Quark Gluon Plasma

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  - Even if Higgs is found, $m_{u,d}$ can be understood only if $g_{qqH} \sim 10^{-6}$ is experimentally established.
  - But QCD uniquely has very high interaction (binding) energies. E.g., $M_{Proton} \gg (2m_u + m_d)$, by a factor of 100 $\rightarrow$ Understanding it is knowing where the Visible mass of Universe comes from.

Quantum Chromo Dynamics (QCD)

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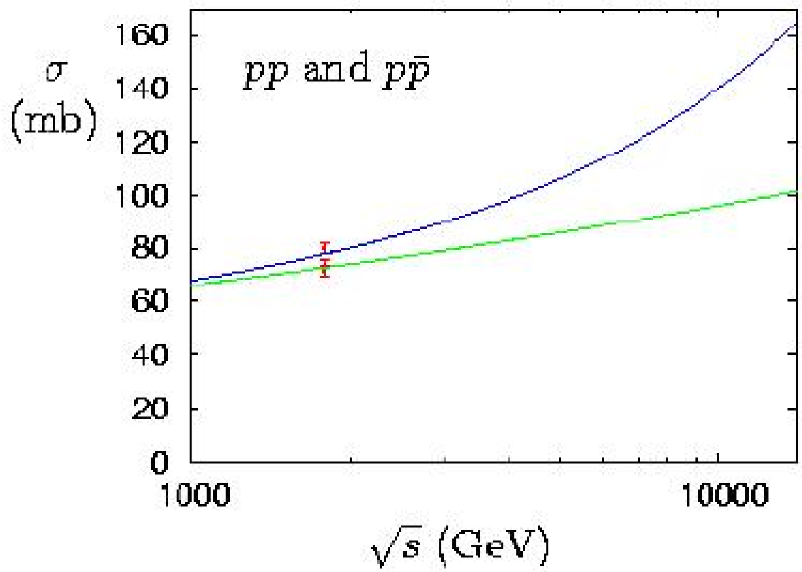
- Much richer structure : Quark Confinement, Dynamical Symmetry Breaking..
- Non-perturbative techniques needed for real precision tests of QCD.
- QCD too complex $\rightsquigarrow$ Simple models based on underlying symmetries are often epmloyed, making them a weak link in precision tests : BSM physics may show up in non-perturbative QCD beyond these models.

Total Cross Section at LHC

Predicted $\sigma^{\mathrm{tot}} = 125 \pm 25$ mb !

P. V. Landshoff, arXiv 0709.0395



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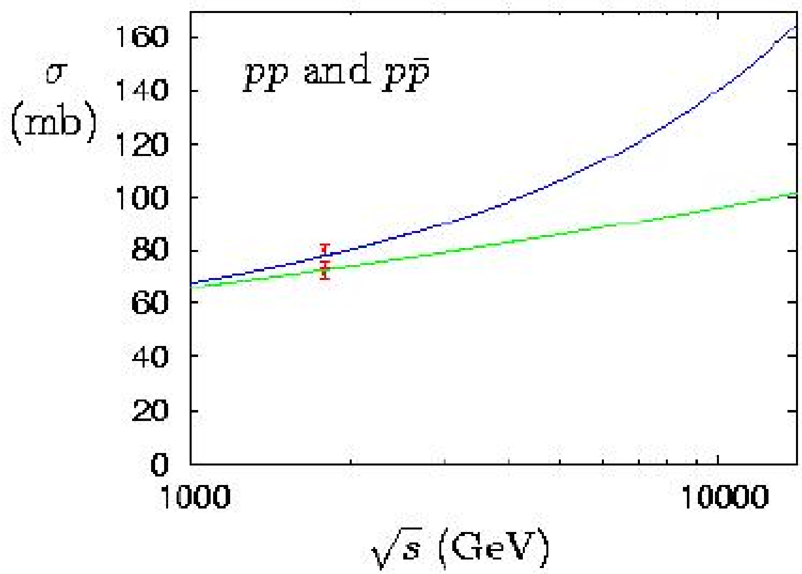

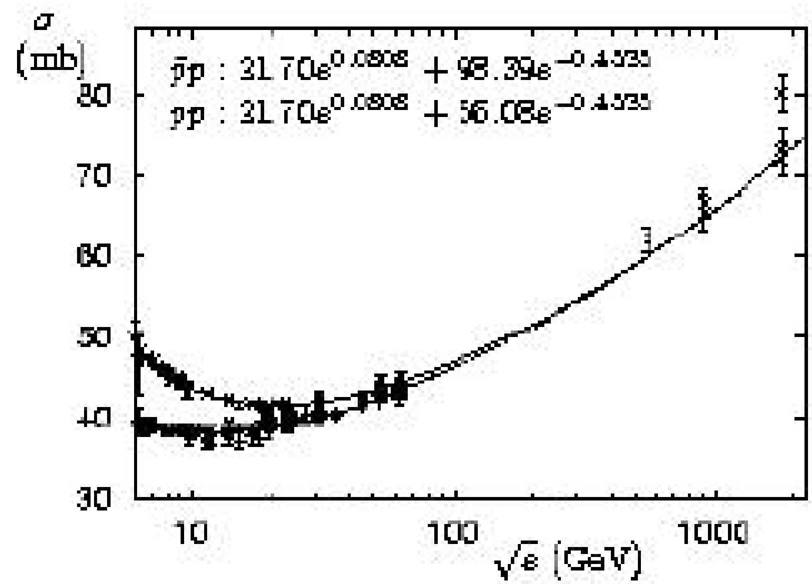

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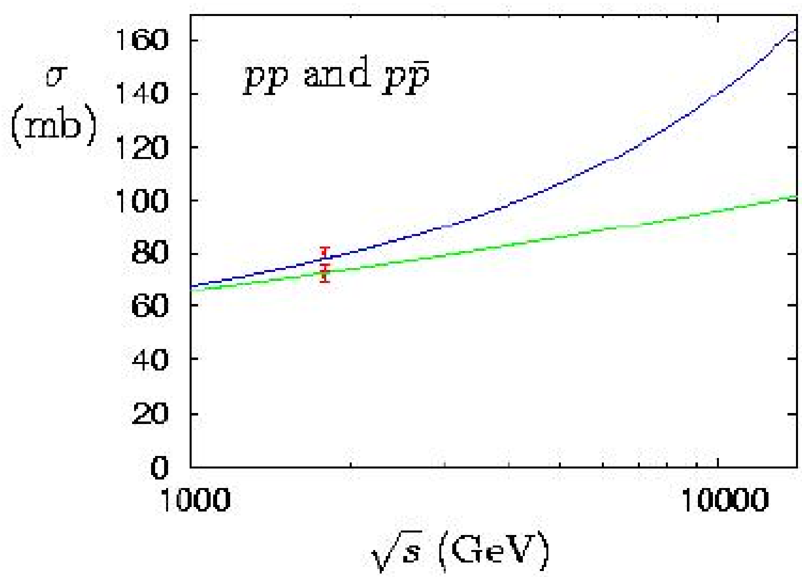
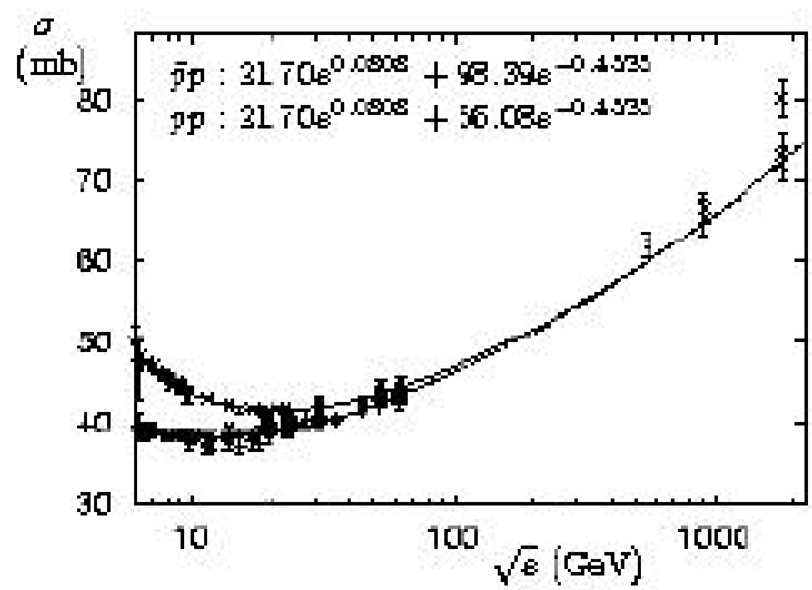
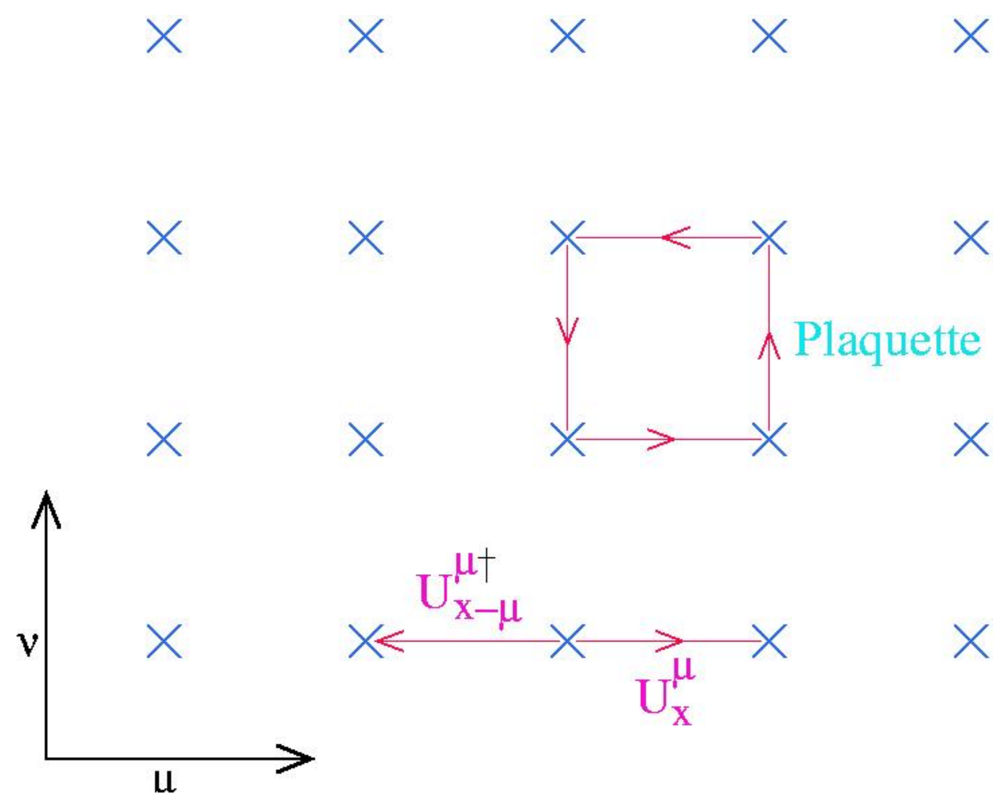




These Regge Models can explain the Q^2-variation of F_2 as well.

Basic Lattice QCD

- Discrete space-time : Lattice spacing a UV Cut-off.



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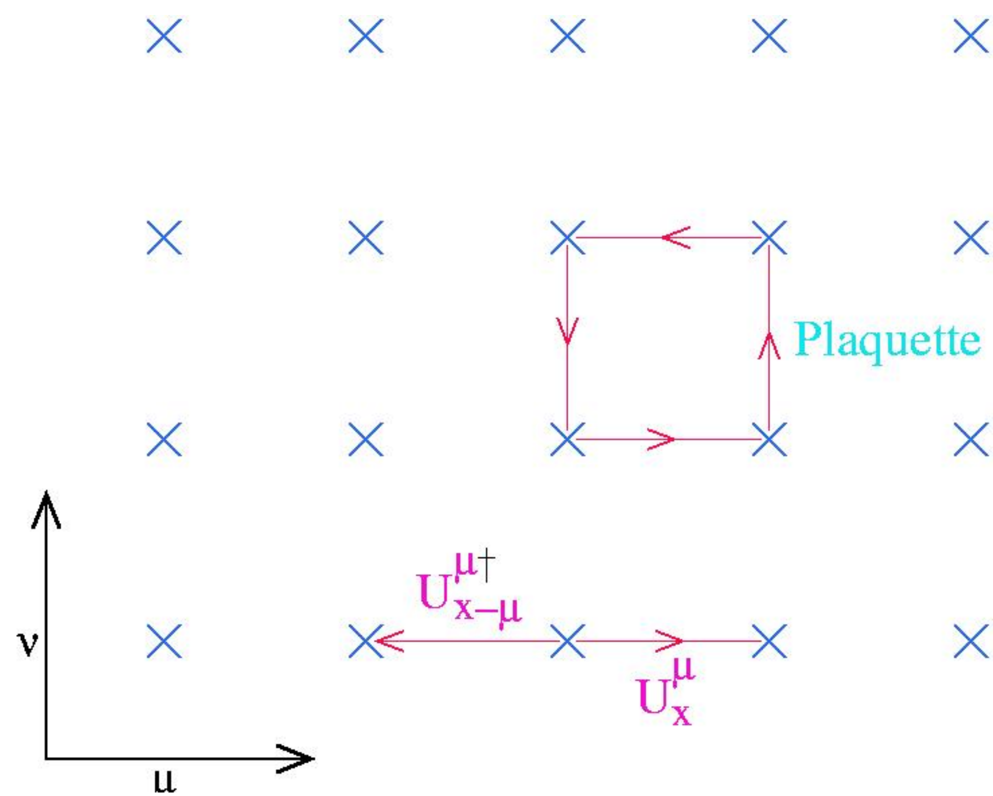

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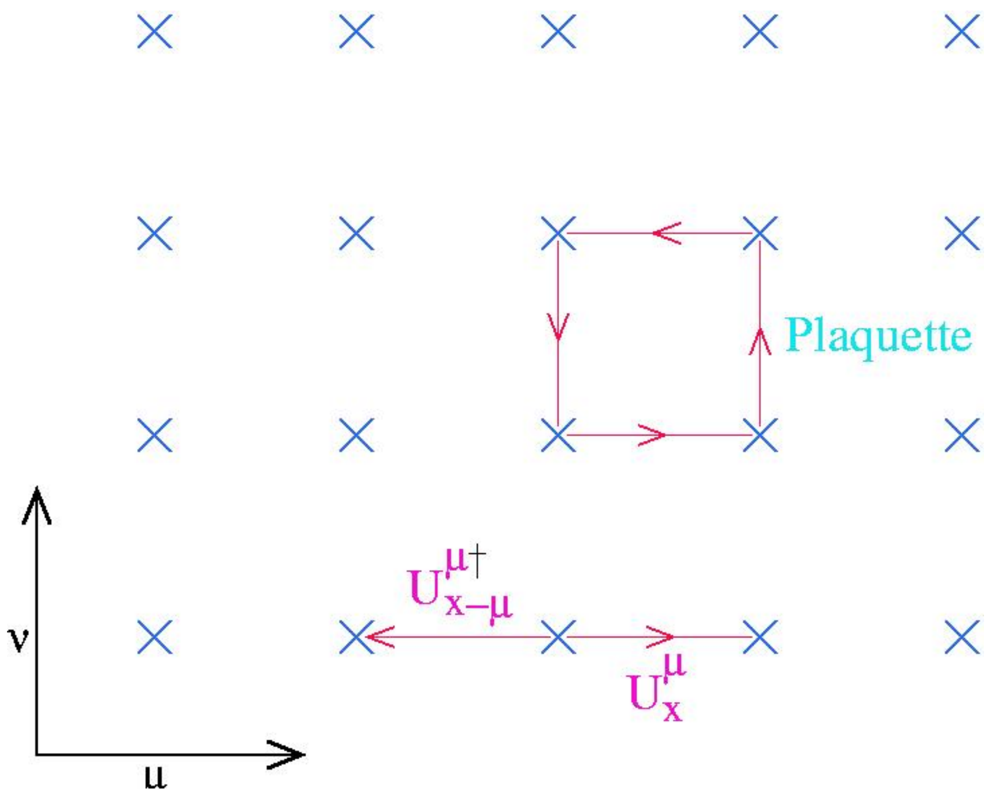

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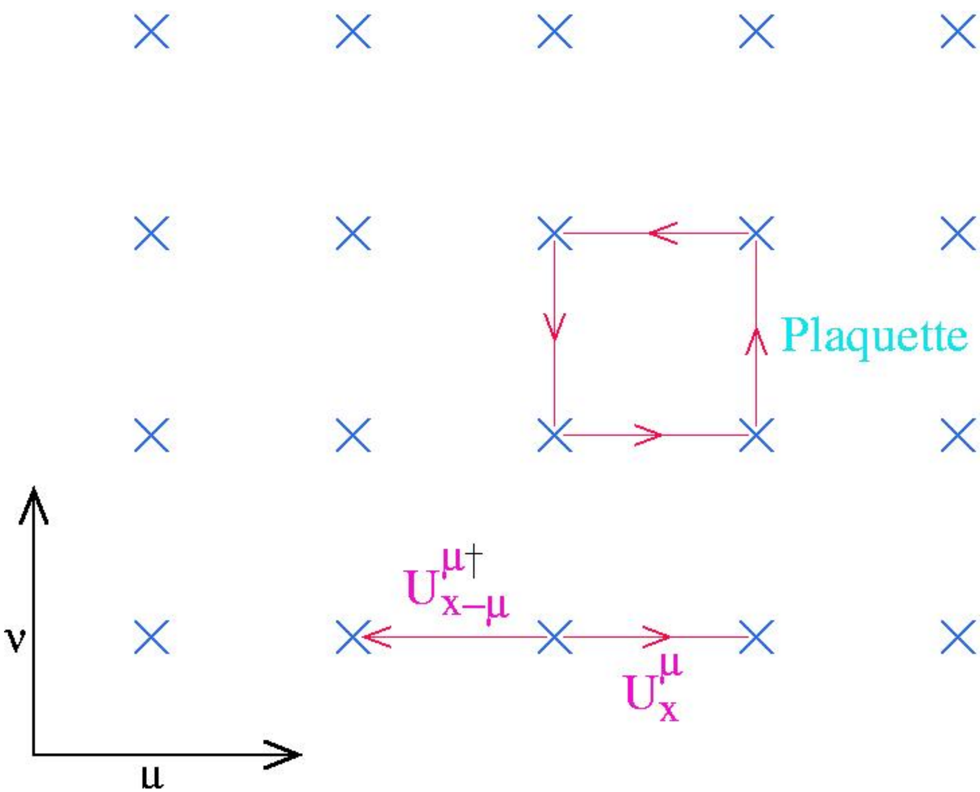
- Fermion Actions : Staggered, Wilson, Overlap..



Typically, we need to evaluate

$$\langle \Theta(m_v) \rangle = \frac{\int DU \exp(-S_G) \Theta(m_v) \ \mathrm{Det} \ M(m_s)}{\int DU \exp(-S_G) \ \mathrm{Det} \ M(m_s)} \ , \tag{1}$$

where M is the Dirac matrix in x, colour, spin, flavour space for fermions of mass m_s, S_G is the gluonic action, and the observable Θ may contain fermion propagators of mass m_v.

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Lattice scaffolding must be removed : Continuum limit $a \to 0$.
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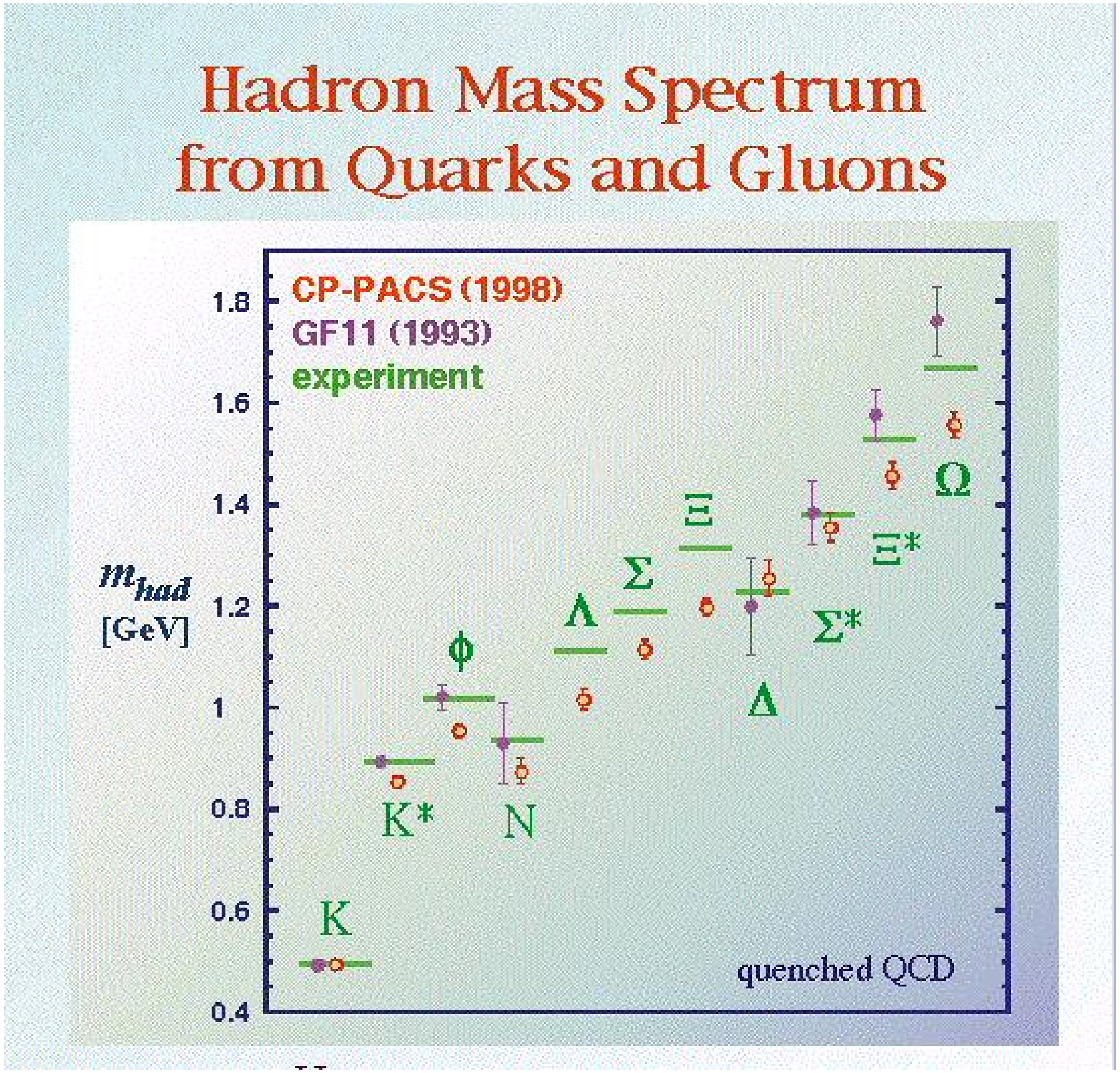
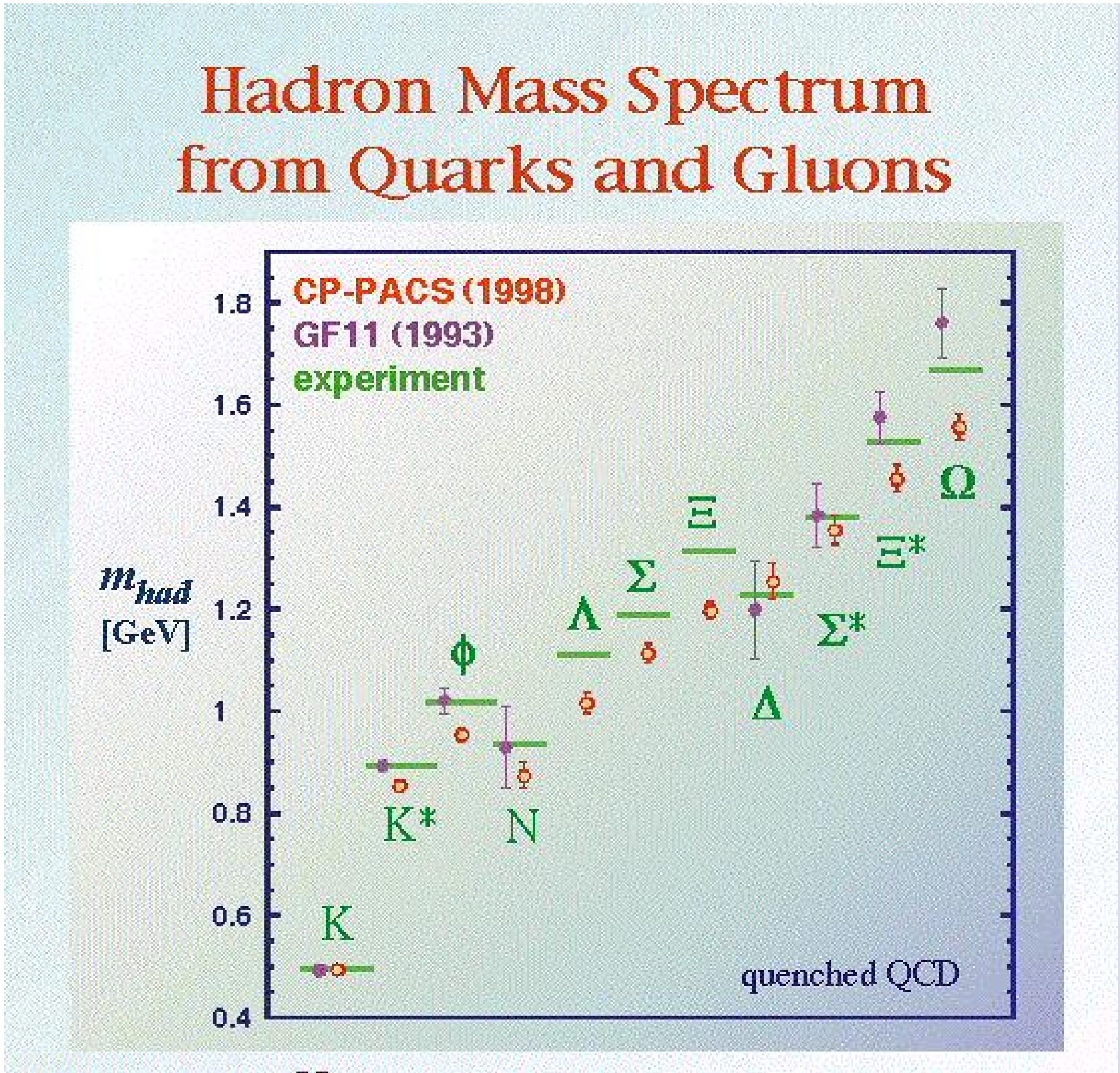
Complexity of evaluation of Det $M \Longrightarrow$ approximations : Quenched ($m_s = \infty$ limit) and Full (low $m_s = m_u = m_d$).

Q $\to$ Full $\rightsquigarrow$ Computer time $\uparrow$ and Precision $\downarrow$.



♡ Baryon mass comes out (almost) right.

(From CP-PACS Collaboration, Japan)



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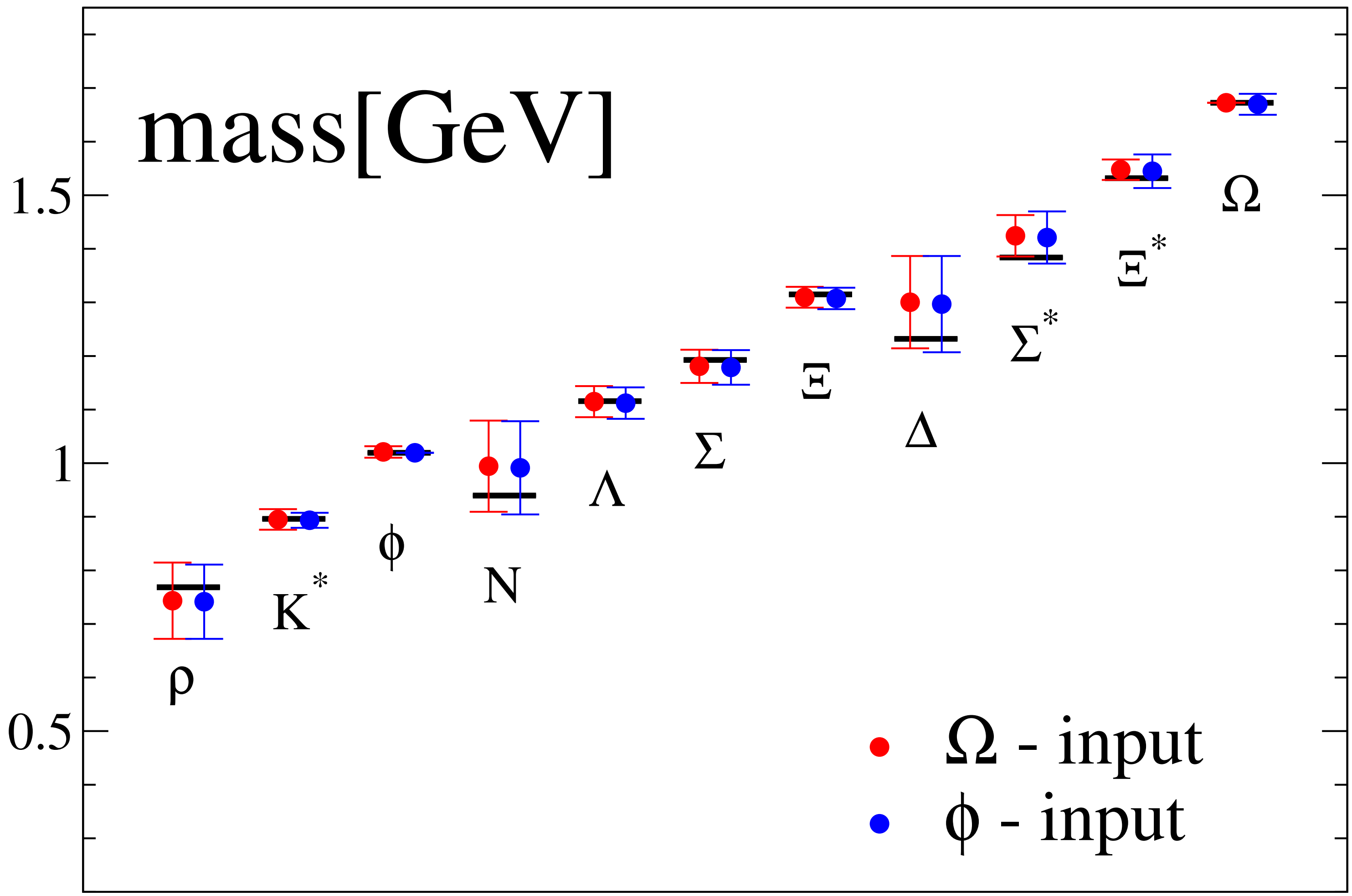
♡ Massless quarks acquire mass dynamically : Vacuum breaks Chiral Symmetry, i.e, $\langle\bar{\psi}\psi\rangle \neq 0$.

♡ Goldstone nature of Pion established: $m_\pi^2 \propto m_q$.



Dynamical 2+1 QCD : N. Ukita et al. [arXiv 0710.3462]

Non-perturbative Test : QCD Phase Diagram

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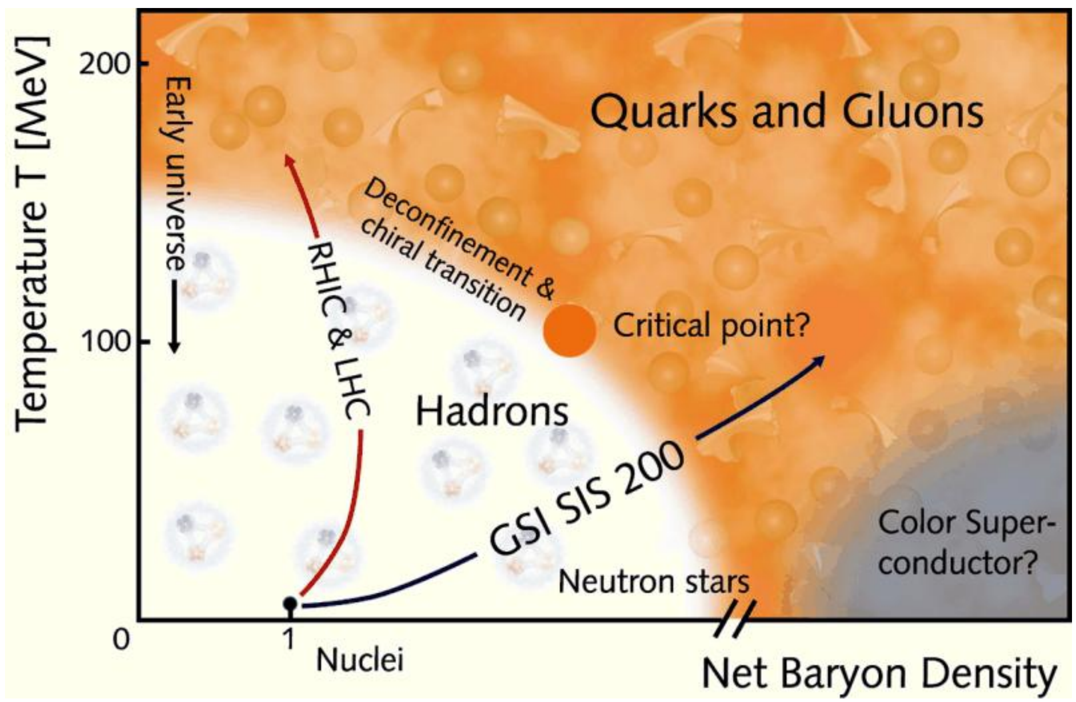

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- QCD defined on a space time lattice – Best and Most Reliable way to extract **Predictions** for non-perturbative physics.
- Lattice ideal tool to establish the phase diagram and properties of the phases.

Lattice QCD : What it can do

- Transition temperature, Critical energy density, Order of Phase Transition, Properties of QGP (EoS, Excitation types, Screening..)

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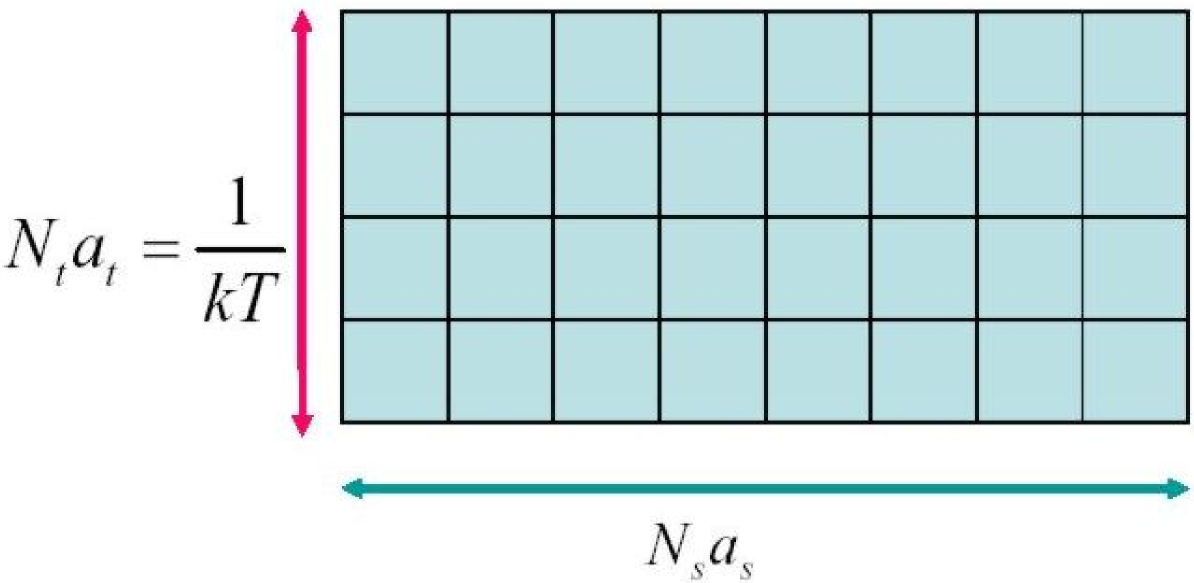

Need $N_s \gg N_t$ for thermodynamic limit and large N_t for continuum limit.

Symmetries and Order Parameters

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- Real world with 2 light + 1 moderately heavy flavours. Both symmetries not exact but the order parameters may still act as beacons for transitions.

Results for QCD at $T \neq 0$

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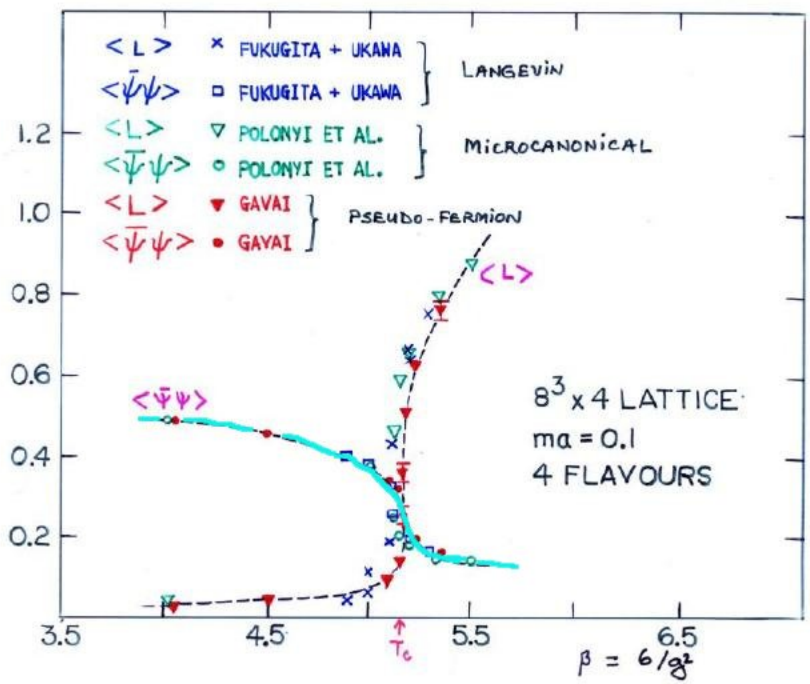

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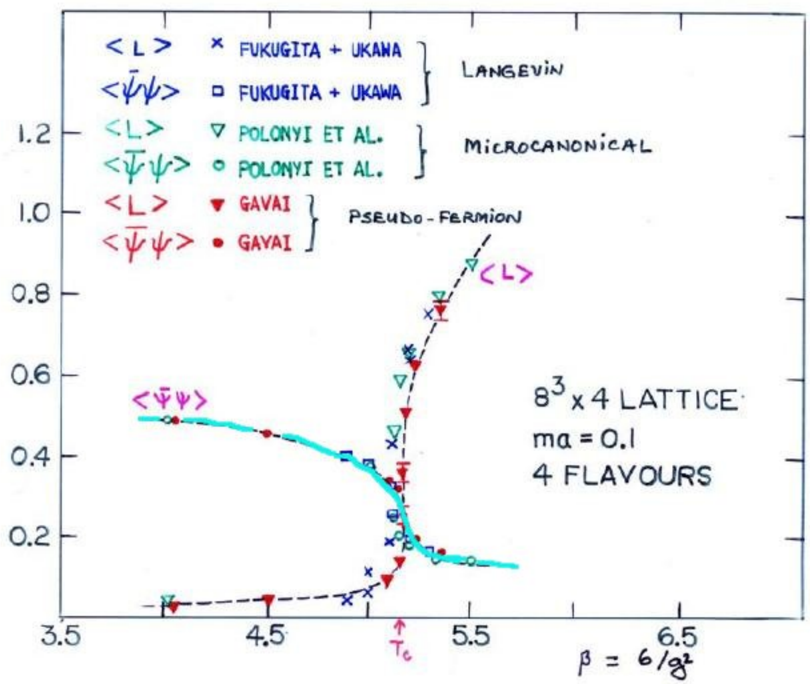
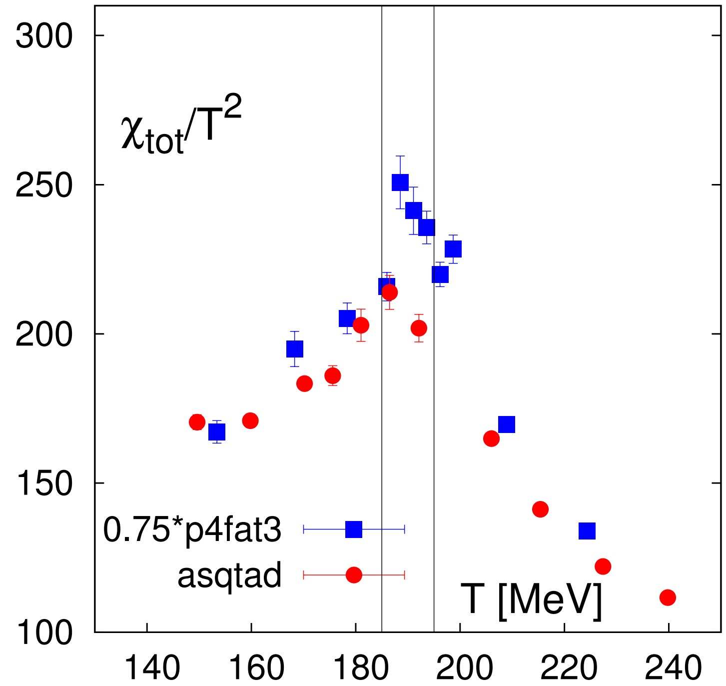
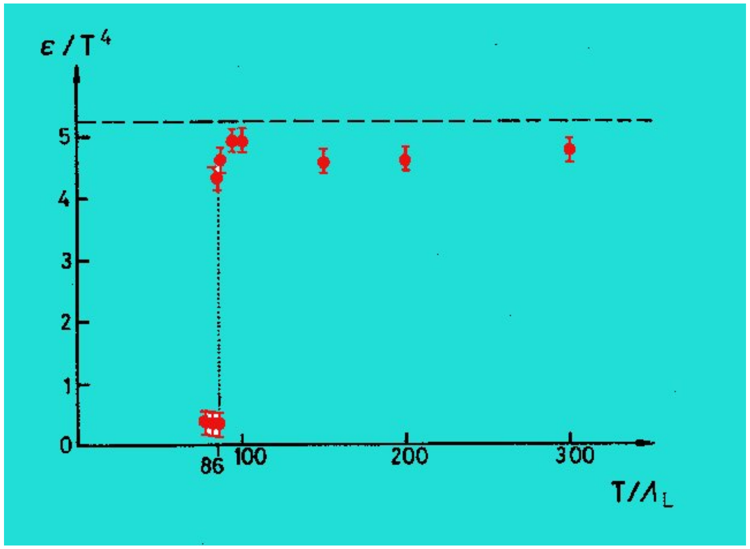




F. Karsch, Lattice 2007, arxiv:0711.0661.

EoS of QGP

– First results from Bielefeld :



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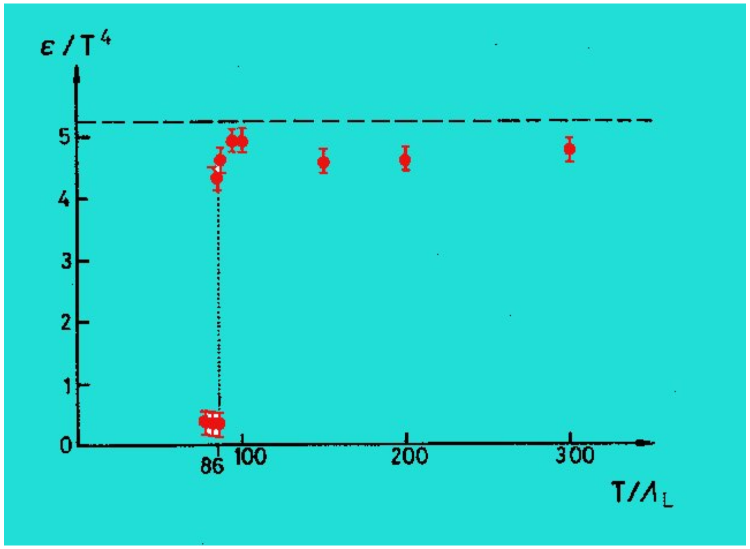

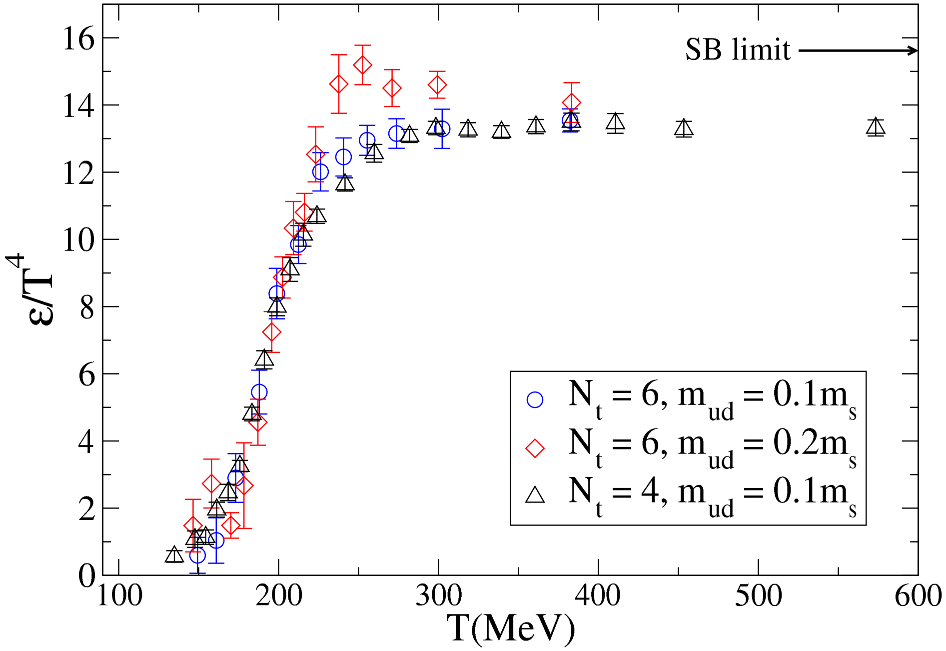

Celik, Engels & Satz, PLB129, 323 1983

Bernard et al., MILC, Phys. Rev. D75 (2007).

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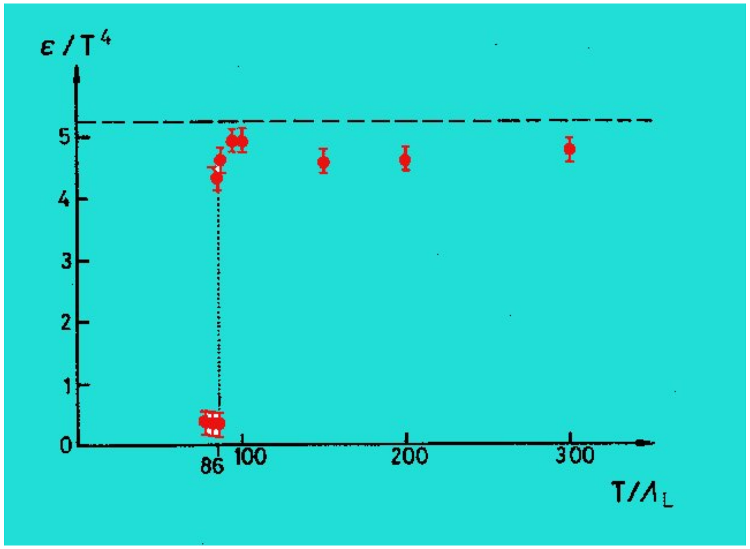

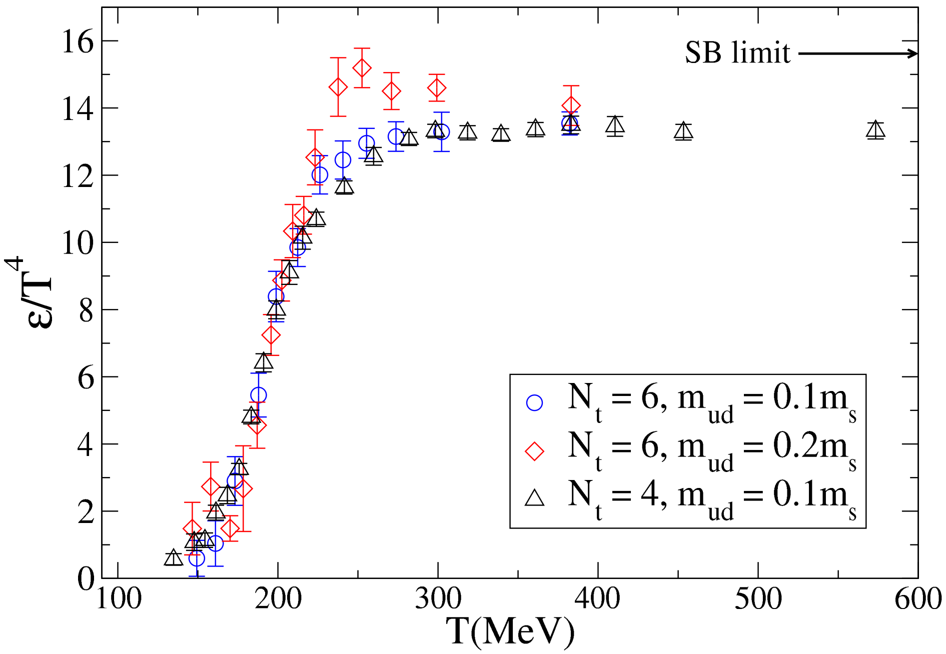

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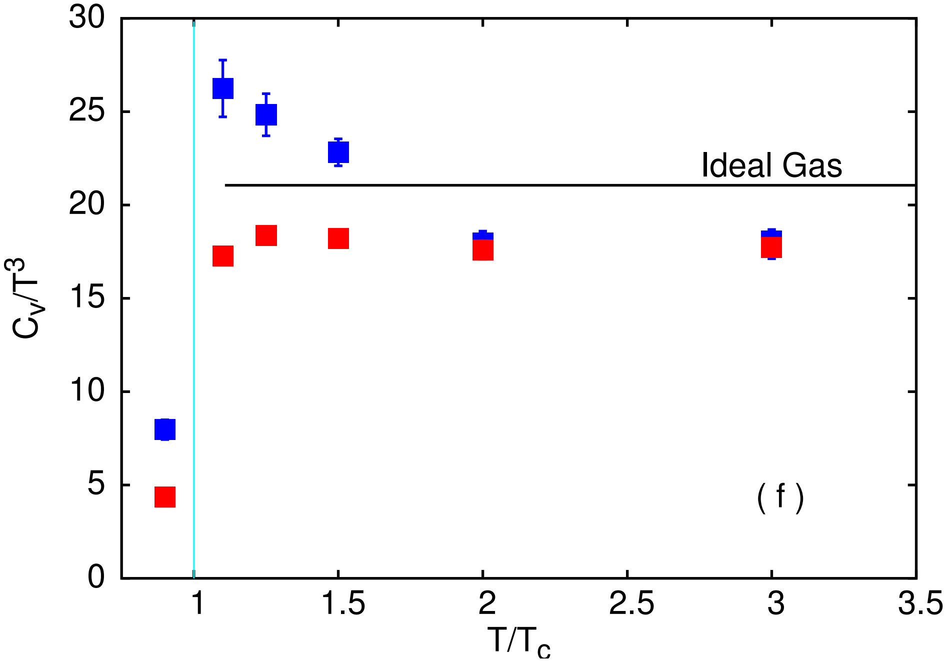
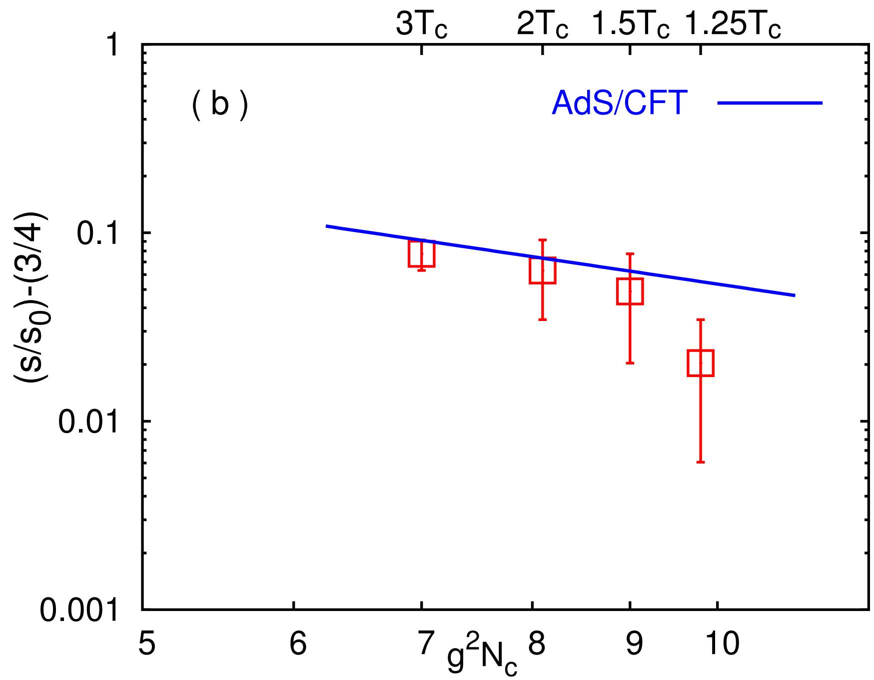
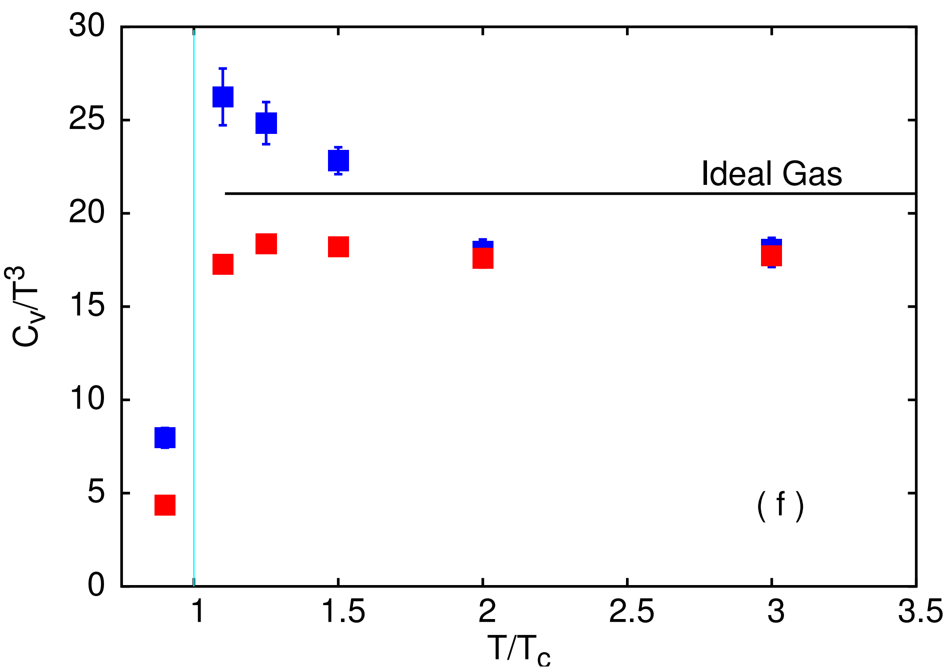
– Recent results for EoS : N_t=6, Smaller quark masses. Small differences for N_t = 4 & 6; $\epsilon(T_c) \sim 6T_c^4$ still. Too small volumes $\longrightarrow$ Thermodynamic Limit ?

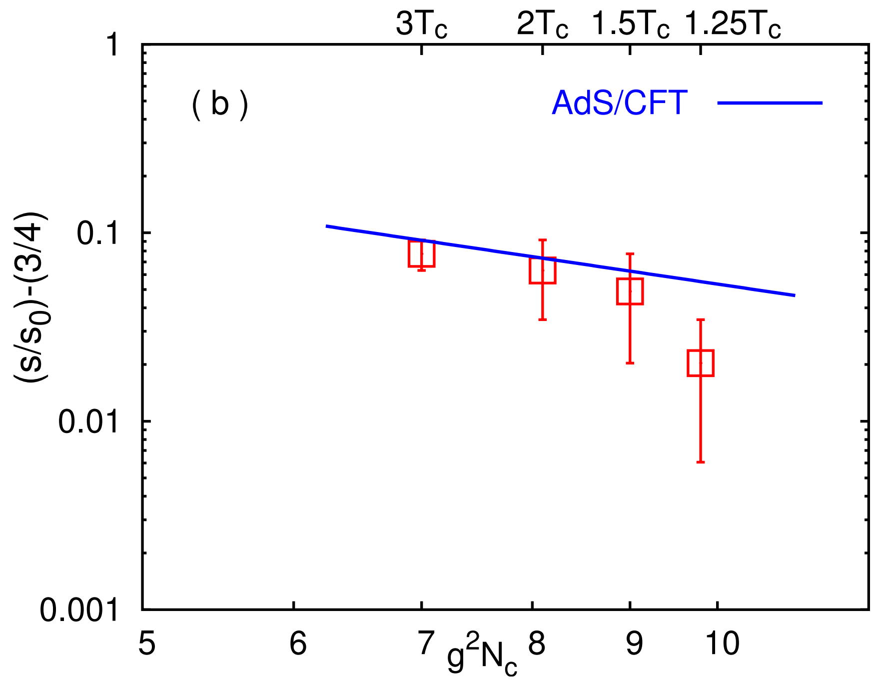




(RVG, S. Gupta and S. Mukherjee, hep-lat/0506015)

♠ $C_v \sim 4\epsilon$ for $2T_c$ but No Ideal Gas limit.





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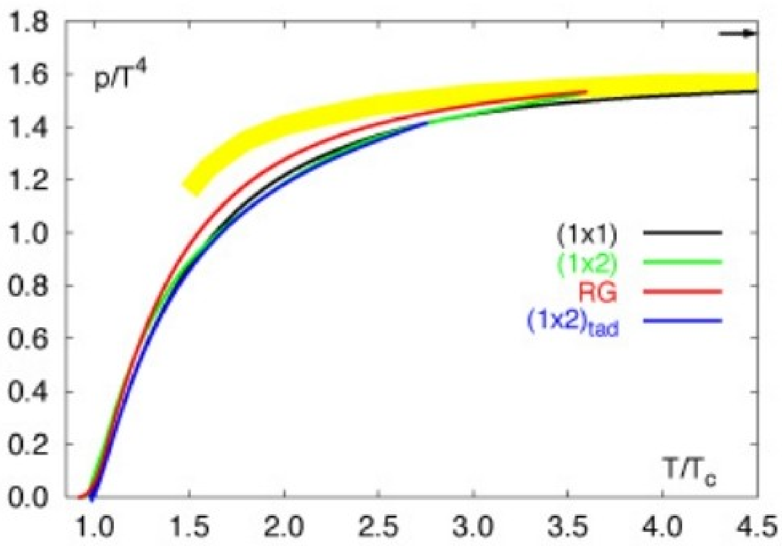
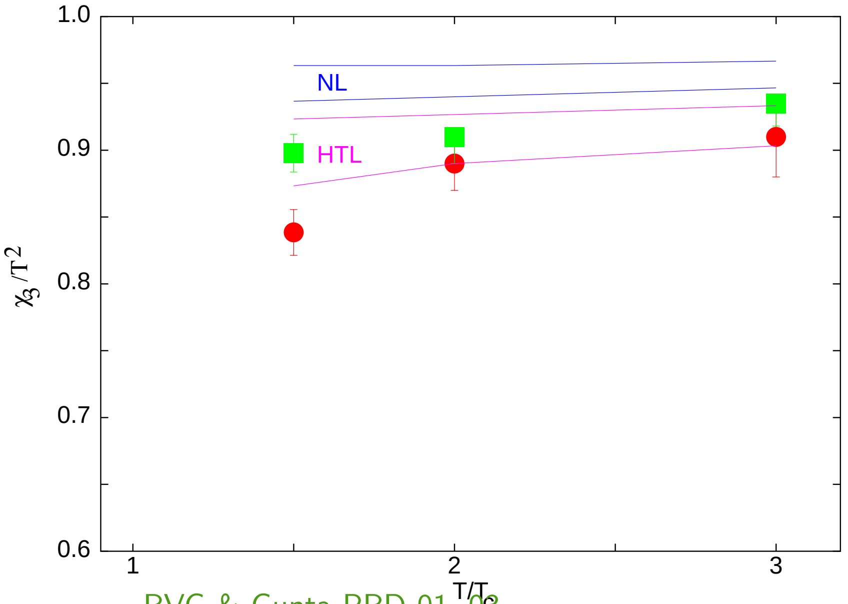
♠ Entropy agrees with strong coupling SYM prediction (Gubser, Klebanov & Tseytlin, NPB '98, 202) for $T = 1.5 - 3T_c$ but fails at lower T, as do various weak coupling schemes : $\frac{s}{s_0} = f(g^2N_c)$, where $f(x) = \frac{3}{4} + \frac{45}{32}\zeta(3)x^{-3/2} + \cdots$ and $s_0 = \frac{2}{3}\pi^2 N_c^2 T^3$.

Weak Coupling



Blaizot, Iancu & Rebhan PRD 01, PLB 01



RVG & Gupta PRD 01, 03

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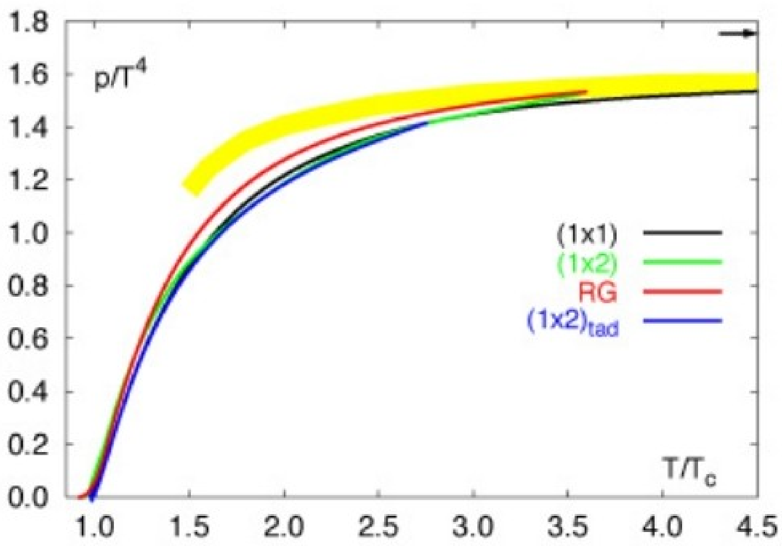

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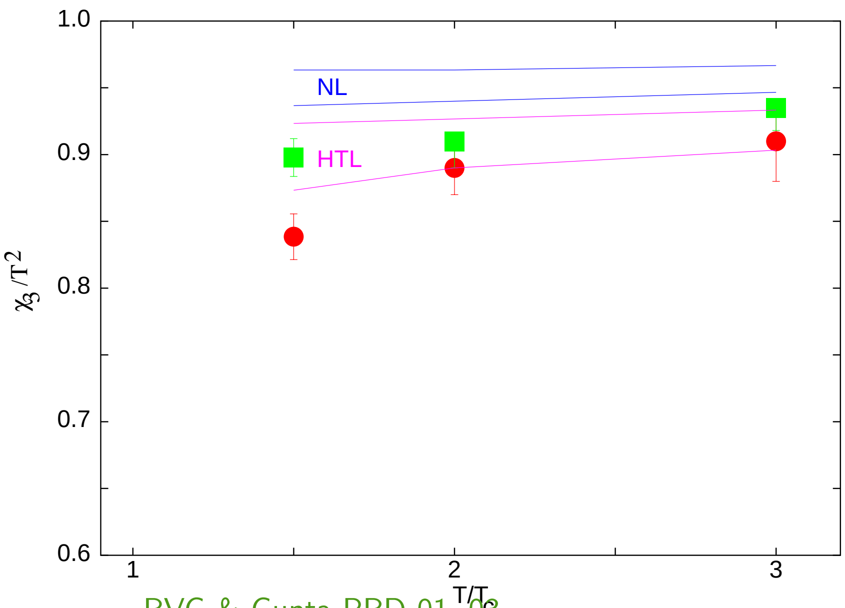

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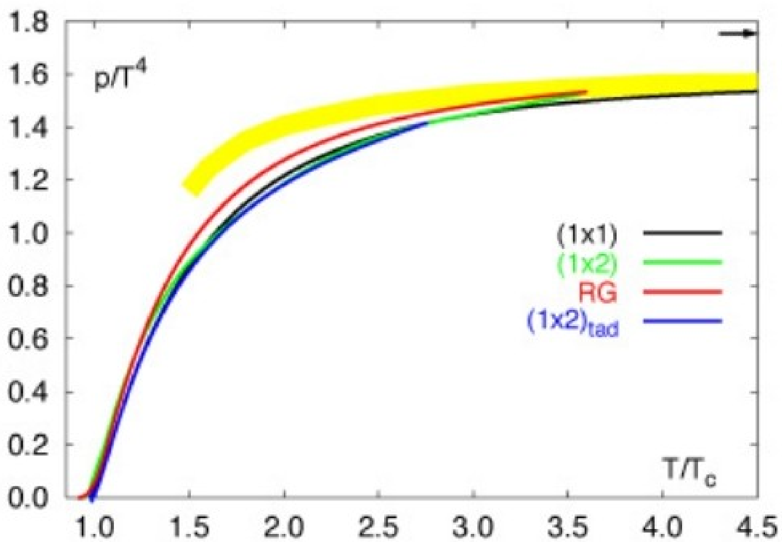

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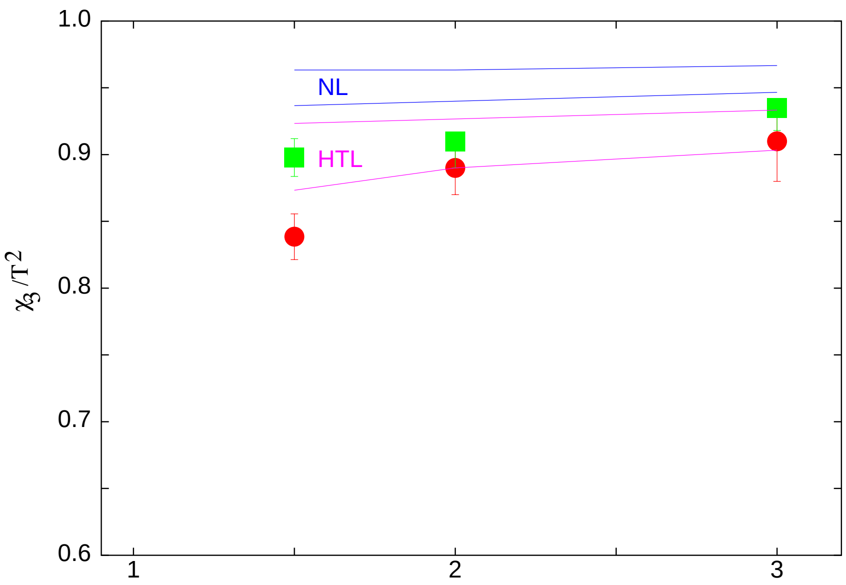


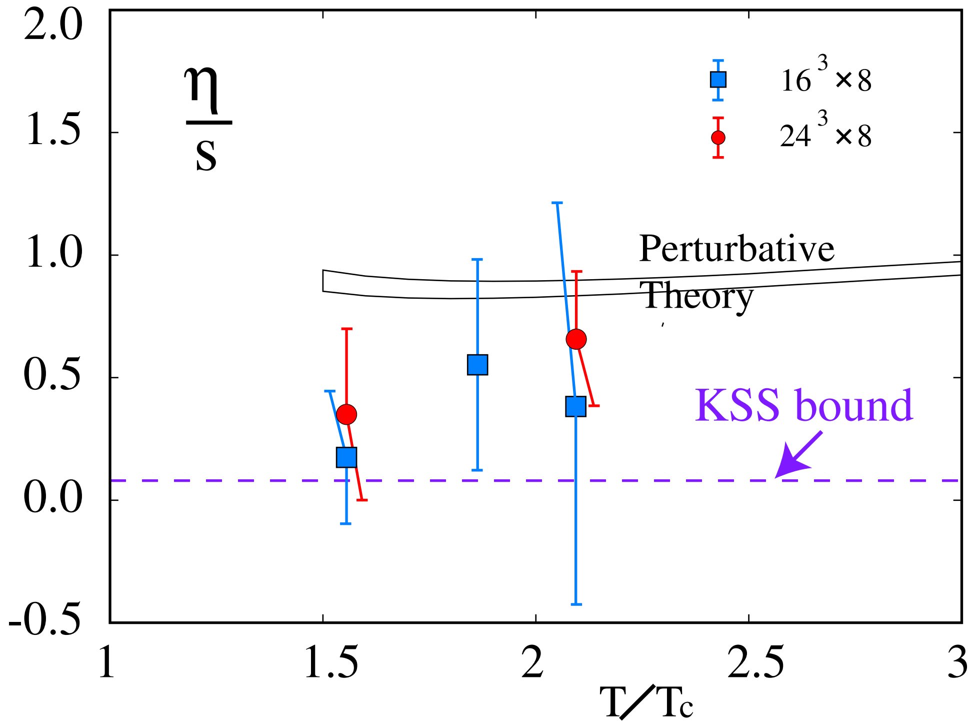
RVG & Gupta PRD 01, 03

♣ Re-summed weak coupling explains lattice results.

♣ So does dimensional reduction (Kajantie et al, Vourinen)

♣ Quasiparticle, PNJL models (Kampfer et al., Wiese et al.).

Shear Viscosity



Nakamura and Sakai, PRL 94 (2005).

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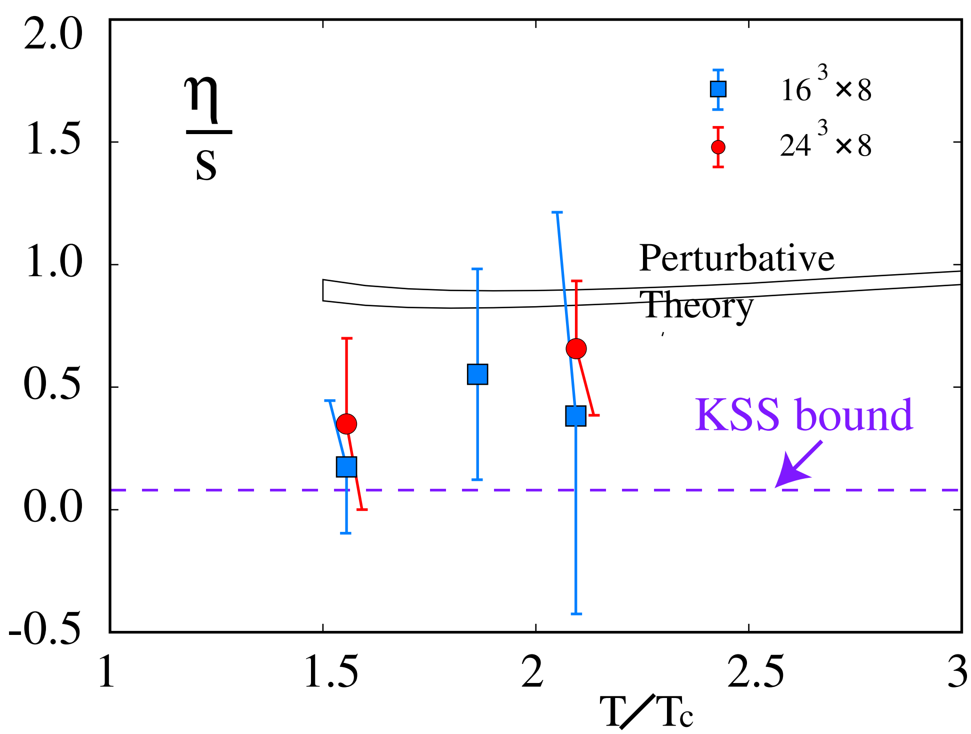

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∗ Kubo's Linear Response Theory : Transport Coefficients in terms of equilibrium correlation functions.

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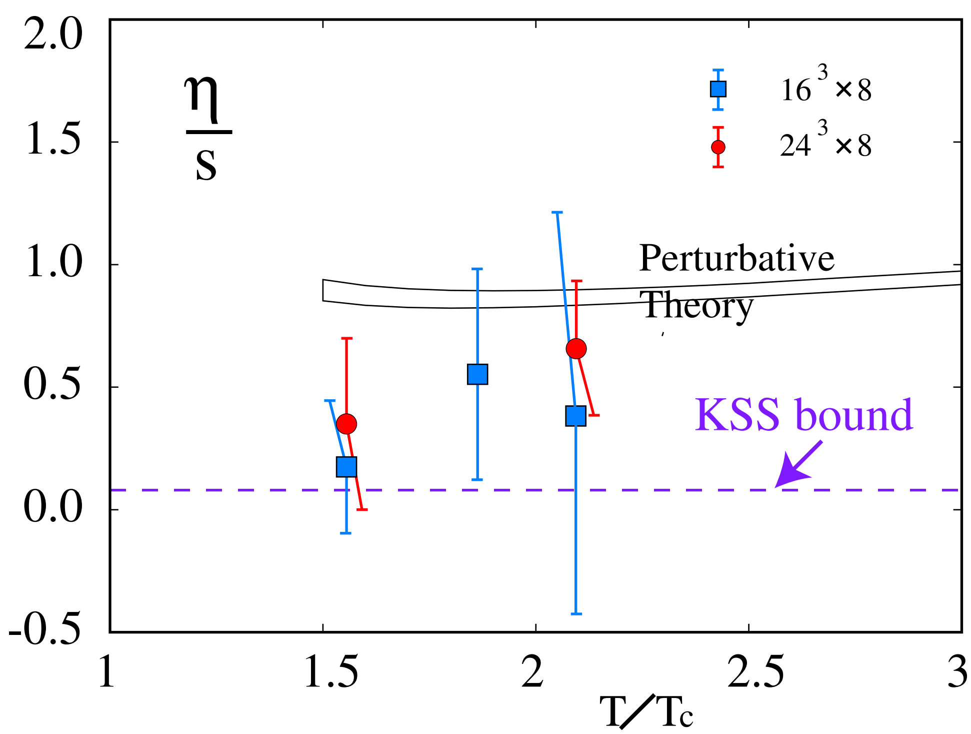

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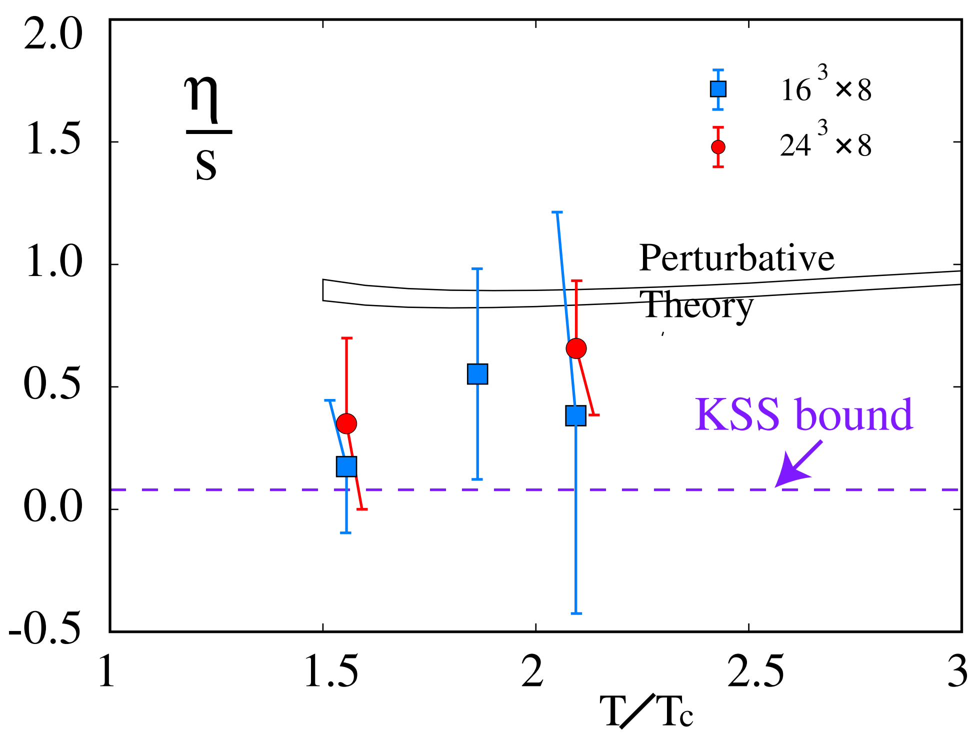
* Kubo's Linear Response Theory : Transport Coefficients in terms of equilibrium correlation functions.

* Obtain Energy-Momentum Correlation functions on Lattice (at discrete Matsubara frequencies).

* Continue them to get Retarded ones $\rightsquigarrow$ Shear, Bulk Viscosities.

Shear Viscosity



Nakamura and Sakai, PRL 94 (2005).

* Kubo's Linear Response Theory : Transport Coefficients in terms of equilibrium correlation functions.
* Obtain Energy-Momentum Correlation functions on Lattice (at discrete Matsubara frequencies).
* Continue them to get Retarded ones $\rightsquigarrow$ Shear, Bulk Viscosities.
* Larger lattices and inclusion of dynamical quarks in future.

Baryon-Strangeness Correlation

♣Correlation between quantum numbers K and L can be studied through the ratio $C_{(KL)/L} = \frac{\langle KL \rangle - \langle K \rangle \langle L \rangle}{\langle L^2 \rangle - \langle L \rangle^2}$.
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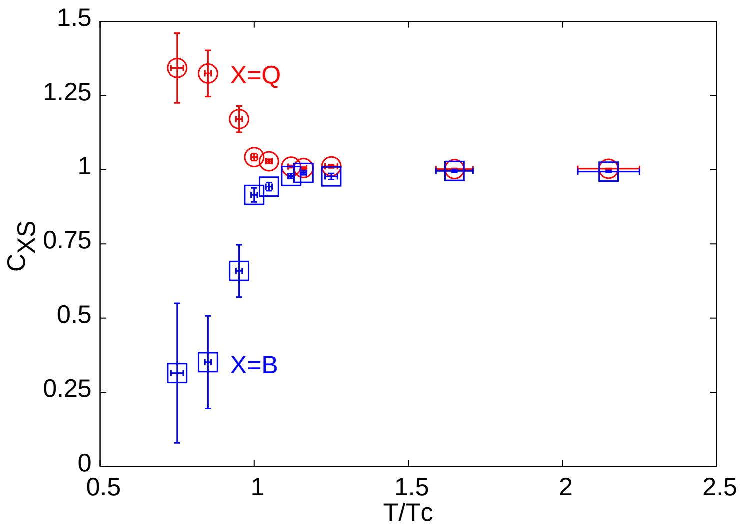

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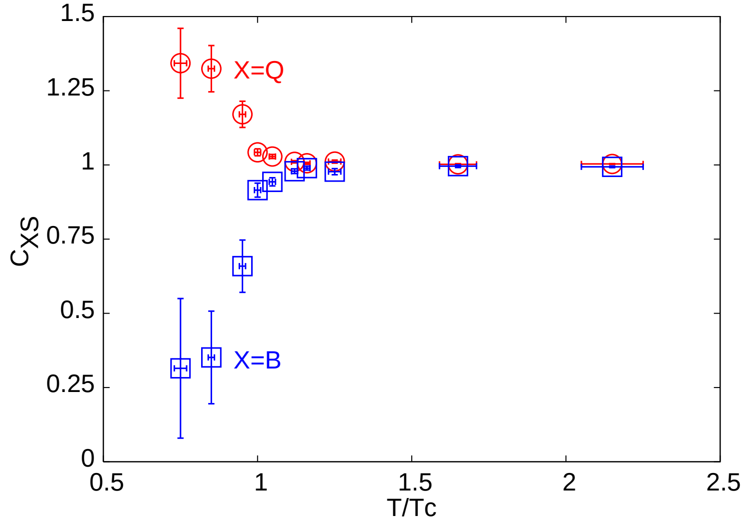

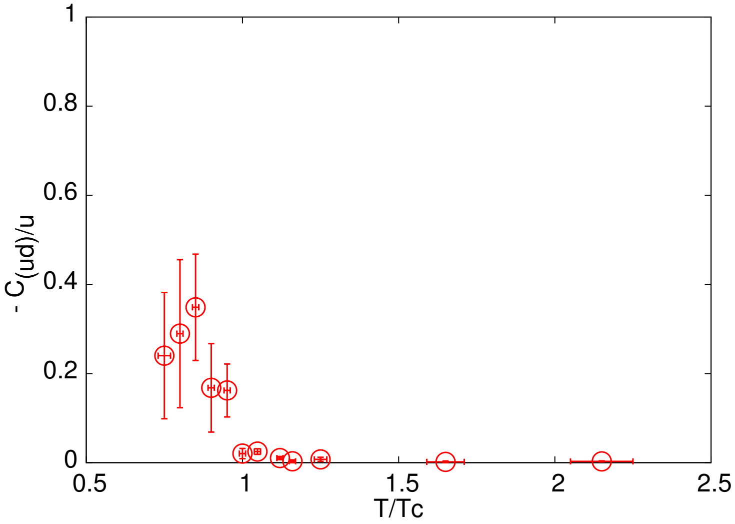

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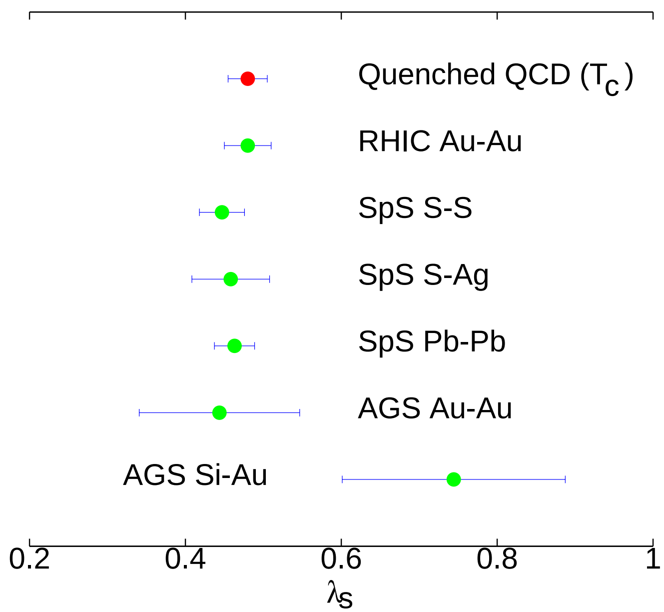

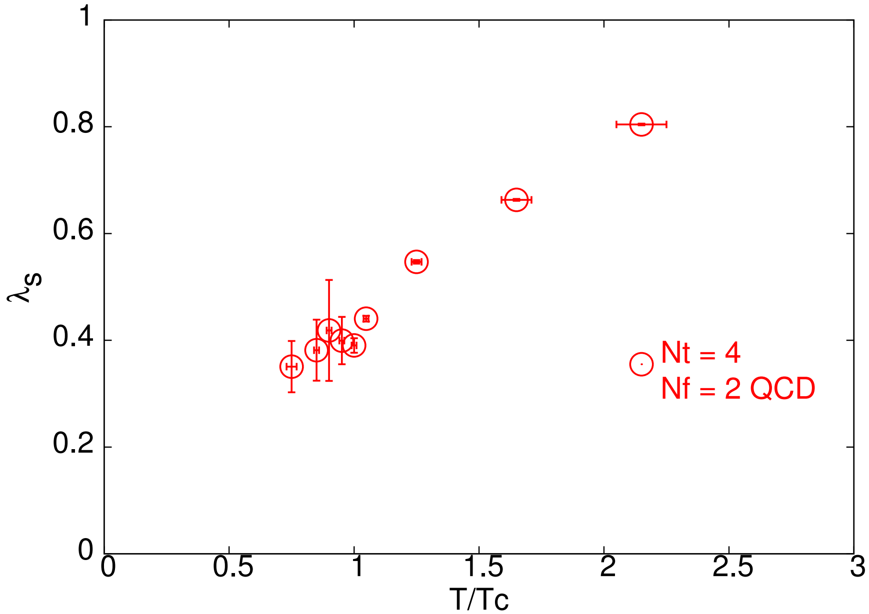

Gavai and Gupta, Phys Rev D65, 2002 and Phys.Rev. D73, 2006.

QCD Critical Point

- New conceptual problems at nonzero baryon density, i.e., nonzero baryonic chemical potential, μ_B : Fermion determinant becomes complex, known analytical/numerical methods fail.

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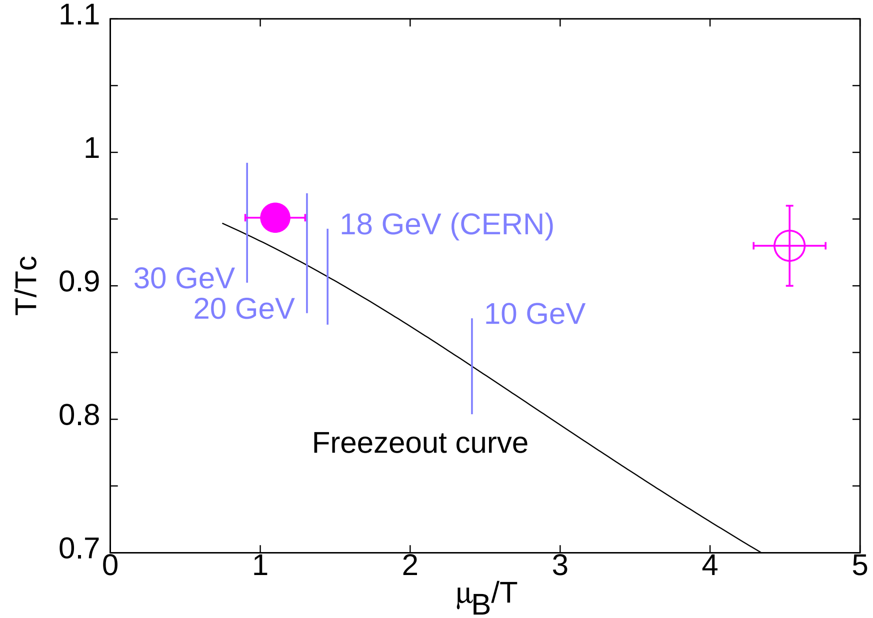
  - Taylor Expansion (C. Allton et al., PR D66 (2002) 074507 & D68 (2003) 014507; R.V. Gavai and S. Gupta, PR D68 (2003) 034506).

Our Workhorse

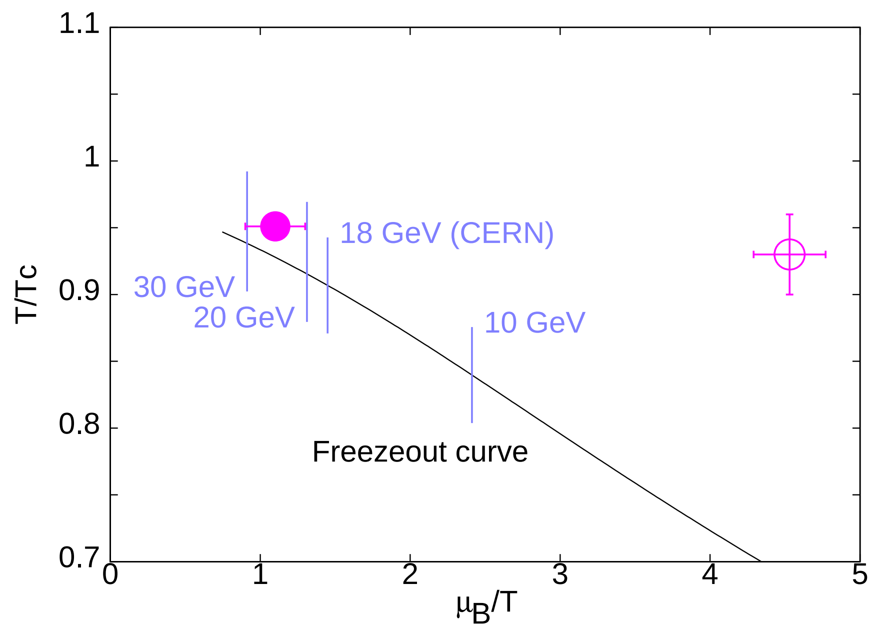
CRAY X1 of I L G T I , T I F R, Mumbai

Our Results



1.1
1
0.9
0.8
0.7
T/Tc
0
1
2
3
4
5
μB/T
18 GeV (CERN)
30 GeV
20 GeV
10 GeV
Freezeout curve

Our Results



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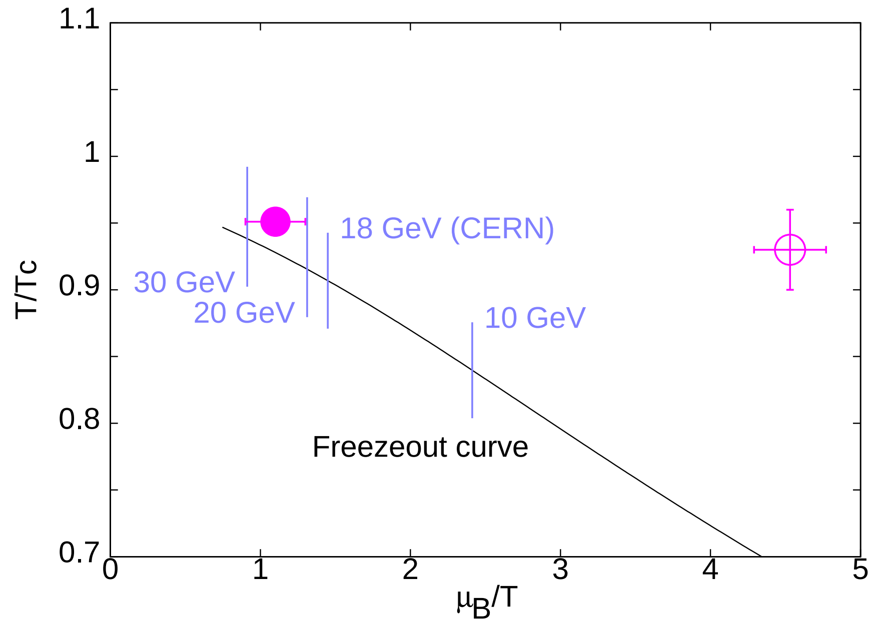

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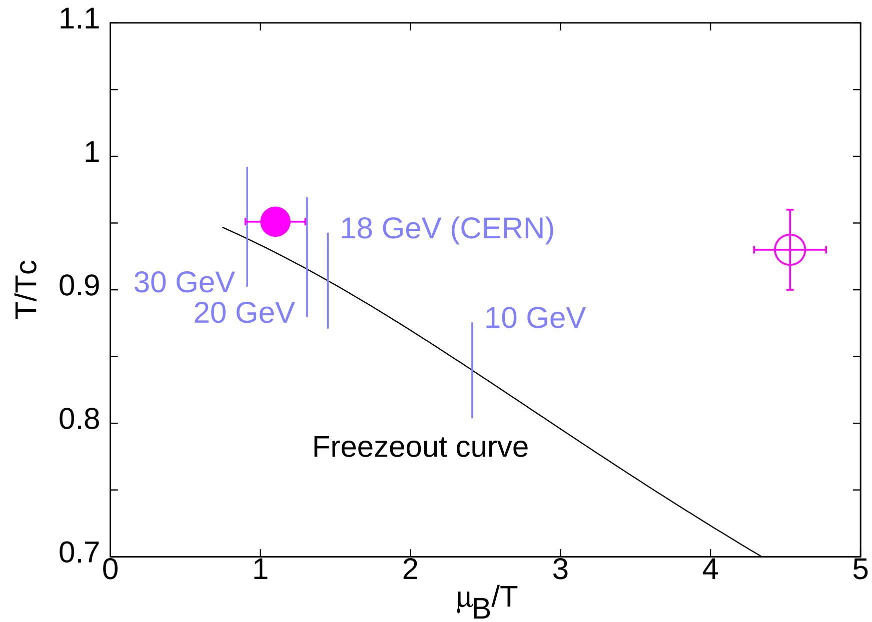

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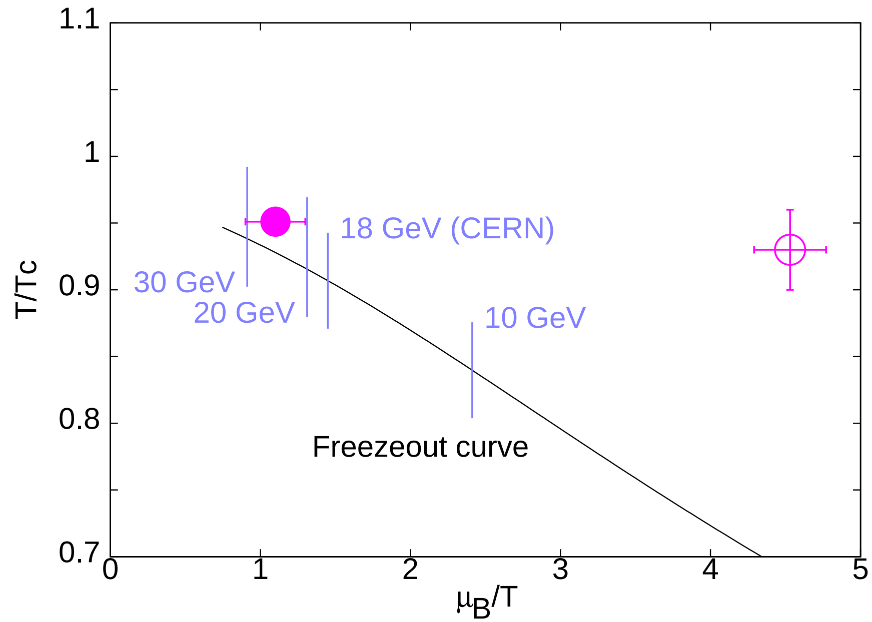

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- Strong finite size effects for small N_s. A strong change around $N_s m_\pi \sim 6$.
- RHIC, if run at lower energy, can potentially discover it.

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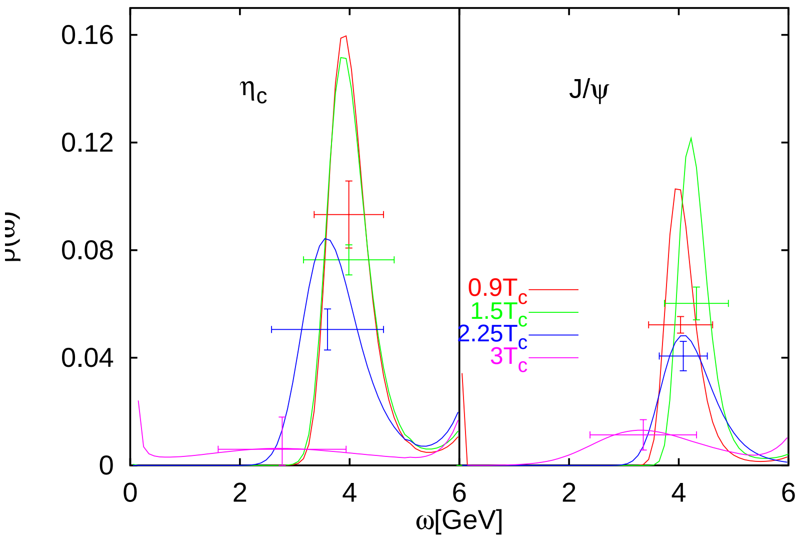
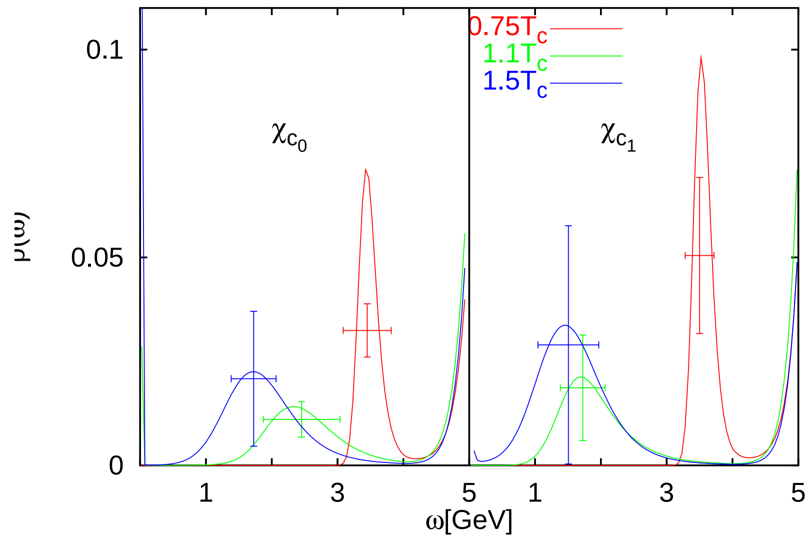
- Caution : nonzero temperature obtained by making temporal lattices shorter.





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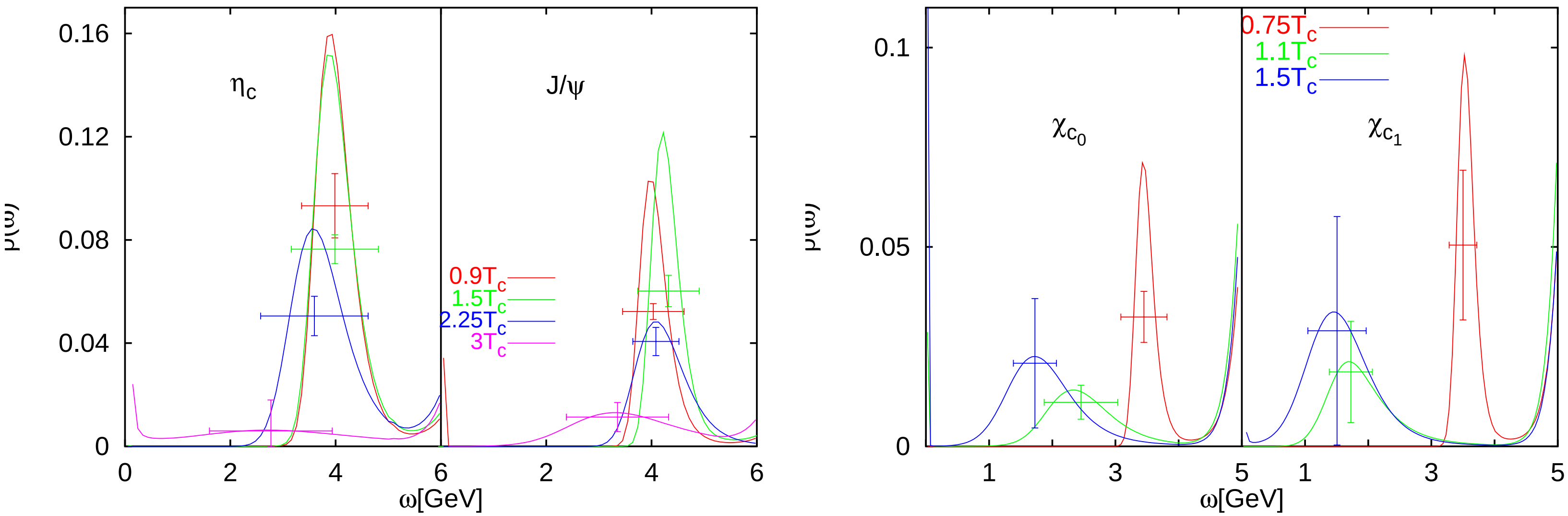

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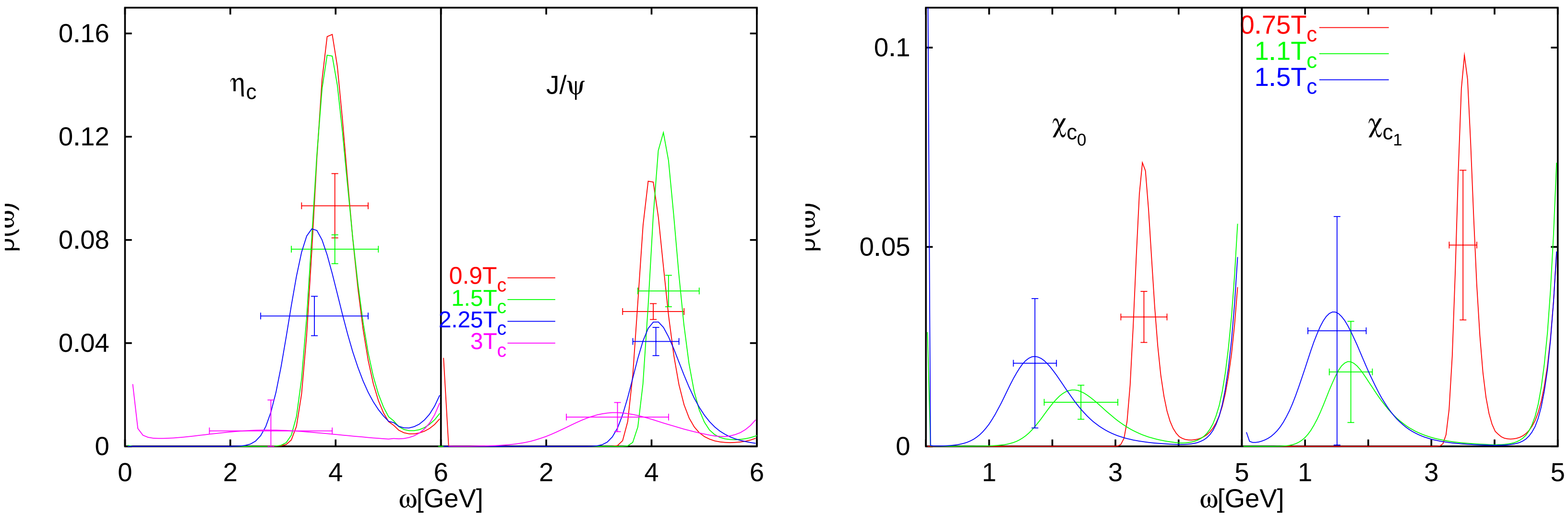

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♠ Effect of inclusion of dynamical fermions ?

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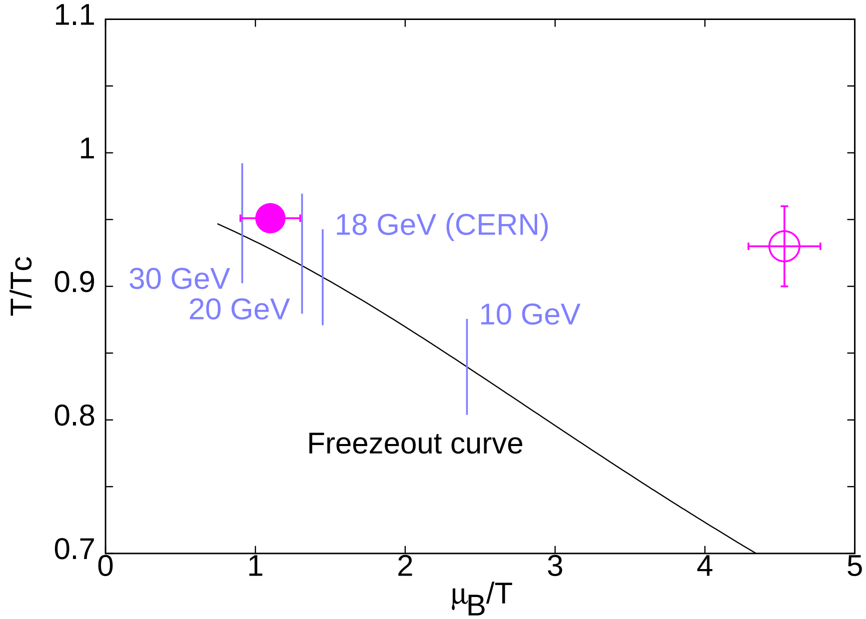

♠ Phase diagram in $T - \mu_B$ plane has begun to emerge: Our estimate for the critical point is $\mu_B/T \sim 1 - 2$.