The QCD Equation of State with Thermal Properties of phi-mesons

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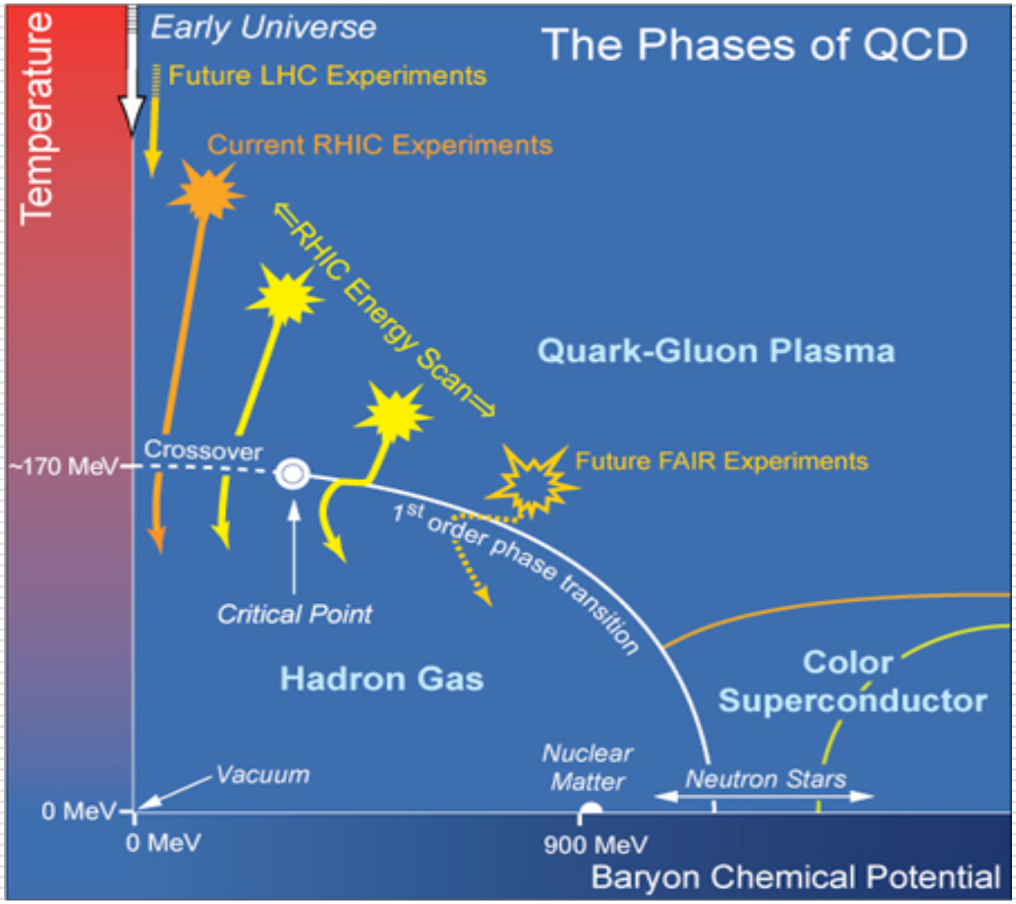
Outline

- ✓ Introduction
- ✓ Results:
  - ✓ Van Hove Signal and order of transition with Φ
  - ✓ Lattice QCD vs data using the Φ-meson
  - ✓ Approach to Tc
- ✓ Summary and outlook

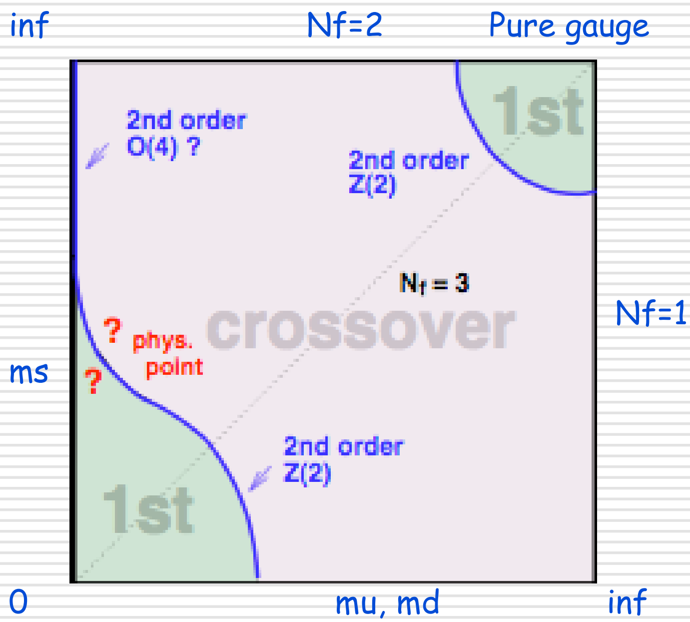
Introduction
The QCD Phase Diagram



Existence of critical point not completely clear from muB>0 lattice calculations , Allton et al, hep-lat/0501030

The order of the transition changes with mu_B, therefore with the sqrt(s) of the collision

Order of transition from lattice QCD at muB=0

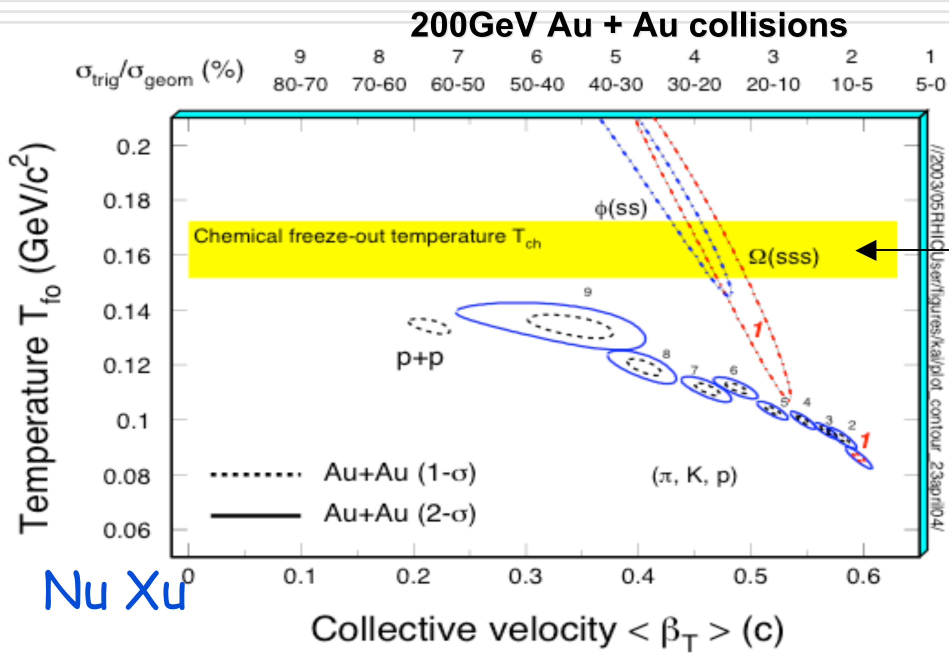


A Peikert, PhD Thesis, Univ. Bielefeld

Order of transition from lattice QCD at mu_B=0 varies with nr of flavours and masses of quarks

--> Address the order of transition using data vs theory

Why the phi meson ?



STAR: NP**A715**, 458c(03); *PRL* ***92****, 112301(04);* ***92****, 182301(04).*

Small hadronic rescattering cross-section, $\sigma(\phi N)$ = 10 mb.

ϕ (and Ω) decouple early: they show larger Tfo and smaller <beta_T> than other hadrons (see 1 for central collisions on the left fig.)

ϕ T(thermal fr. out) ~ T(chem. fr. out) within errors

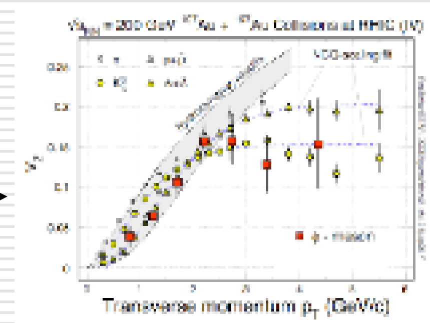
life time =45 fm/c --> decay products (phi-->K+K- channel) are not influenced much by rescattering

-> ϕ(as well as Ω) are interesting probes for studying EoS and nature of phase transition

Observables for phi:

Tth(thermal freeze out) : reflect information below or near Tc

Yields, Teff, flow eg v_T (radial flow), v2 (elliptic flow) etc: can reflect information below and above Tc (e.g. suggested by n_q scaling of v2)



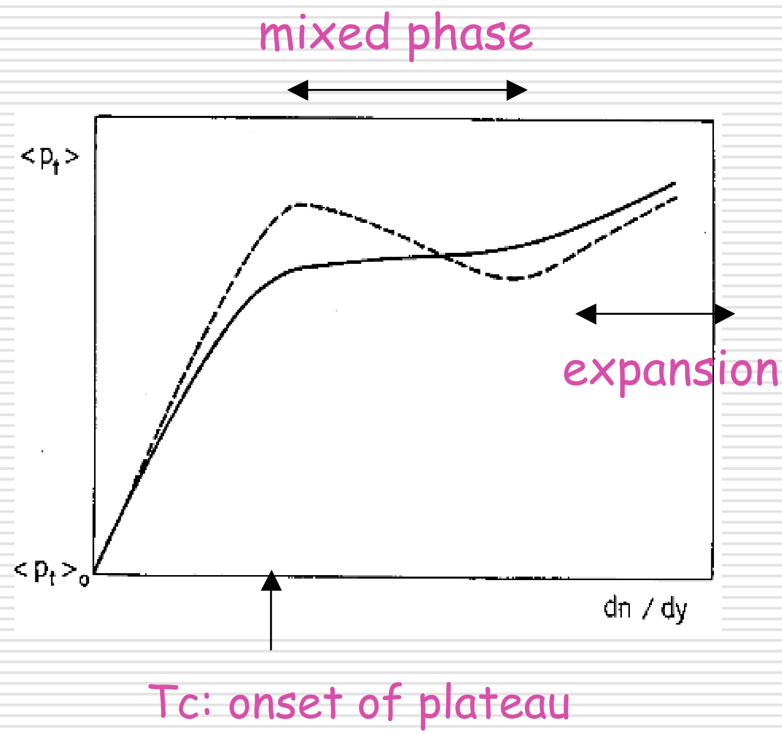
→ Here we attempt to use phi data and confront them to lattice and simple thermodynamic expectations like the Van Hove signature

The Van Hove Signal of 1st order Phase Transition

L. Van Hove: *Phys. Lett. B 118, 138 (1982)*

The flattening of the $<p_T>$ with increasing multiplicity in proton-anti-proton collisions, at mid-rapidity, may serve as a probe for the equation of state of hot hadronic matter.

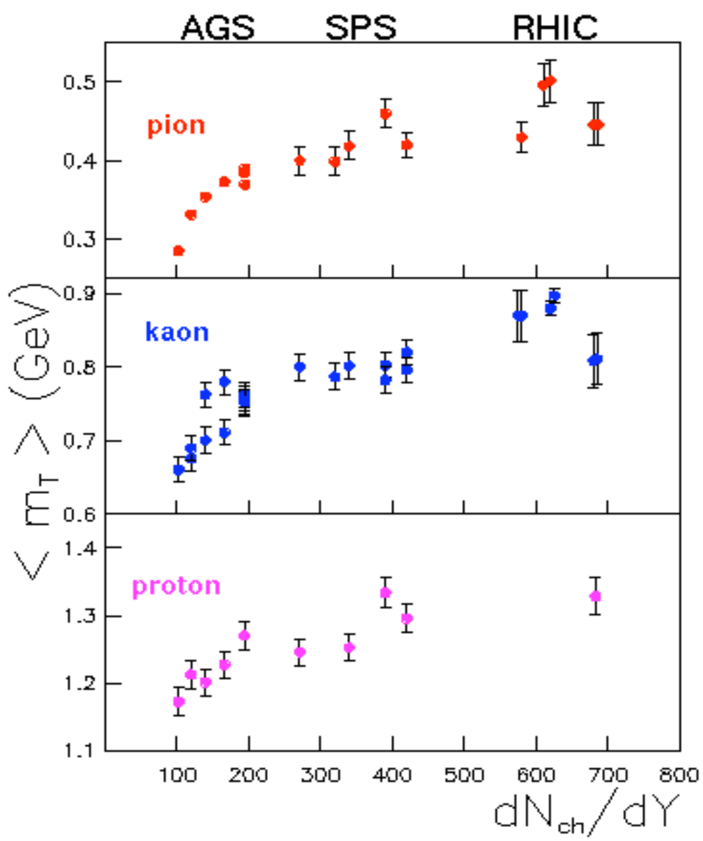
Multiplicity reflects the entropy and $<p_T>$ the effect of temperature and transverse expansion.



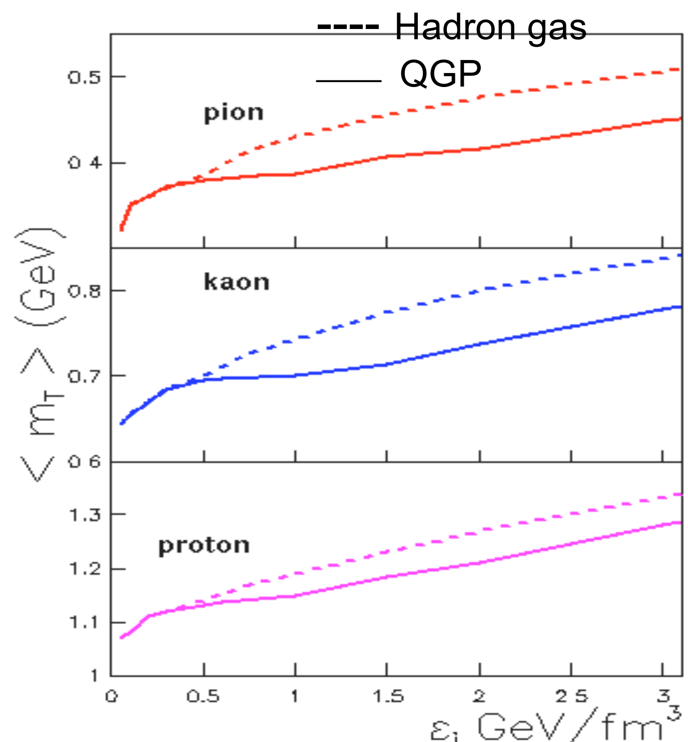
The observation of an increase, a central plateau, followed by a second increase in <pT> as a function of dN/dy is suggested as signature of latent heat (1st order phase transition).

Van Hove Signal in π,k,p

Mohanty, Alam, Sarkar, Nayak, Nandi
PRC 68 (2003) 021901 (R)



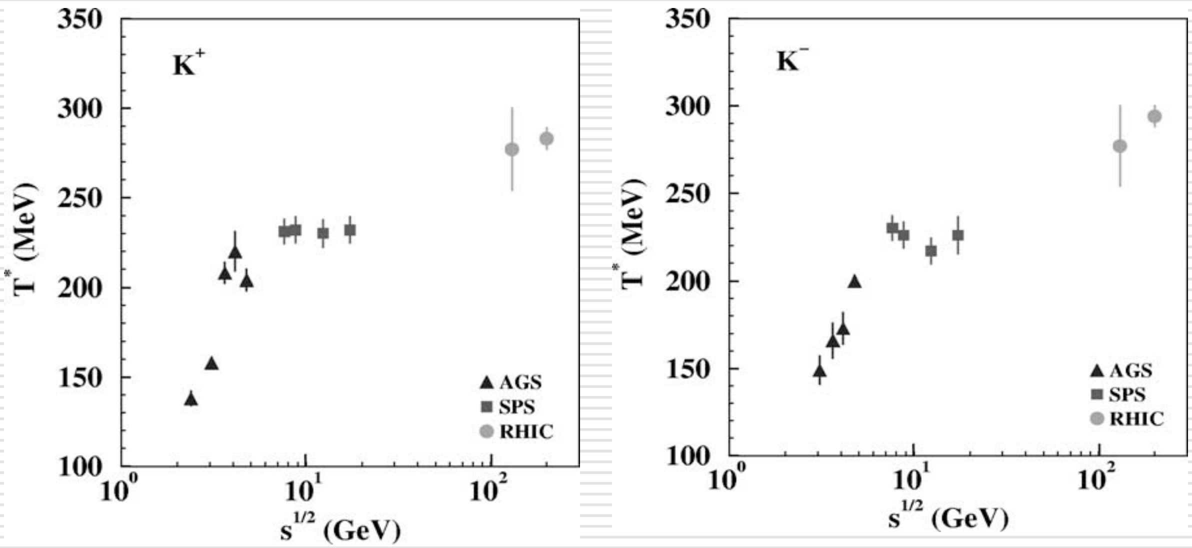
Hydrodynamic calculation with (3+1) dimensional expansion



- Rapid rise in $<m_T>$ going from AGS to SPS energies and indication of flattening towards RHIC.

Hydrodynamic calculation with QGP reproduces the general trend of data
Observation of a central plateau indicates 1st order phase transition

Collision energy dependence of inv. slope of K+-



M. Gazdzicki et al
PLB 567 (2003) 175

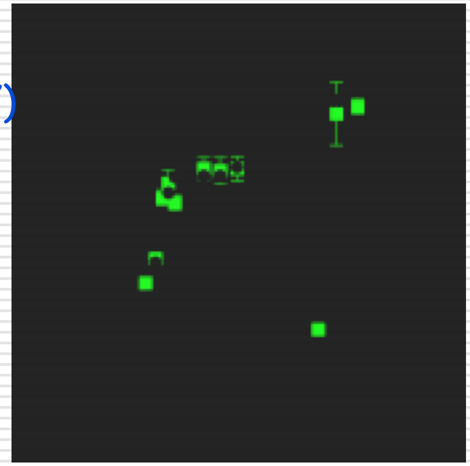
T*= inv. slope =T+flow instead of <pt>

sqrt(s) instead of dN/dy

Indication of phase co-existence (1st order phase transition) in Kaon production in A+A collisions.

Hydrodynamic calculation with 1st order phase transition can reproduce these data.
Y. Hama et al, Acta Phys Pol B, 35, (2004).

T* (MeV)

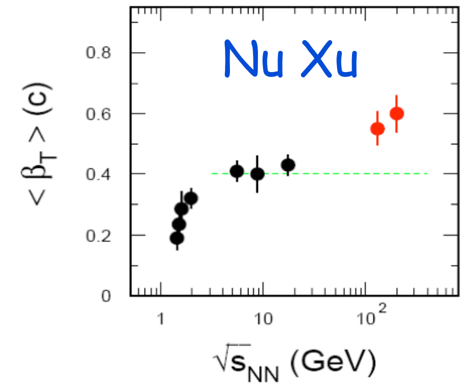


sqrt(s) (GeV)

Results I

Van Hove Signal and order of transition with Φ

Van Hove Signal in phi-meson : √s dependence

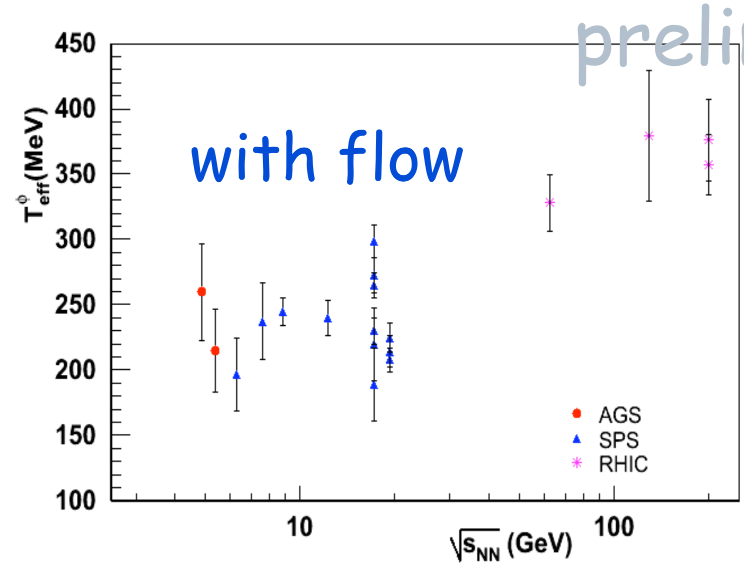


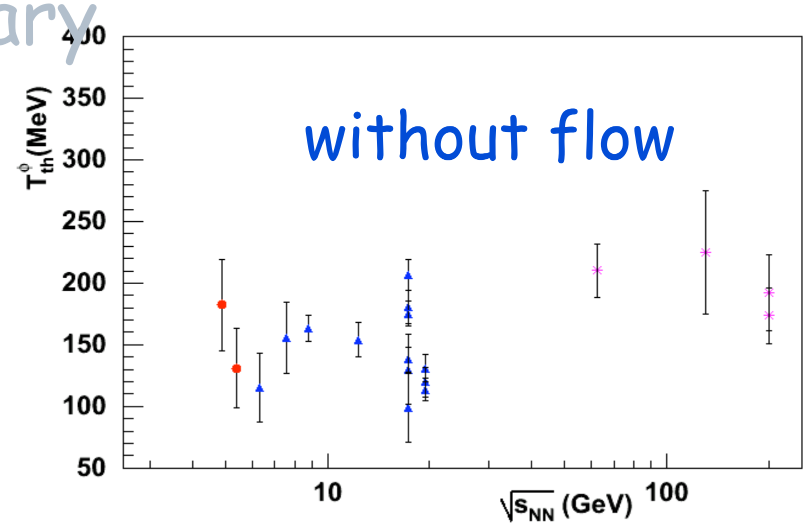
Teff : inverse slope

Tth ; T(thermal freeze out)

$T_{eff} = T_{th} + 0.5\, m_{\Phi} \langle\beta_T\rangle^2$,
$\langle\beta_T\rangle$: average coll. radial flow velocity

preliminary





Teff of phi shows a plateau and increases at sqrt(s)=62 GeV --> indicating a possible 1st order transition
T(th. fr. out) of phi at RHIC exhibits high values, while an enhancement remains after flow subtraction.
Tth is approx. near T(chem. fr. out).

Van Hove Signal in ϕ-meson: ε(Bjorken) dependence

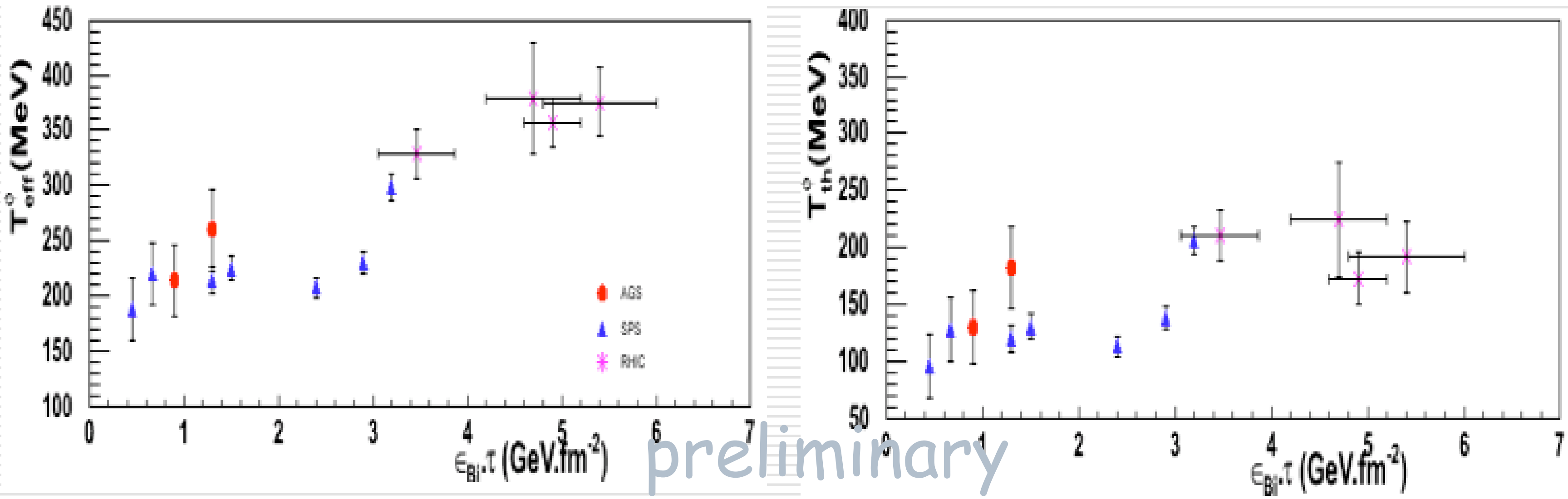
Teff : inverse slope

Tth ; T(thermal freeze out)

e(Bj)=(dEt/dy) / (pi*R^2*τ)

1 fm/c formation time

$T_{eff} = T_{th} + 0.5\, m_{\Phi} \langle\beta_T\rangle^2$, $\langle\beta_T\rangle$: average coll. radial flow velocity

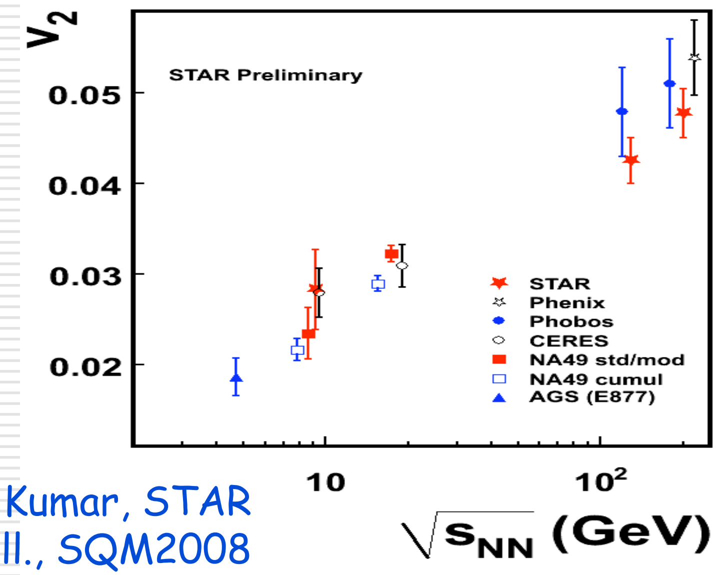


Teff of phi shows a plateau below 3 GeV/fm^3, and subsequent increase above ~3.2-3.8 GeV/fm^3.

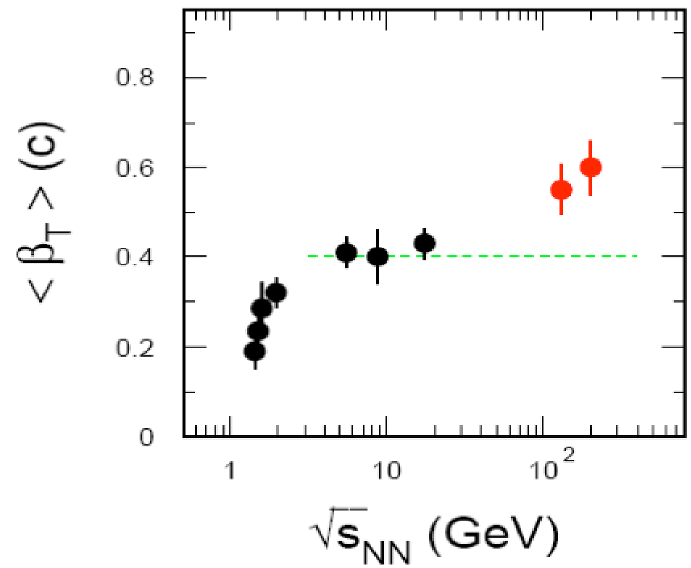
More phi data are needed below 1 GeV/fm^3 to asses the increase and onset of pleateau ->or one can look also other particles than phi for this.

T(th) shows a plateau, while a small increase is still observed above 3 GeV/fm^3 after radial flow is subtracted.
Note that taking the measured beta_T(phi) will enhance the T(th) phi points at RHIC (work in progress).

Van Hove signal in flow



L. Kumar, STAR coll., SQM2008



Nu Xu

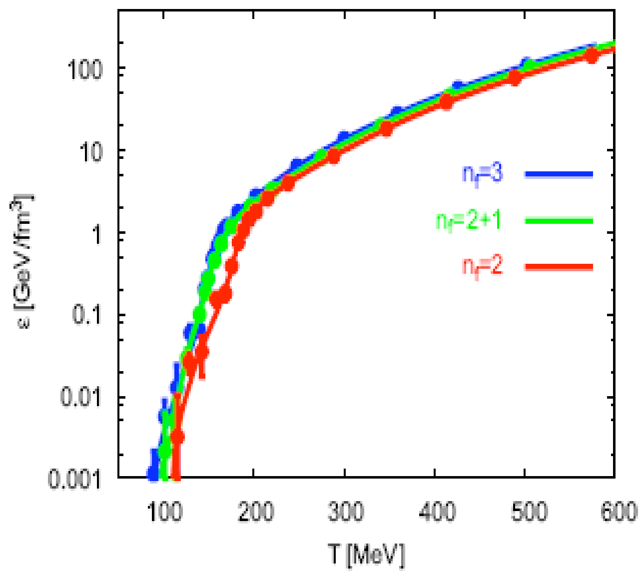
- The central plateau is seen also in parameters characterizing collective expansion namely in beta_T as a function of sqrt(s).
- The v_2 as a function of sqrt(s) may indicate a plateau structure too. Need more data and plot versus e(Bj) will be usefull.
- Those parameters may reflect the initial pressure, the latter expected to remain constant during mixed phase in 1st order transition.

[For v_T hadronic rescattering phase may be important: Y. Hama et al, Acta Phys Pol B, 35, (2004).]

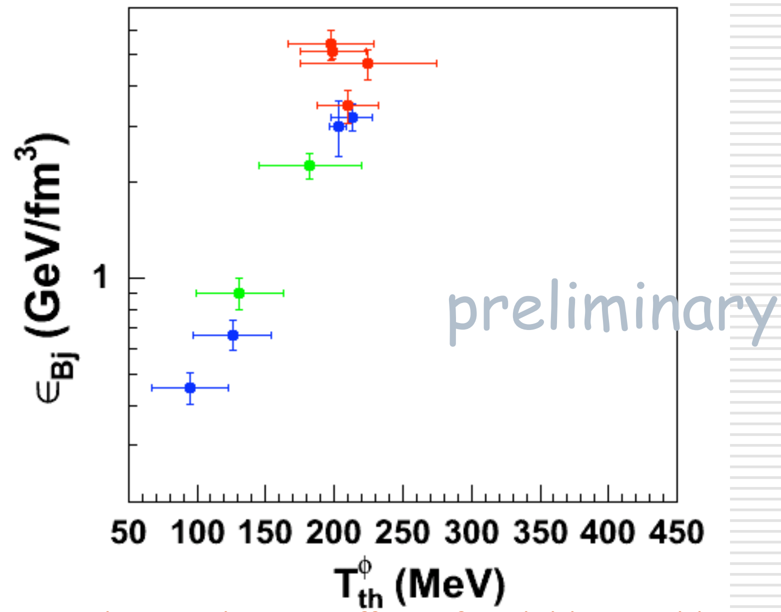
Results II
Lattice QCD vs data using the Φ-meson

Lattice QCD & EoS: F-meson
The energy density as a function of the T

D.E. Miller / Physics Reports 443 (2007) 55–96



Assuming t = 1 fm/c



T is about 192 MeV and density about 1 GeV/fm^3 where the discontinuity in slope occurs.
(cross over at mu_B=0)

Energy density combines the effects of the initial conditions which are controlled by the impact parameter the nuclei used, and the collision energy.

- Tth(phi) is hadronic thermal freeze out T, probably near chemical freeze out T, and below or at Tc.

- e(Bj) and T(th) in data (right) are 'measured' at different times

---> Note that the curve is artificially approaching Tc.

(Because the high e points correspond in reality to T(init) of QGP above Tc)

--> To overcome this we use as next a 'measure' of T(init) or Pressure(init) from data

Lattice QCD & EoS: F-meson
The energy density as a function of the Teff

D.E. Miller / Physics Reports 443 (2007) 55–96

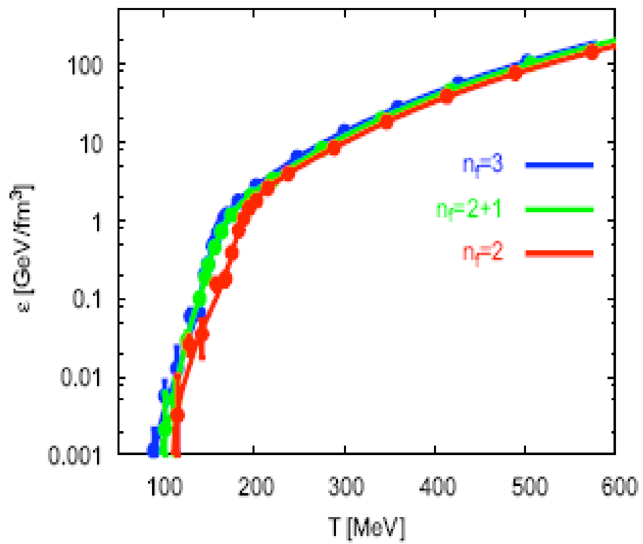
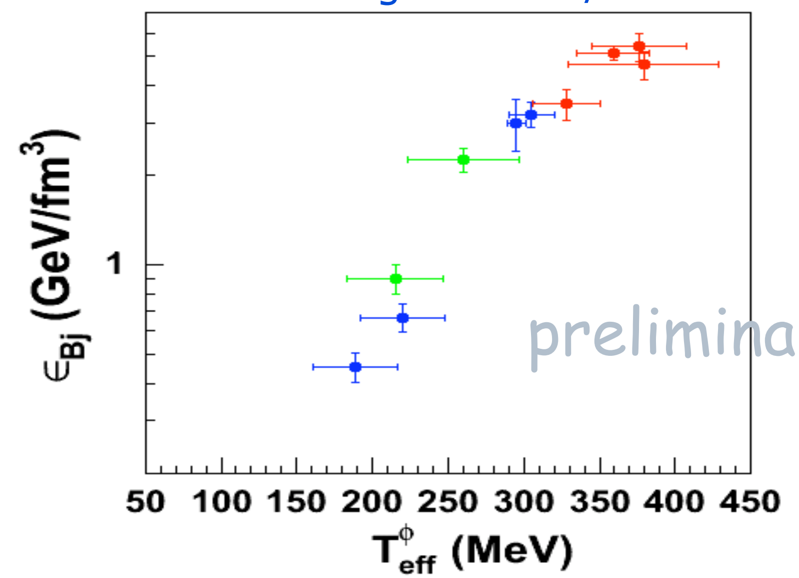


Fig. 8. The energy density for the three values of $n_f = 2, 2+1, 3$ with massive dynamical quarks.

Assuming t = 1 fm/c



Since T(init) QGP above Tc, is not measurable with phi, we use Teff in order to reflect the behaviour of the initial state variables which can be above Tc, and in particular of the pressure (flow) term in Teff.

Teff is not a temperature but reflects the initial energy (T+flow).

(In the right plot, e and Teff from data are not measured at the same time. In lattice they are.)

--> Some similarity is exhibited in lattice vs data.

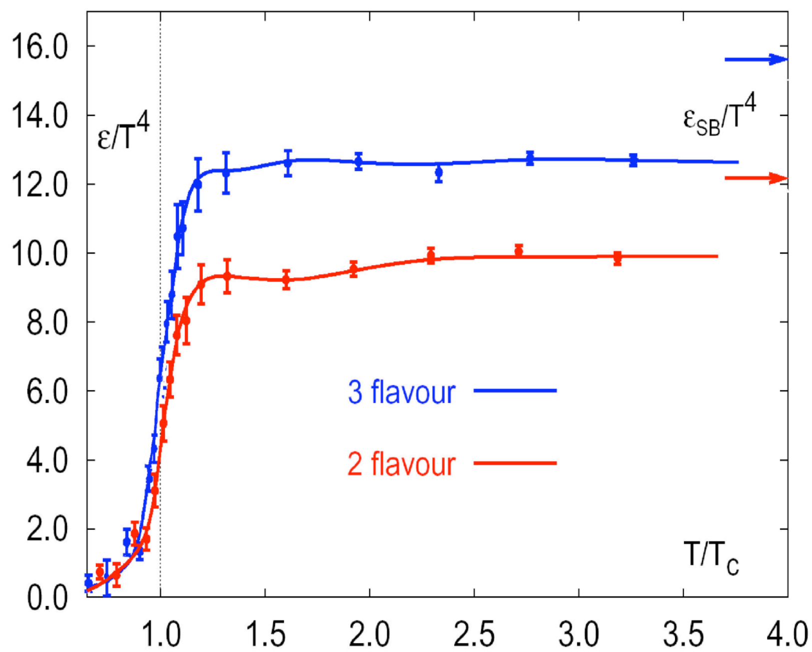
--> More data needed (especially in low Teff).

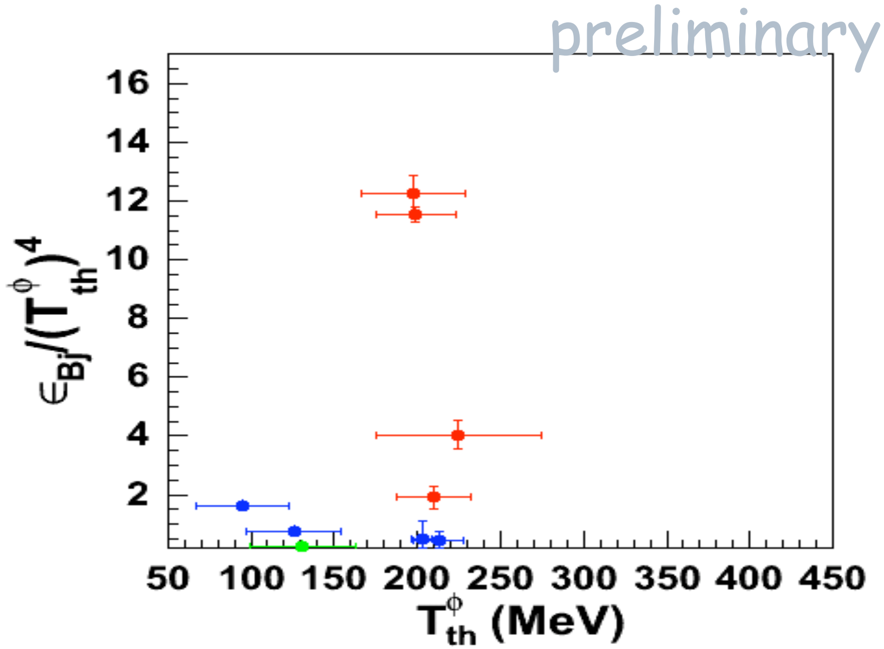
→ Use hydro for this study

→ study also for e(Bj) versus v_2 and for e(Bj) vs beta_T

(work in progress)

Lattice QCD & EoS: phi-meson
The energy density/T^4 as a function of the T





formation time parametrized as a function of E

y axis arbitrarily normalized

Tth is below or at Tc, even if e(Bj) is above Tc, causing an artificial increase approaching Tc.

To access the T>Tc part, one can try to use Teff, reflecting qualitatively properties of the T>Tc range.

Results III

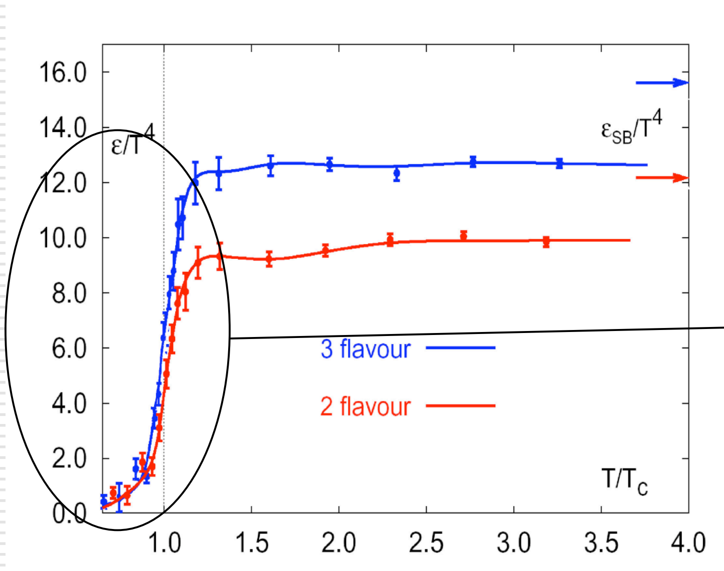
Lattice QCD vs data:
Approach to Tc using T(chem. freeze out) of all hadrons at mu_B=0

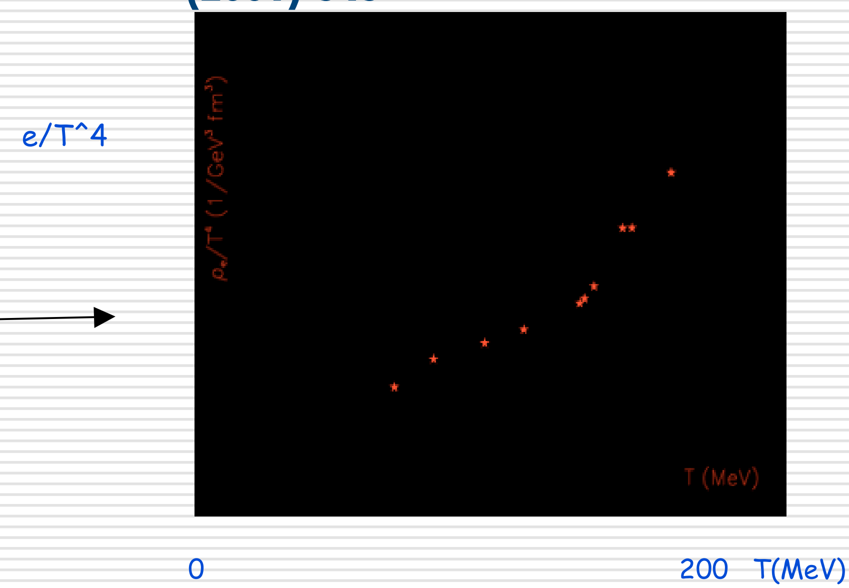
Lattice QCD & EoS:
The energy density/T^4 as a function of the T at mu_B=0, at the chemical freeze out

We now look at the e/T^4 vs T dependence, using e, T at the chemical freeze out extracted with a thermal model from particle ratios, and extrapolated to mu_B=0

S. Kabana, P. Minkowski, New J Phys 3:4, 2001, hep-ph/0010247.

S. Kabana, hep-ph/0104001, Eur. Phys. J. C 21 (2001) 545

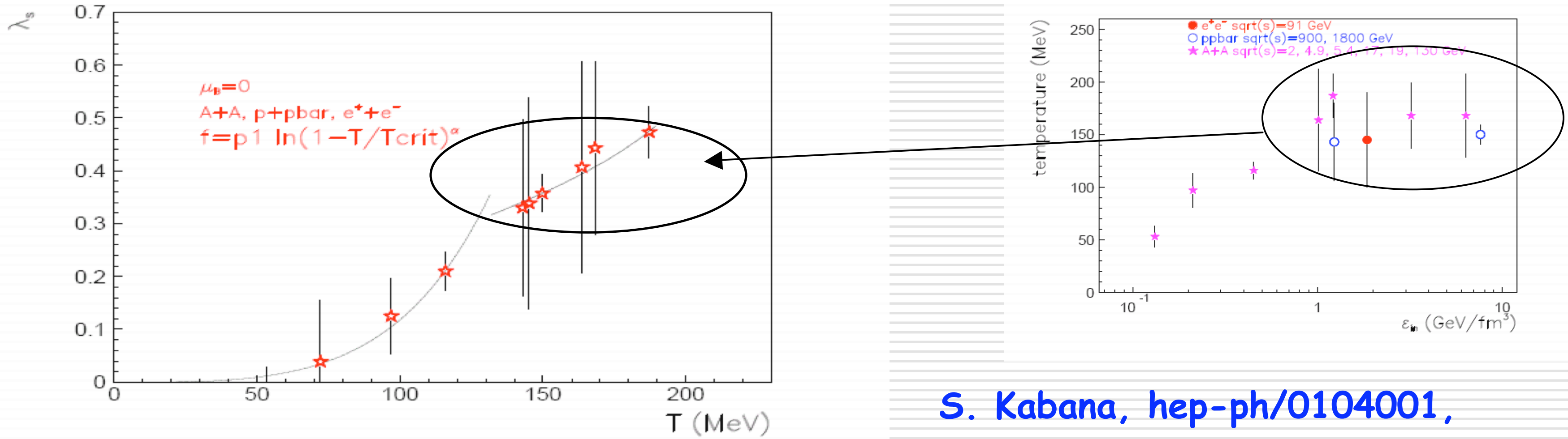




The e, T here are measured at same time, namely at chem. freeze out, and mu_B=0

The increase of e/T^4, approaching Tc is observed

An attempt to extract a critical exponent



S. Kabana, hep-ph/0104001,

Eur. Phys. J. C 21 (2001) 545

First study of the approach of lambda_s to the Temperature, both extracted from data using a thermal model, for the colliding systems which are near T_c (SPS and RHIC) is fitted by a function

$$F = c\,|\ln(1 - T/T_c)|^a$$

We find Tc=218 +- 70 MeV and a=0.54 +- 0.47

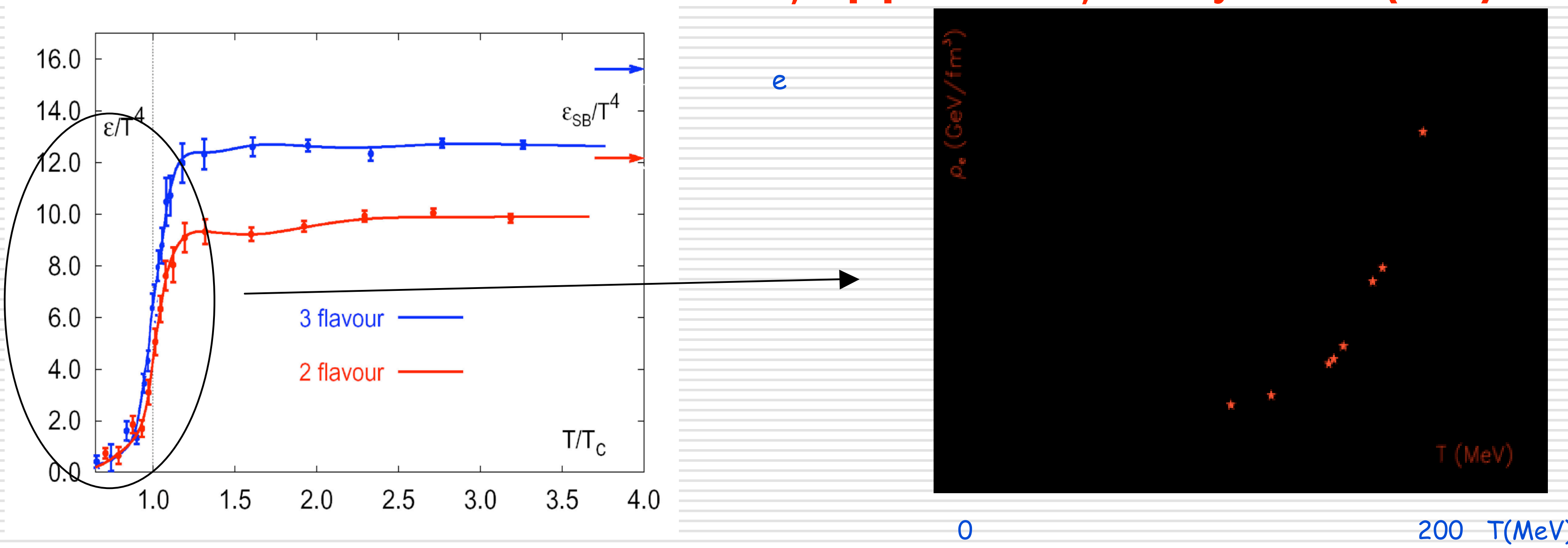
Despite the large errors one can observe that the T_c value is within the error in agreement with previous T_c estimates

(Errors can be improved with new data)

Lattice QCD & EoS:
The energy density as a function of the T at mu_B=0 and at chemical freeze out

e vs T dependence, using e, T at the chemical freeze out, and at mu_B=0 (as a normalization to same mu_B for all collisions, and to compare to mu_B=0 lattice results)

S. Kabana, hep-ph/0104001, Eur. Phys. J. C 21 (2001) 545



The e, T here are measured at same time, namely at chem. freeze out, and mu_B=0

The increase of e approaching Tc is observed, and can be studied in terms of a critical exponent. Same can be done for rho_s, rho.

Summary and outlook

❖ The phi shows the Van Hove signature in the inverse slope (= T + flow) versus e(Bj) or sqrt(s) dependence (like pi,K,p too).

❖ Hydrodynamic calculations for pi,K,p assuming 1st order transition reproduce the plateau and the latter enhancement of the slopes.

❖ Flow (and therefore Teff too) could reflect initial conditions above and below Tc.

❖ beta_T shows a signature of a 1st order transition a la van Hove, in terms of a equivalent of pressure P : beta_T=f(P) vs e(Bj).

In particular the 'pressure'-equivalent remains ~constant, while e(Bj) increase from 1 to 3 GeV/fm^3.

Lattice calculations suggest that the order of the transition changes with mu_B and therefore along the data points shown versus sqrt(s) or e.

❖ The above observations suggest a mixed phase up to e(Bj)=3.2-3.8 GeV/fm^3, where the plateau seems to end.

❖ This does not exclude the change of the order at higher sqrt(s) (RHIC), as predicted by lattice towards muB=0

Summary and outlook

✓The thermal properties of the phi-meson have been used to compare data to lattice calculations and to study the nature of the QCD phase transition.

✓The e(Bj) vs Teff(phi) = Tth + flow : both variables may relate to initial observables below and above Tc -->
Comparison to lattice QCD (preliminary results).

✓ Study approach to Tc from below and near Tc, and at muB=0 : e, T measured at same time namely at chemical freeze out from hadron ratios. Extract critical exponents.

Outlook :

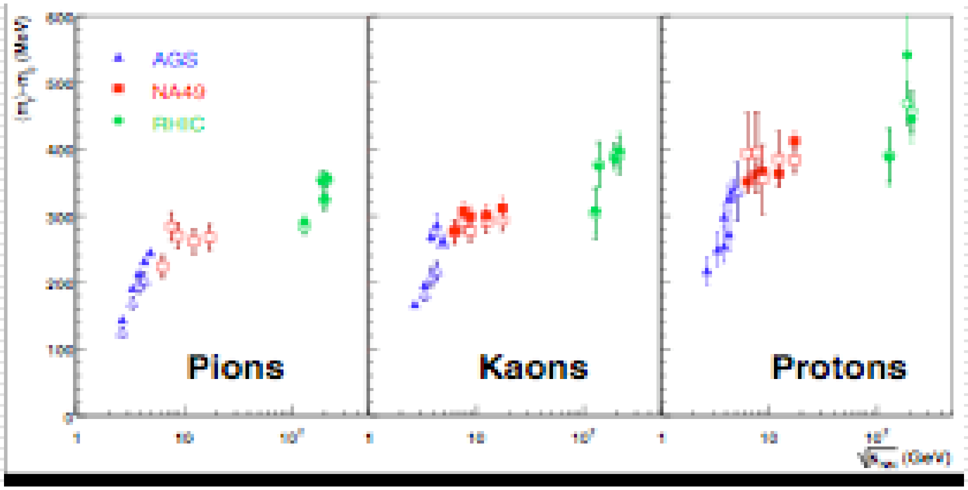
- ✓**Work in progress with hydrodynamic calculations for the phi.**
- ✓**Study approach to Tc (for e=1-3 GeV/fm^3, e> 3 GeV/fm^3)**
- ✓**Use beta_T(phi) for T(th) phi estimate**
- ✓ **Use more phi data, especially at low sqrt(s) if available.**
- ✓**Use v_2, v_T for qualitative lattice comparisons.**

Thank you very much !

BACKUPS

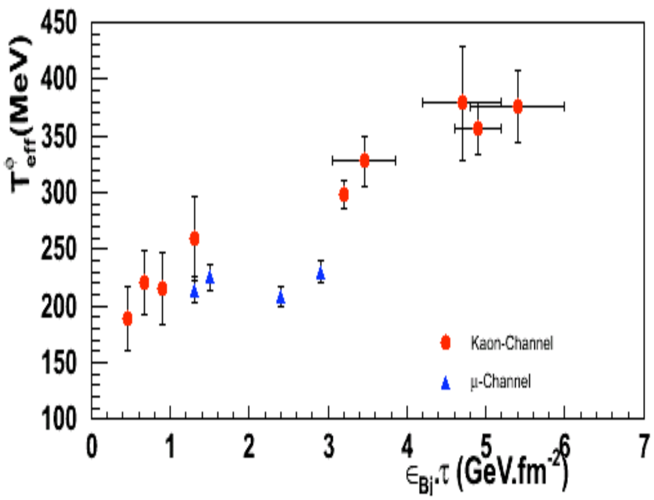
Van Hove signal in pi,K,p NA49 plot

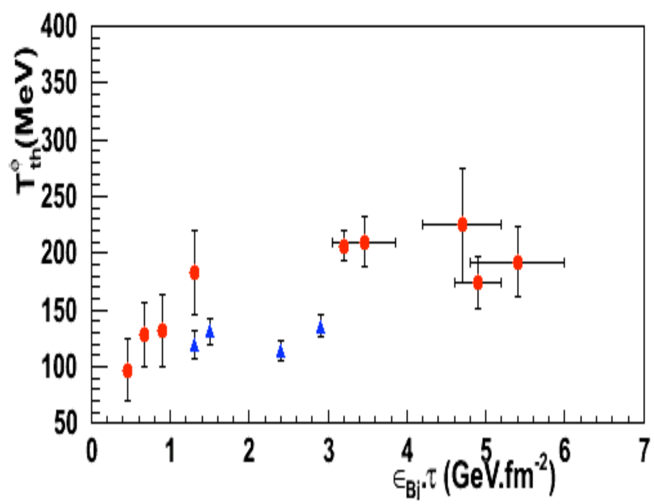
Central AuAu or PbPb collisions



Ch. Blume, J Phys G31 (2005) 57.

Van Hove Signal & Φ-puzzle





Φ is reconstructed from its hadronic and leptonic decay channels.

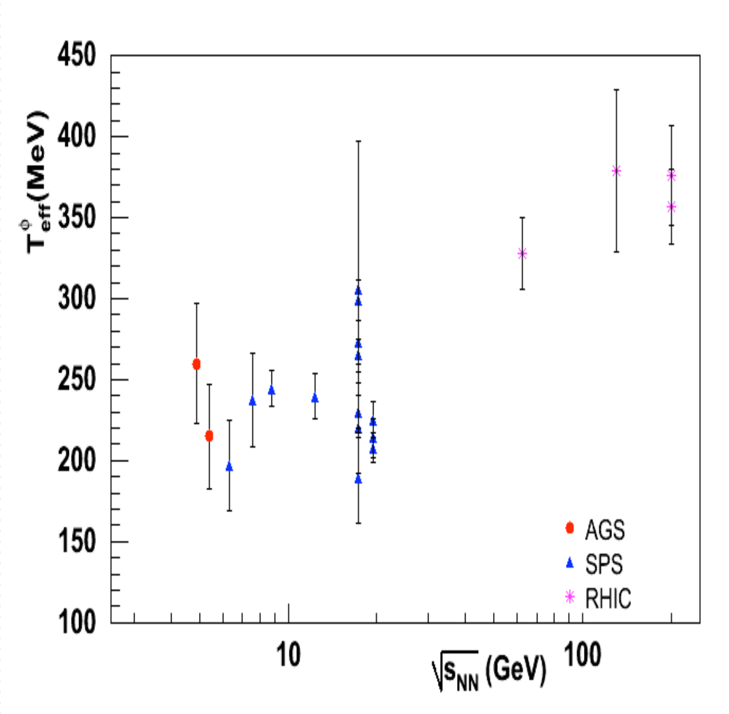
<u>The puzzle:</u>

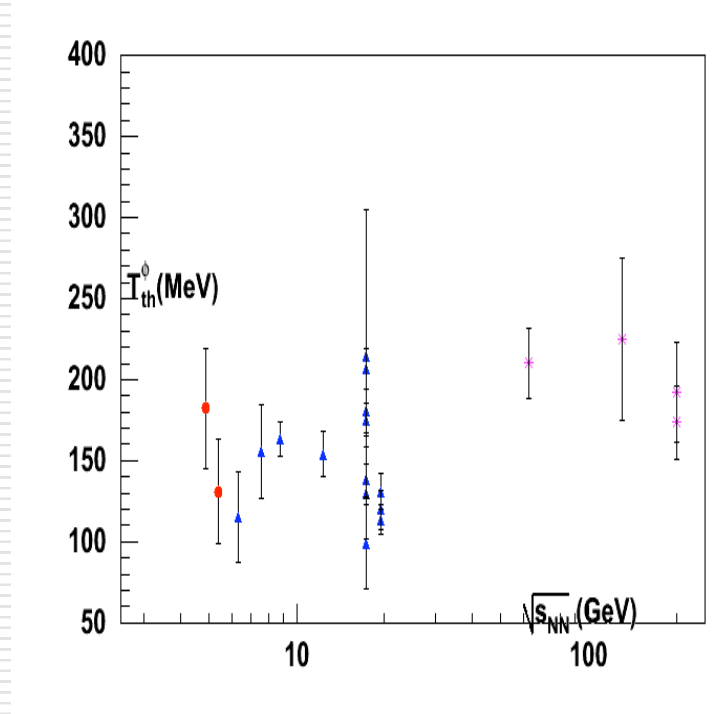
- **the yield is lower for hadronic channel compared to the leptonic channel of reconstruction**
- **the inverse slope parameter T_{eff} is higher for hadronic channel**

Does Φ-puzzle make the central plateau?
However this plateau is seen in pi, K, p too

Note: Φ Thermal freeze out temperature near ~ T_c

Backups





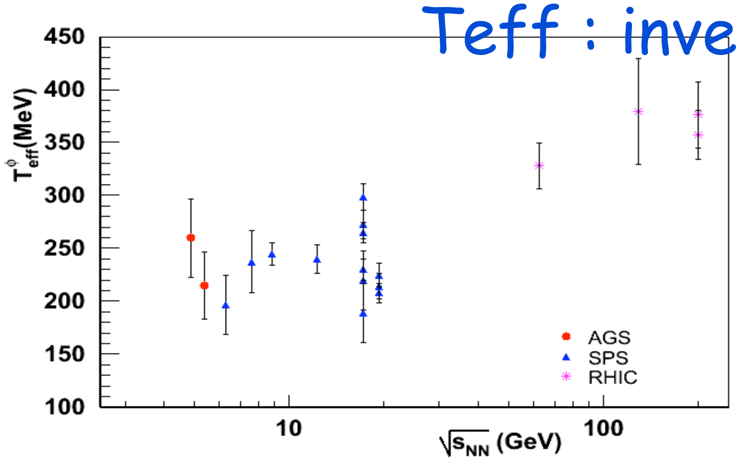
Inclusion of CERES leptonic channel data which has error 92 MeV

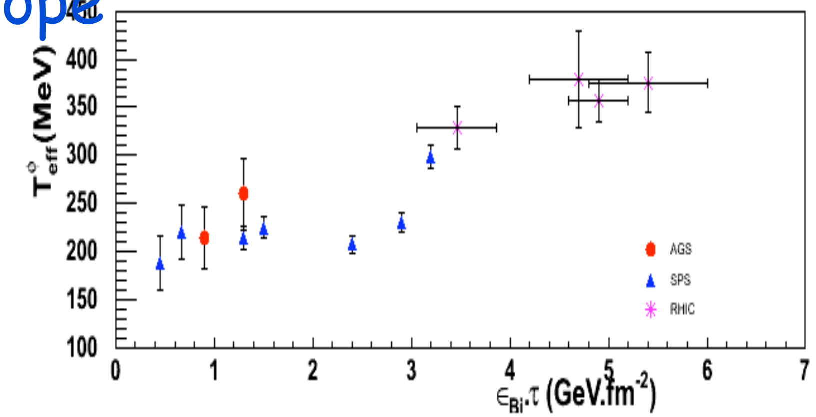
There plots are with new NA49 and CERES data at SPS.

Van Hove Signal in phi: e(Bj) and sqrt(s)

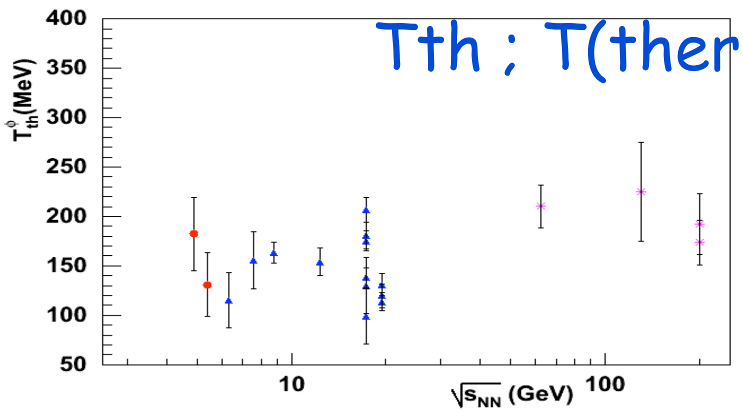
$T_{eff} = T_{th} + 0.5\, m_{\Phi} \langle \beta_T \rangle^2$

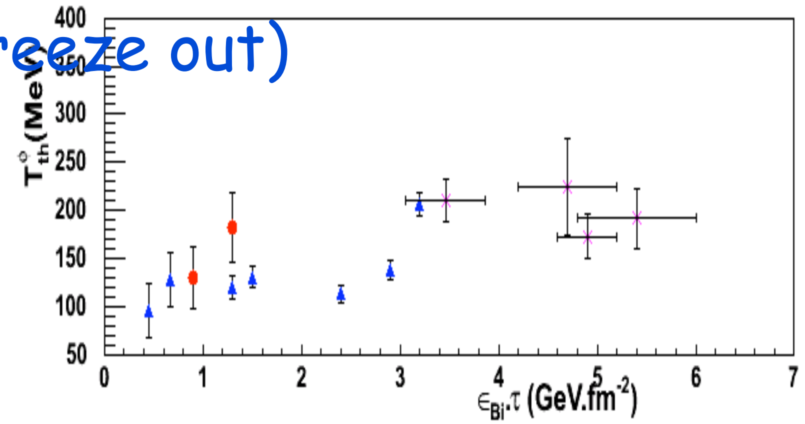
Teff : inverse slope





Tth ; T(thermal freeze out)



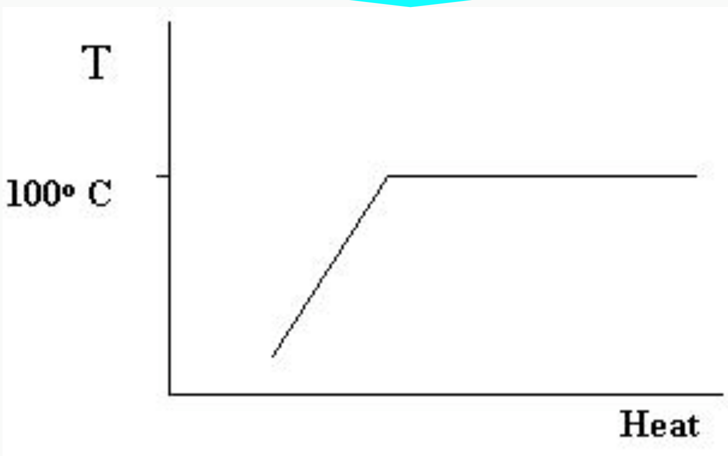


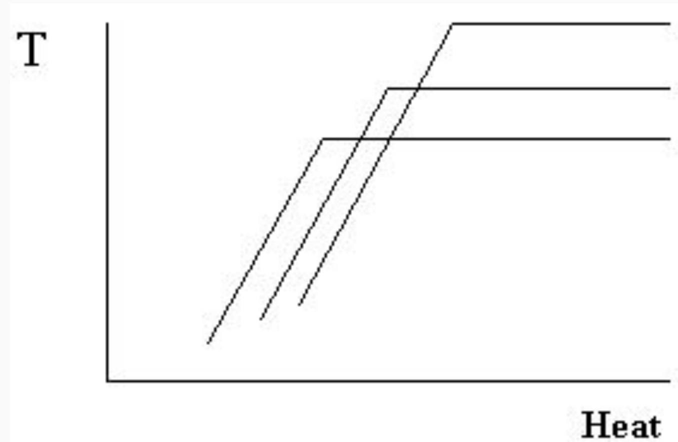
e(Bj) dependence improves from sqrt(s) in taking also into account effects like the different nuclei and impact parameters

Gap of sqrt(s) between SPS and RHIC is less pronounced on e(Bj) scale

Gedanken experiment to identify the water steam phase transition:

We heat a box with water more and more and measure its temperature T. We can only measure the T of the water (Had. Gas) and not of the steam (QGP). We plot T versus heat. T will rise until we heat enough to reach T=100° C. From then on, it will remain the same, namely T_{lim} ~< 100° C. Each time steam is present, we have to wait until it is again water, to measure its T. (E.g. R.Hagedorn (1965), H. Stocker et al (1981) etc.)





Now we repeat the experiment adding each time salt to the water. The T versus heat curve will not be as before, and we can not find the T_{lim}= 100° C.

S. Kabana, J. Phys. G27 (2001) 497

The baryochemical potential is like salt for hadronic systems.

Therefore, in order to measure a unique curve of T at freeze-out as a function of ε (init) in hadronic particle systems, one has to use the same conditions, with the same μB, the simplest one beeing μB=0.