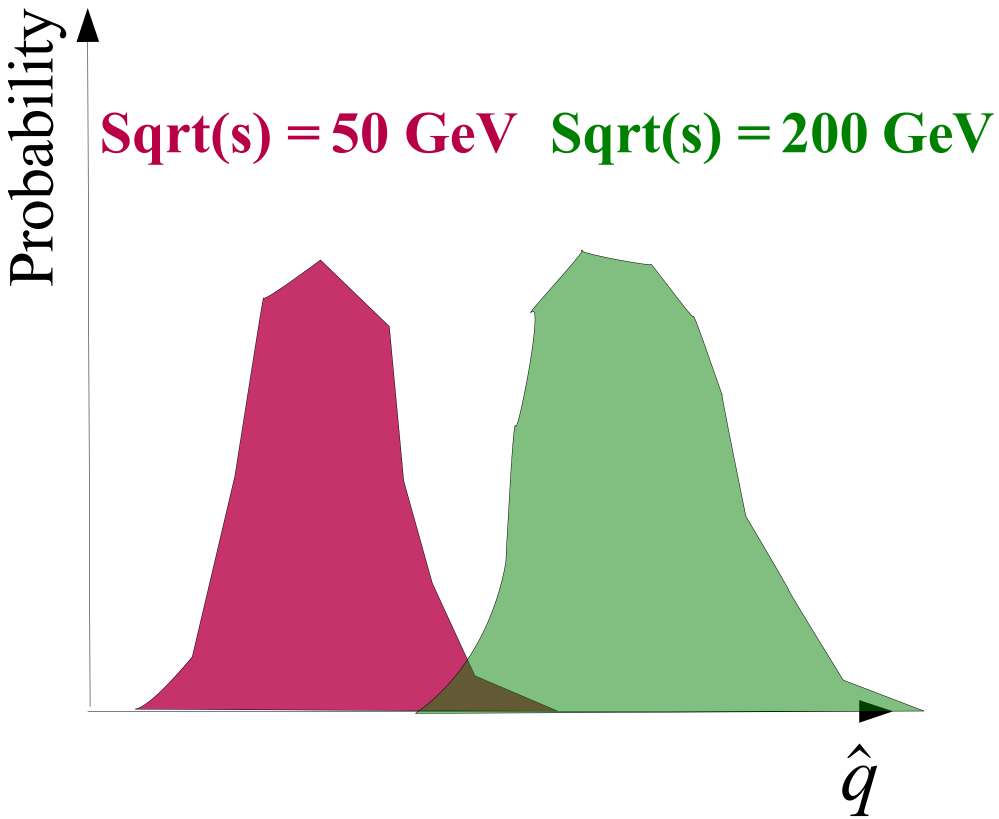
- Can we specify or provide limits on:
  - EOS ?
  - Phase structure ?
  - transport coefficients ?
  - speed of sound ?
  - index of refraction ?
  - mean free path, q-hat ?
  - value of chiral condensate, chiral order parameter ?
- Which of those change with energy (system size)

Thanks to RHIC results these seem doable.

Need same quality data set also at “SPS-like” energies and more (LHC)

Towards numbers

- First attempt to explore limits on jet energy loss $\hat{q}$
  - needs improvement (γ-jet ...)
- Similar efforts for
  - viscosity
    - detailed visc. hydro
    - p_t co-variance (S Gavin)
    - v_2 co-variance
  - pressure (EOS)
  - etc.



Towards numbers: Charm

"Conserved" charge with new mass scale!

- Flow:
  - equilibration time
    - system size dependence of charm flow relative to light flow
    - Measure: Flow for p+p, Au+Au, Cu+Cu, O+O ...
  - test of hydro
- Jets
  - clean tag for quark (charm) jets; charm does not come from fragmentation
- Longitudinal c-c_{bar} correlations:
  - equilibration time
  - Bjorken flow? (ridges etc)

other observables

- Photons: Thermal, γ-jet
- Dileptons / axial current (γ-pion) (chiral condensate)
- Correlations:
  - cones, ridges
  - v_2 for events with jet (do we have the same density)
  - susceptibilities: Can we extract them!
  - ....

Challenge for Theory

- Goals
  - qualitative and QUANTITATIVE understanding of system/matter created
  - deeper understanding of QCD
- Strike healthy balance between
  - Phenomenology
  - new ideas / approaches (e.g. AdS-CFT)
  - formal developments (re-summations, low-x etc)
  - ab initio QCD calc. (e.g. Lattice)

This is the golden age

- RHIC and LHC and FAIR
- Needs:
  - Beam time, luminosity **(RHIC II)**
  - Timely detector upgrades (charm, dileptons, detailed studies of correlations ...) **(RHIC II)**
  - Coherent theory effort
    - Re-discover phenomenology!
      - Extract viscosity, mean free path etc from data
    - Develop and constantly challenge the theoretical framework

Summary

- Find evidence for phase structure
  - Systematic energy scan
  - Coherent theory effort to develop robust observables
- Quantify the matter we have found at top RHIC energies and how it changes with Sqrt(s)
  - Charm measurements will be essential
    - viscosity
    - equilibration time
    - mean free path, q-hat
    - .....

Excerpt from future textbook

Heavy Ion collisions have revealed a new form of matter called the “sQGP” which shows remarkable features such as hydrodynamic evolution, loss of energy by fast particles (p >> T) traversing it....

For standard conditions, T= 200 MeV and μ = 50 MeV, the matter is characterized by the following quantities:

- The mean free path of a parton with p = 20 GeV is ...±...* fm
- The shear viscosity of the matter is ...±...* fm^{-3}
- The pressure is ....±...* MeV/fm^3
- The chiral condensate is ....±...*
- ....

*To be worked out by student as homework problem.

RHIC has been a great success

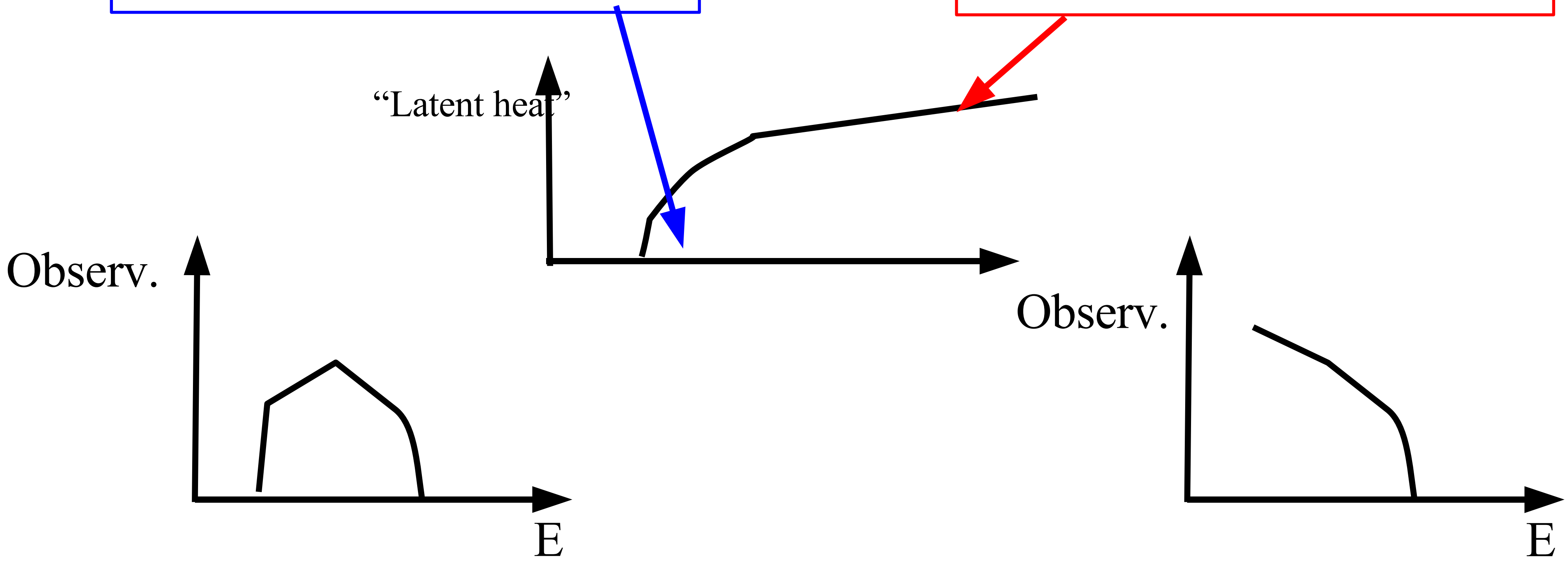
With RHIC II we can make it a lasting success

Backup

Excitation function

Second order:
- Critical fluctuations
- Diverging Susceptibilities

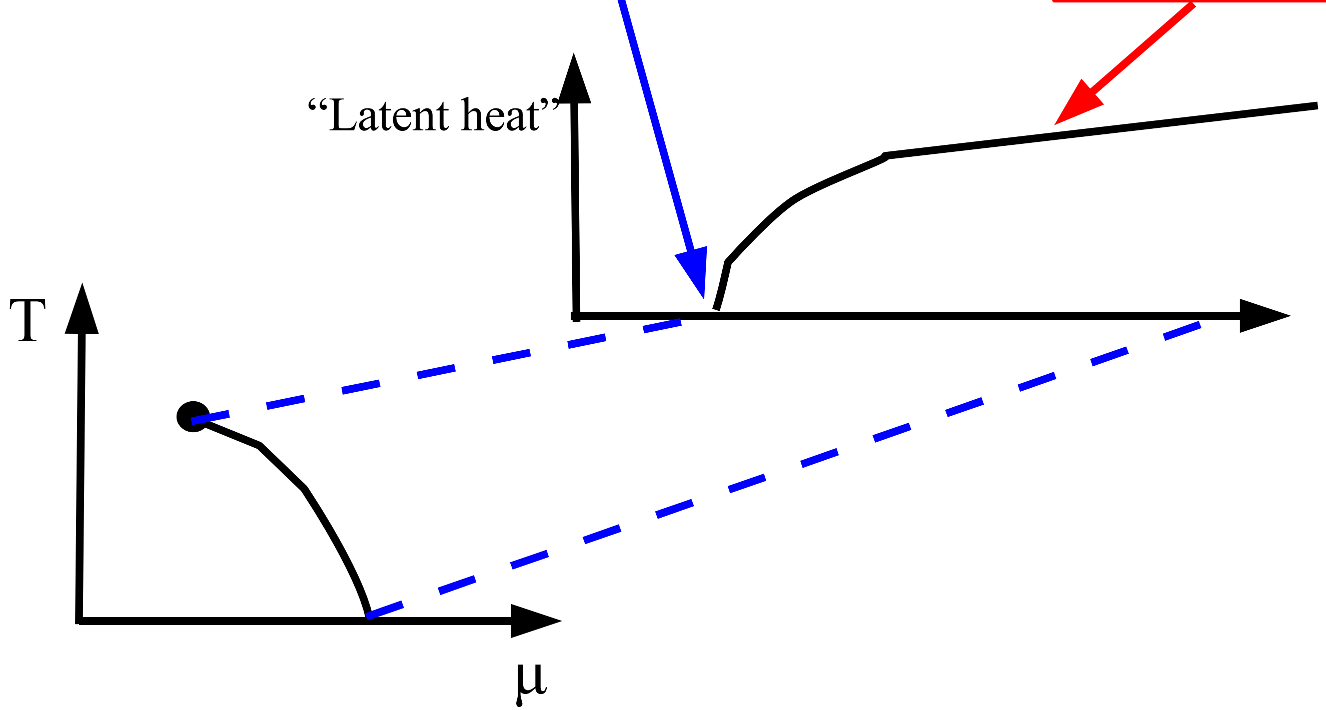
First order:
- Phase coexistence, bubbles
- Spinodal instabilities



First order or second order?

Second order:
- Critical fluctuations
- Diverging Susceptibilities

First order:
- Phase coexistence, bubbles
- Spinodal instabilities



Compelling reasons for higher luminosity*

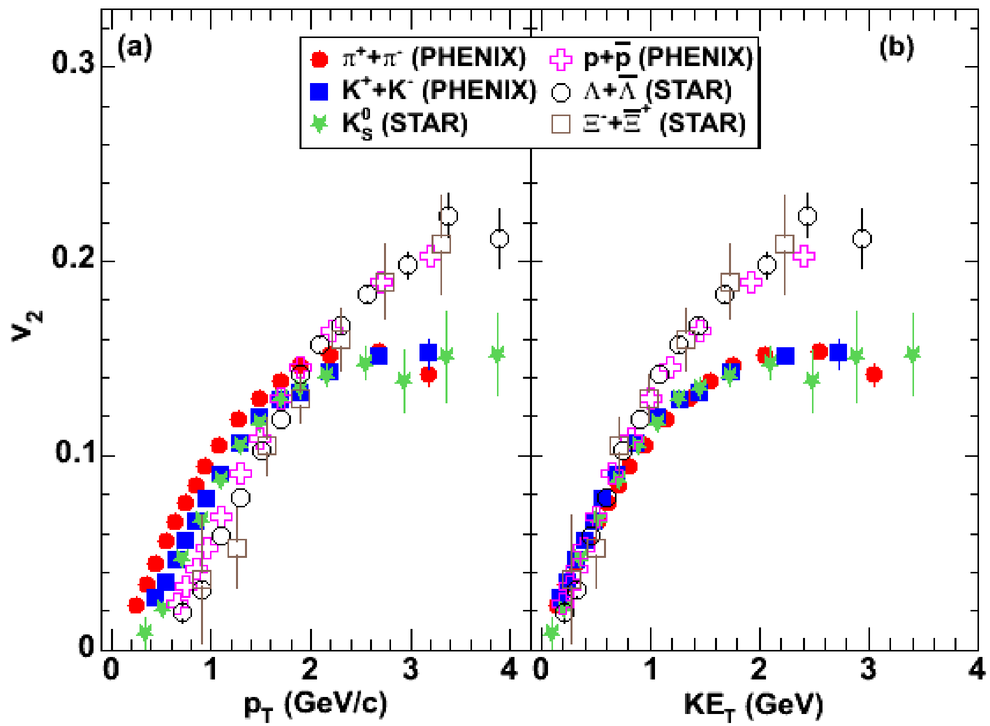
*** and upgrading STAR, PHENIX**

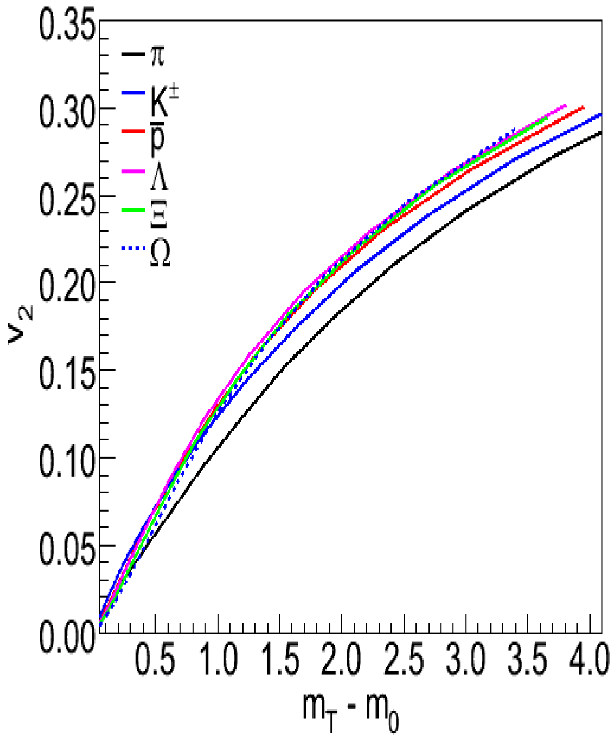
- Entirely new questions posed by RHIC
  - fast thermalization mechanism?
  - how low is the viscosity of the liquid?
  - response of the plasma to deposited energy?
  - what is the color screening length?
  - is the initial state a color glass condensate?

- Early questions still outstanding
  - nature of phase transition? critical point?
  - equation of state of hot QCD matter?
  - do heavy quark bound states melt?
  - can dilepton observables provide evidence for chiral symmetry restoration?

B. Jacak, QM 2006)

Need for precision data?





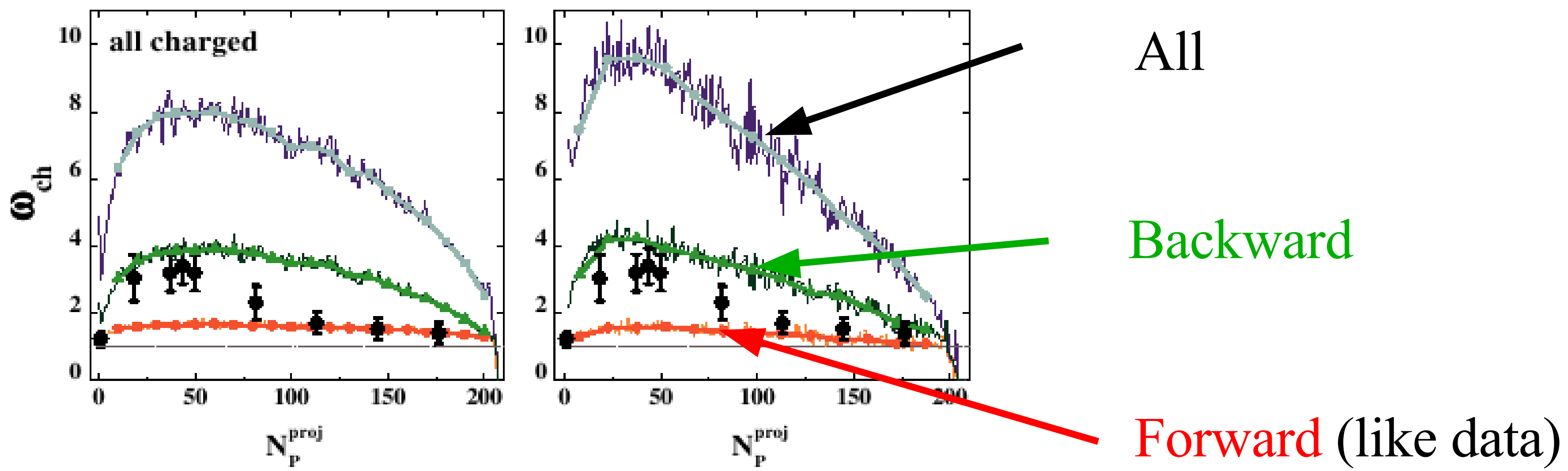
Kinetic energy scaling at RHIC, not SPS?

No kinetic energy scaling in hydro, but close...

Dynamics, event selection ...

(or why a symmetric detectors are good)

Konchakovski et al, nucl-th/0511083



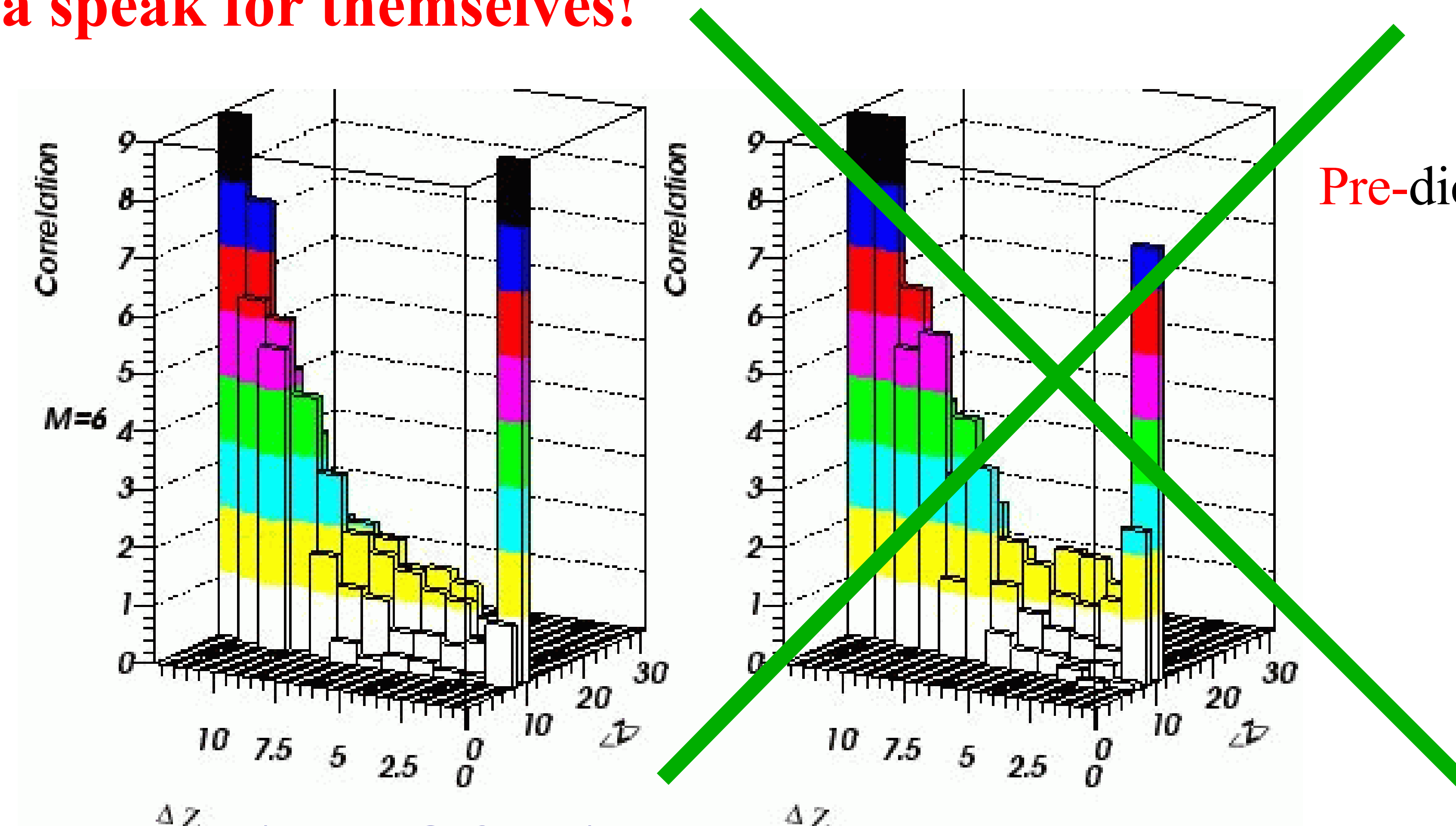
•Fluctuations are sensitive to dynamics (mixing of projectile and target material?)

•Event selection/trigger affects fluctuations → large Acceptance!

Spinodal decomposition in nuclear multifragmentation

occurs!

Data speak for themselves!

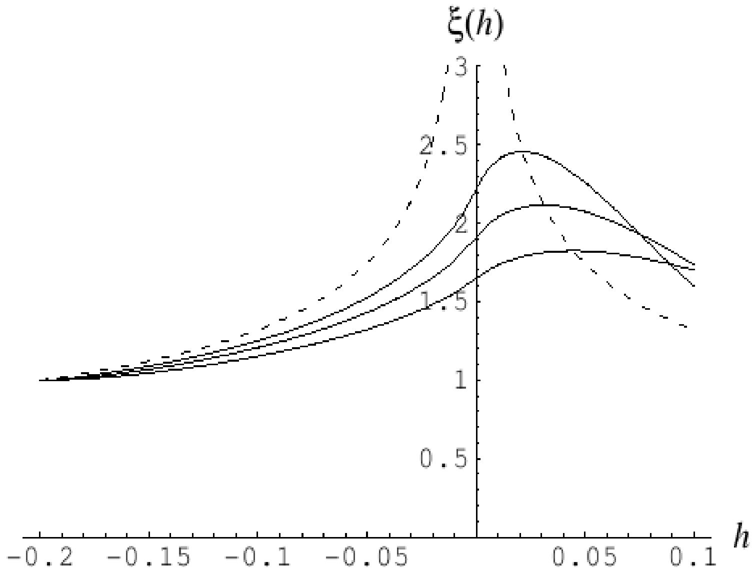


Experiment (*INDRA @ GANIL*)
Borderie *et al*, PRL 86 (2001) 3252

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

Second order

correlation length ~$1/m_\sigma$

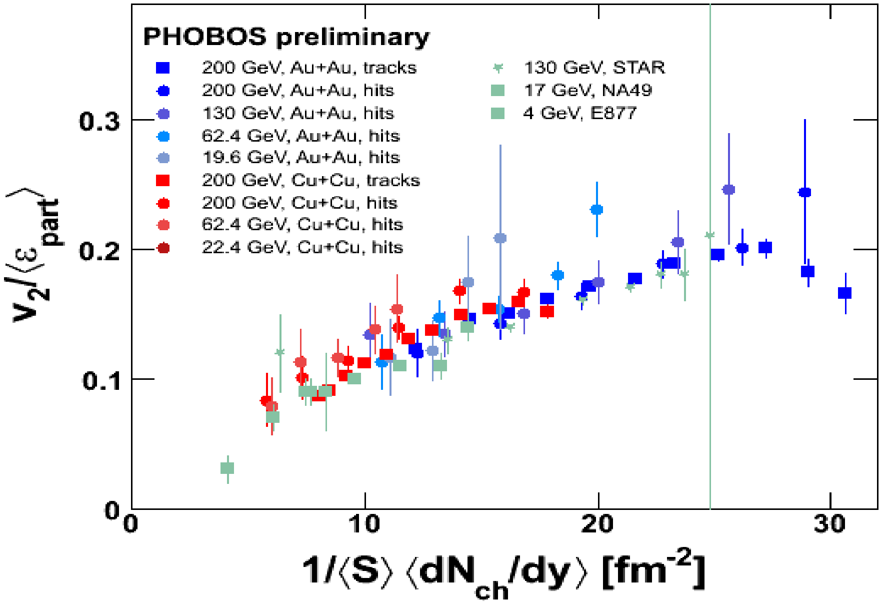


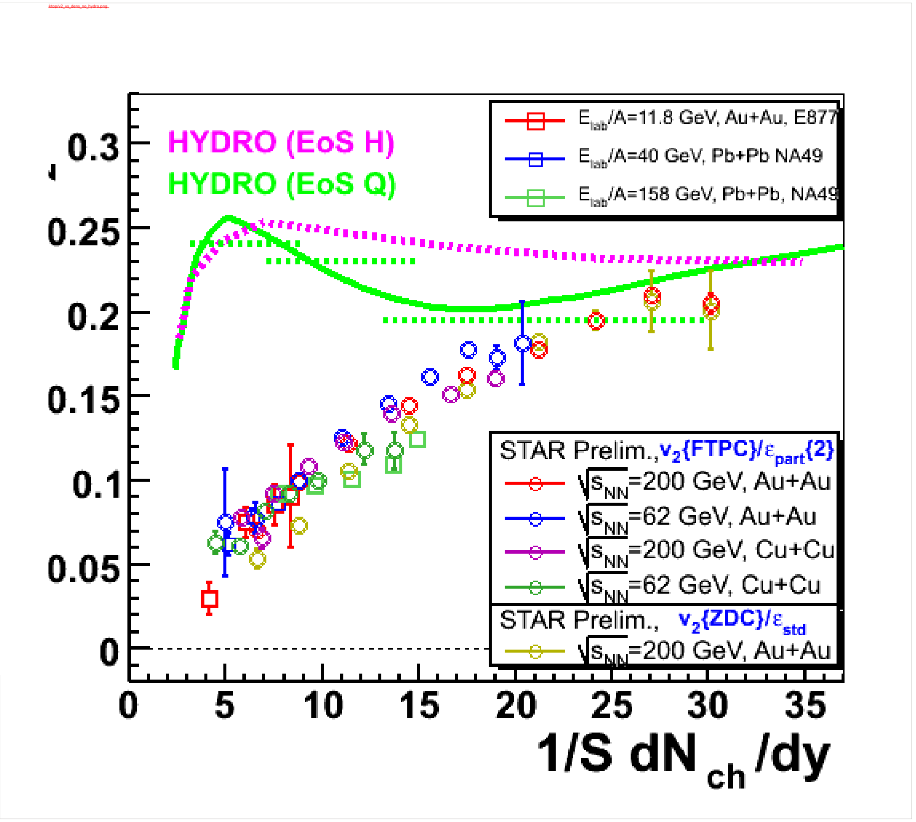
T/MeV 180 140 120

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

V2


PHOBOS preliminary
200 GeV, Au+Au, tracks
200 GeV, Au+Au, hits
130 GeV, Au+Au, hits
62.4 GeV, Au+Au, hits
19.6 GeV, Au+Au, hits
200 GeV, Cu+Cu, tracks
200 GeV, Cu+Cu, hits
62.4 GeV, Cu+Cu, hits
22.4 GeV, Cu+Cu, hits
130 GeV, STAR
17 GeV, NA49
4 GeV, E877
v2/⟨εpart⟩
1/⟨S⟩ ⟨dNch/dy⟩ [fm-2]


HYDRO (EoS H)
HYDRO (EoS Q)
Elab/A=11.8 GeV, Au+Au, E877
Elab/A=40 GeV, Pb+Pb NA49
Elab/A=158 GeV, Pb+Pb, NA49
STAR Prelim., v2{FTPC}/εpart{2}
√sNN=200 GeV, Au+Au
√sNN=62 GeV, Au+Au
√sNN=200 GeV, Cu+Cu
√sNN=62 GeV, Cu+Cu
STAR Prelim., v2{ZDC}/εstd
√sNN=200 GeV, Au+Au
1/S dN ch /dy