New Phases of Strongly Interacting Matter

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Introduction : What and Why

QCD Phase Diagram

Heavy Ion Collisions

J/ψ Suppression

Speed of Sound

Summary

Introduction

- Known Interactions and Particles a century ago: Electromagnetism, Gravity and Electrons, Atoms.

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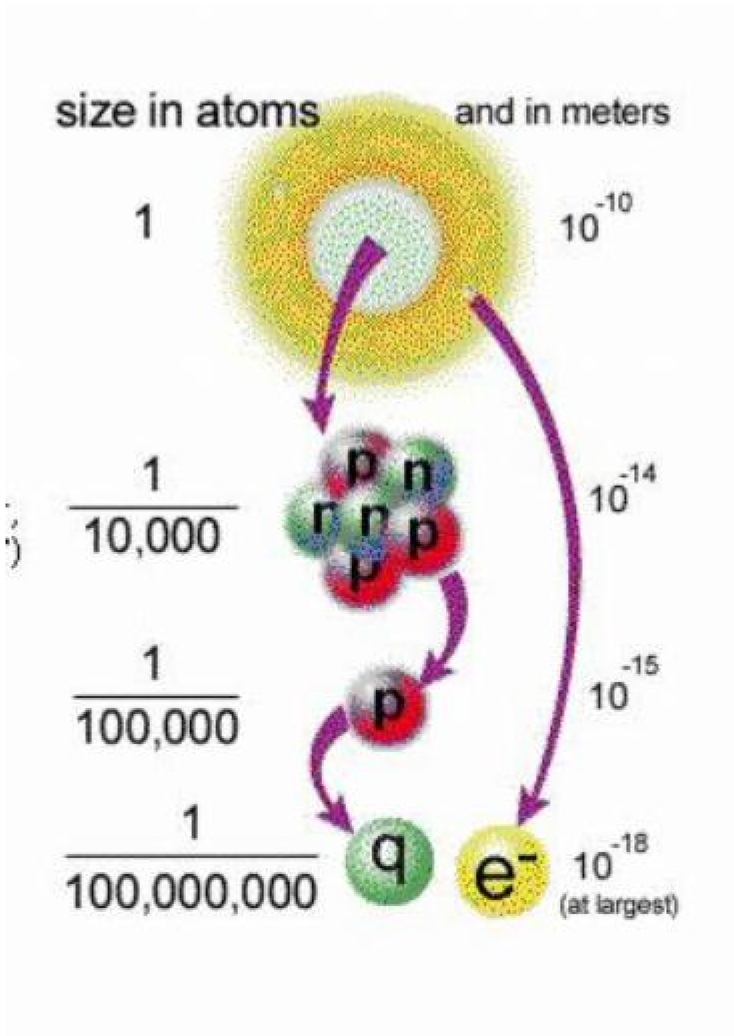
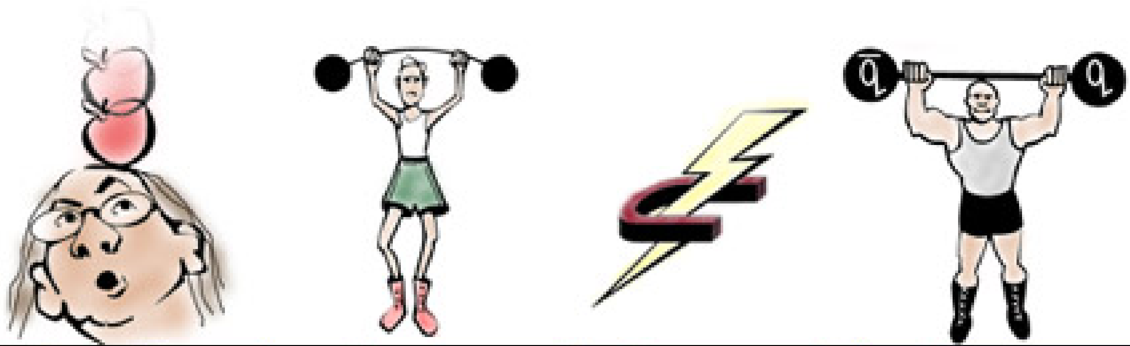
- Quarks and Leptons – Basic building blocks : Proton (uud), Neutron (udd), Pion ($u\bar{d}$)....

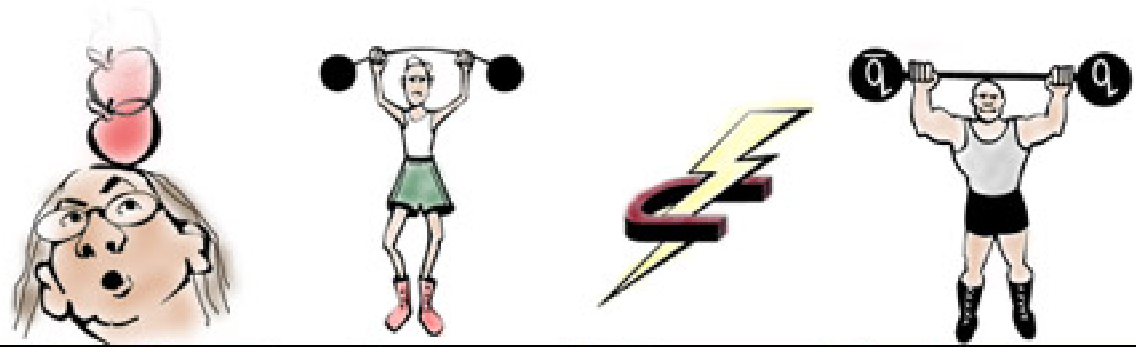
- A Variety of Vector Bosons : Carriers of forces.





	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	$W^+ \; W^- \; Z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+ \; W^-$	Quarks and Gluons

Strengths in a ratio $10^{-39} : 10^{-5} : 10^{-2} : 1$



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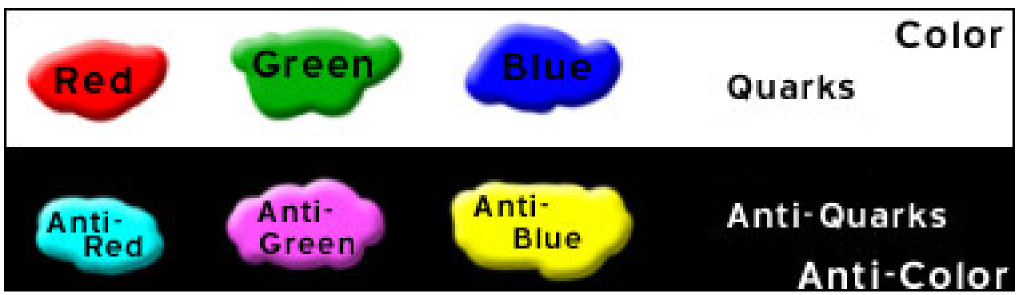

(Anti-)Quarks come in three (anti-)colours, making gluons also coloured.

Quantum Chromo Dynamics (QCD)

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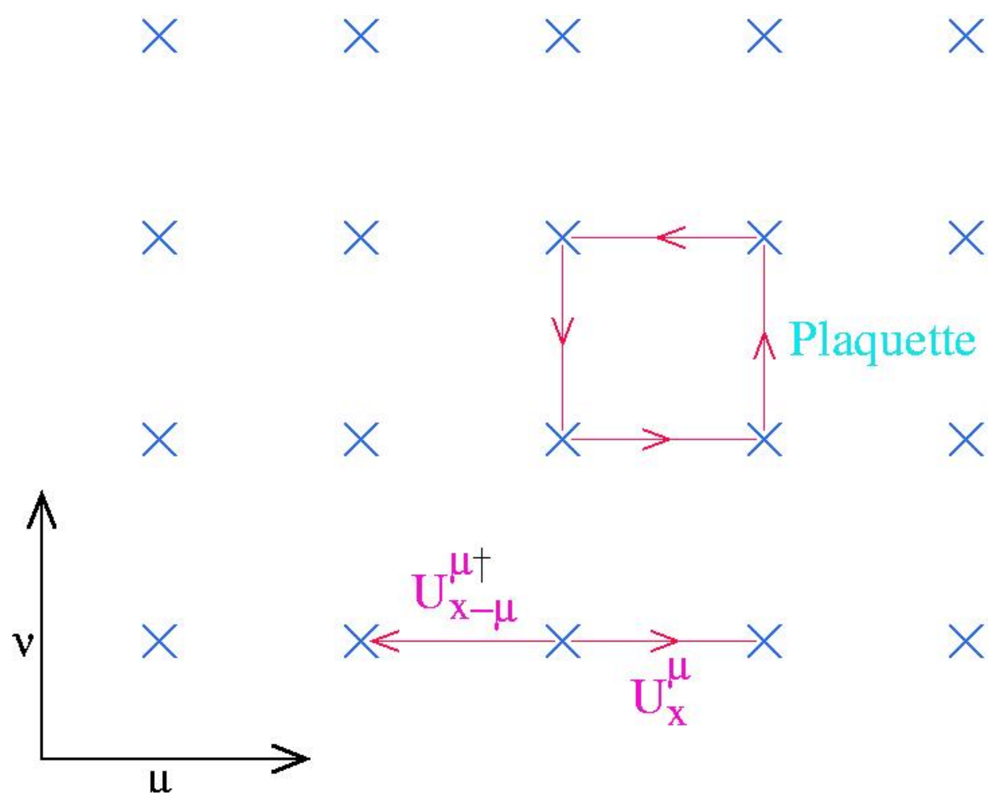
- Many more "photons" (Eight) which carry colour charge & hence interact amongst themselves.
- *Unlike QED*, the coupling is usually very large.
- Much richer structure : Quark Confinement, Dynamical Symmetry Breaking..
- Very high interaction (binding) energies. E.g., $M_{Proton} \gg (2m_u + m_d)$, by a factor of 100 $\rightarrow$ Understanding it is knowing where the Visible mass of Universe comes from.

Basic Lattice Gauge Theory

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



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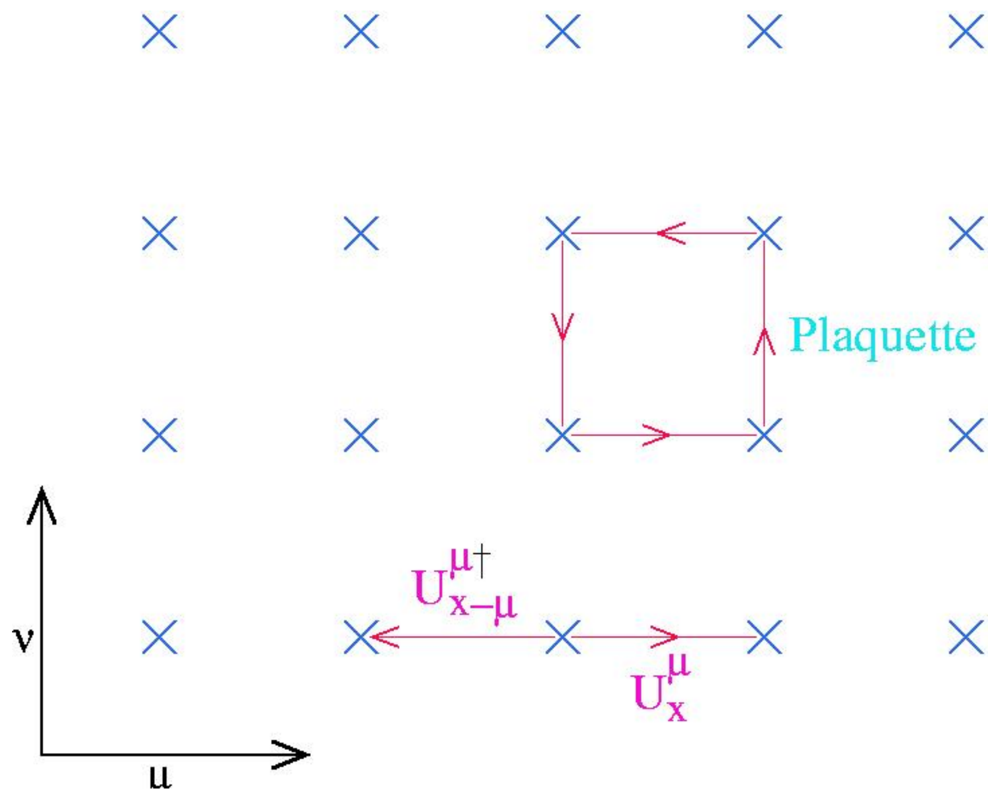

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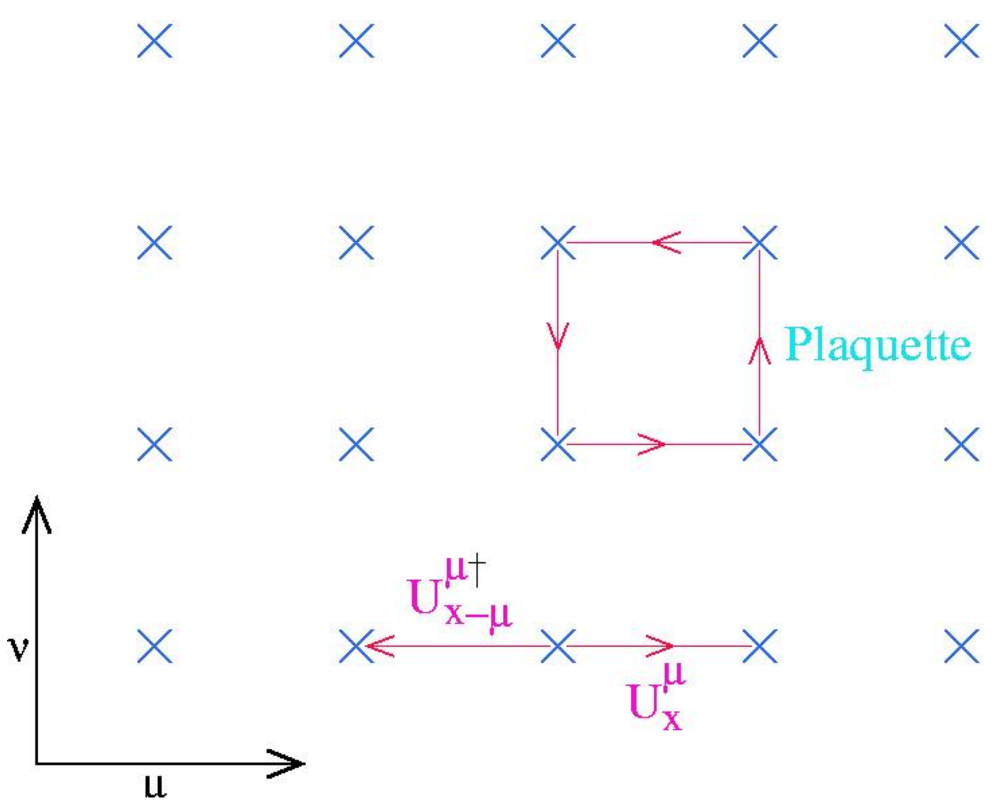

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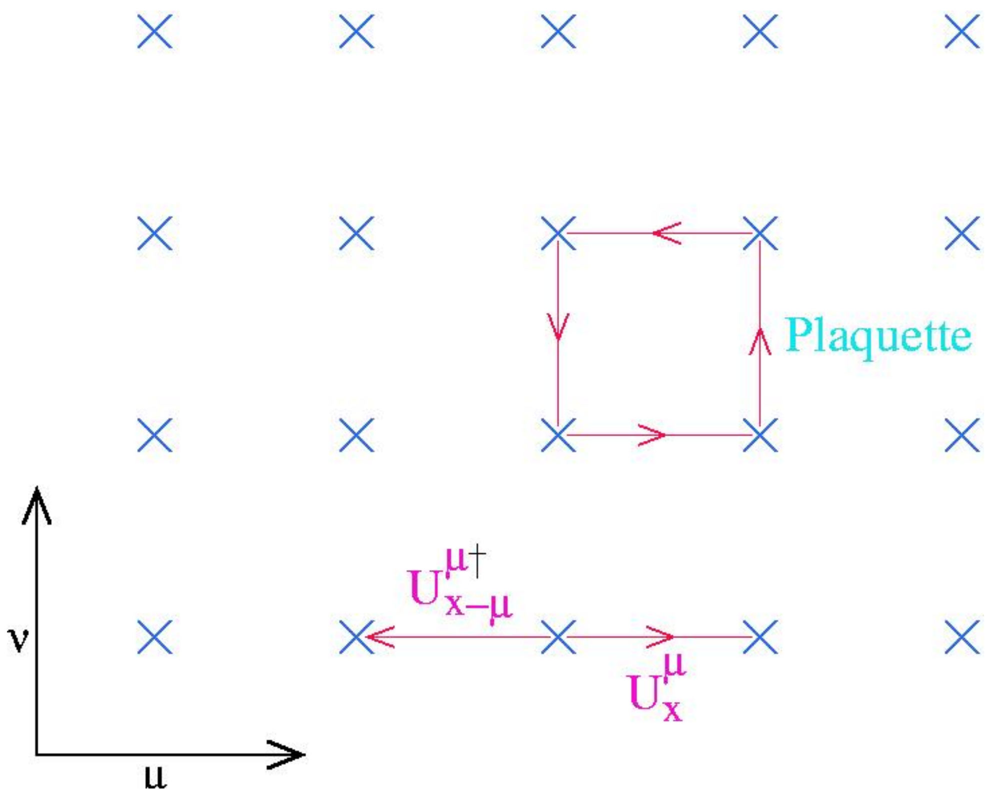
- Fermion Actions : Staggered, Wilson, Overlap..



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

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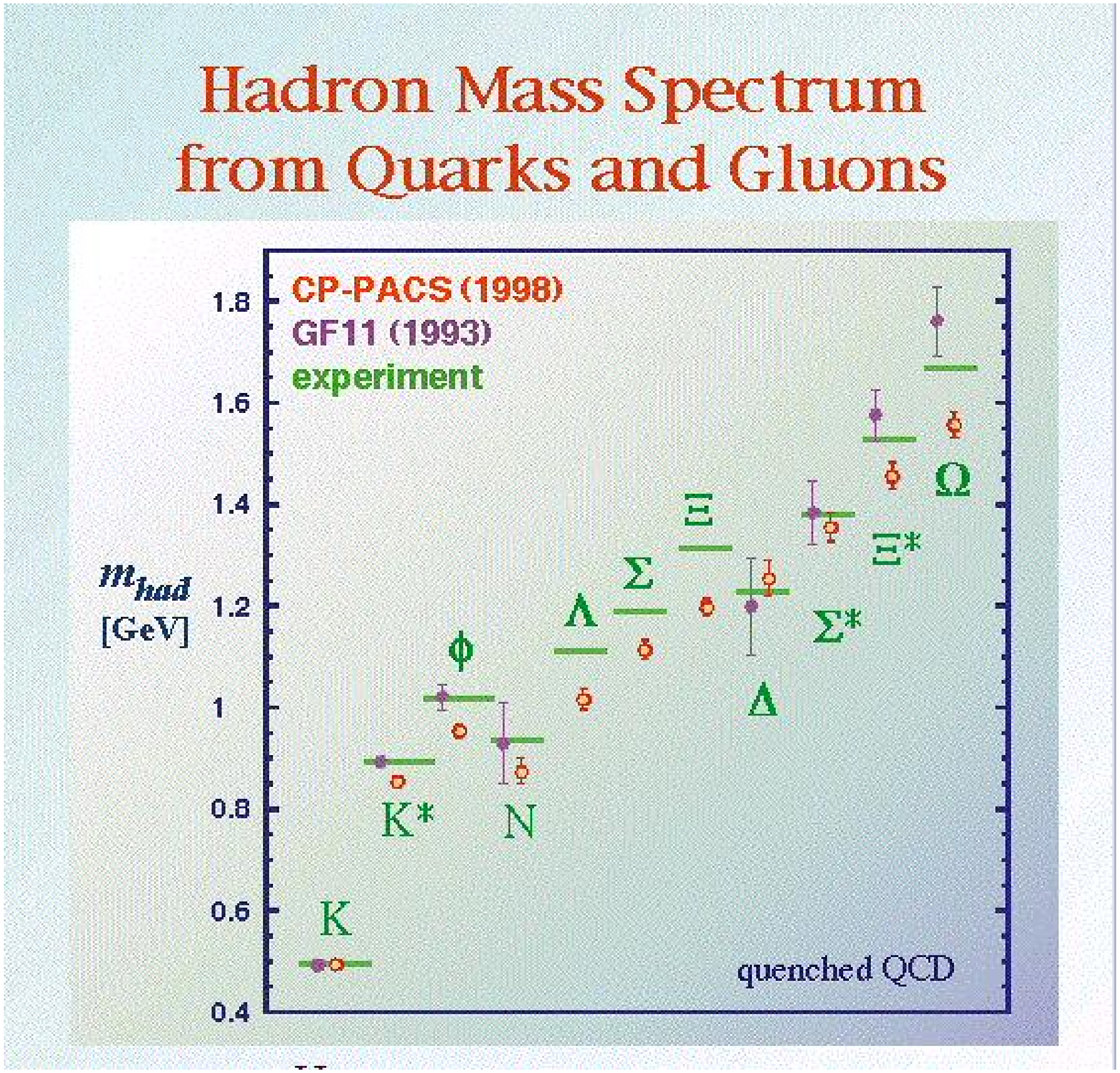
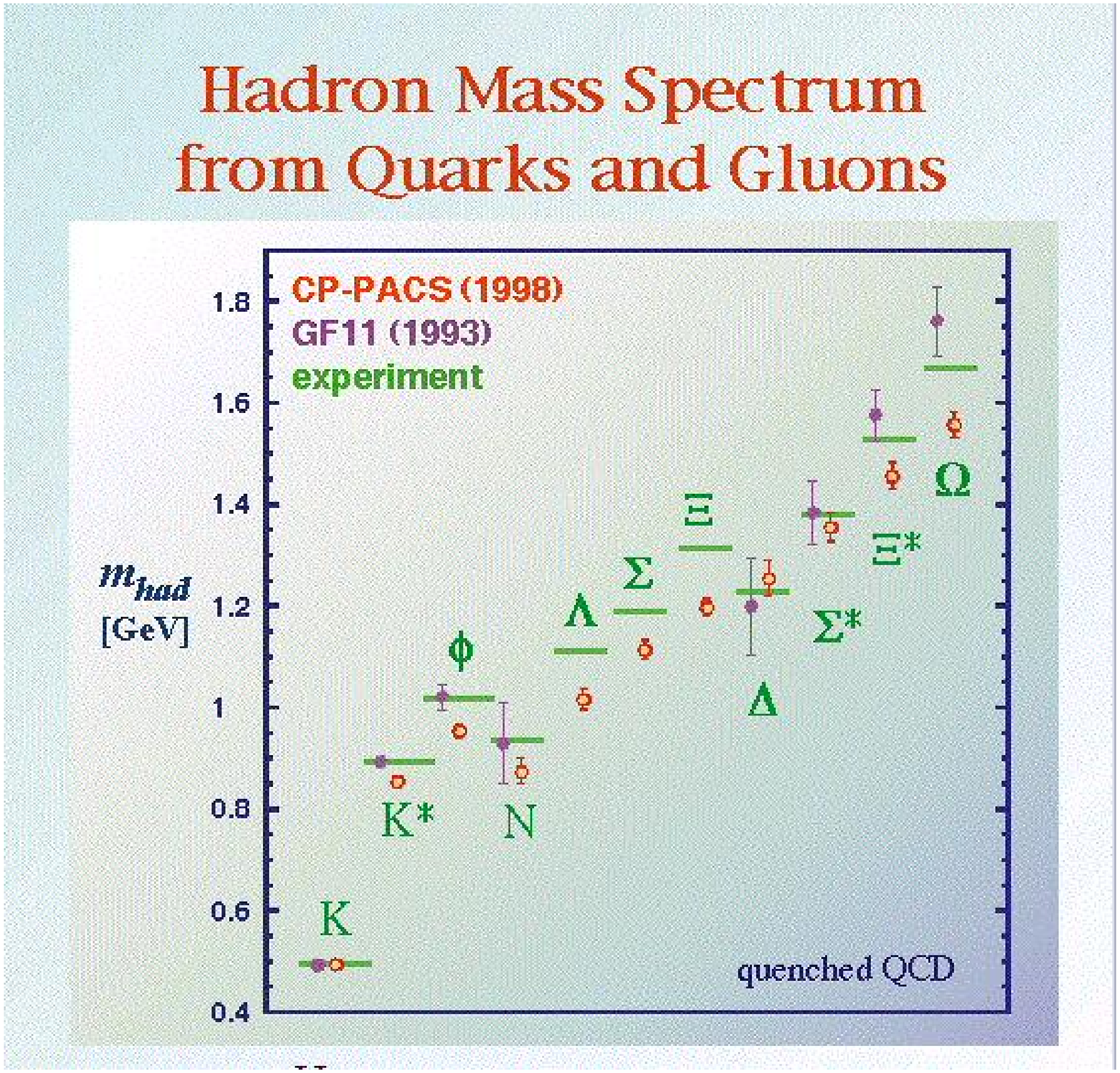
Complexity of evaluation of Det $M \Longrightarrow$ approximations : Quenched ($m_s = \infty$ limit) and Full (low $m_s = m_u = m_d$).

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: $m_\pi^2 \propto m_q$.

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QCD defined on a space time lattice – Best and Most Reliable way to extract **Predictions** for non-perturbative physics.

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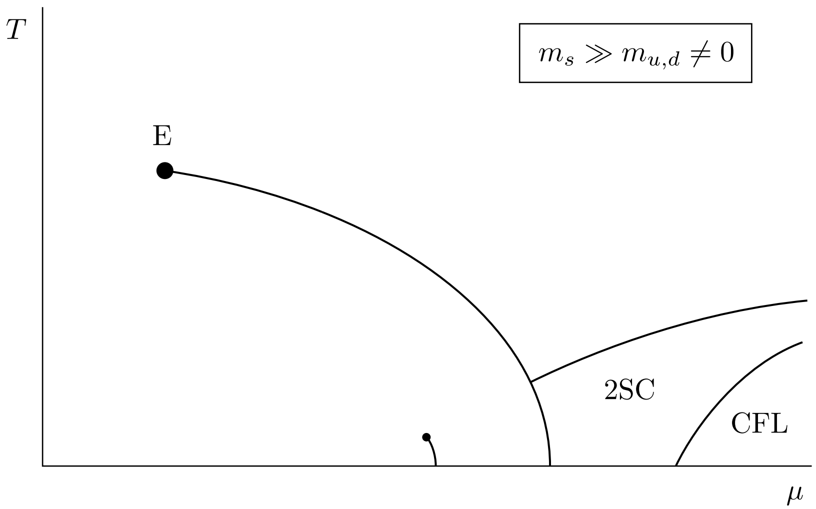

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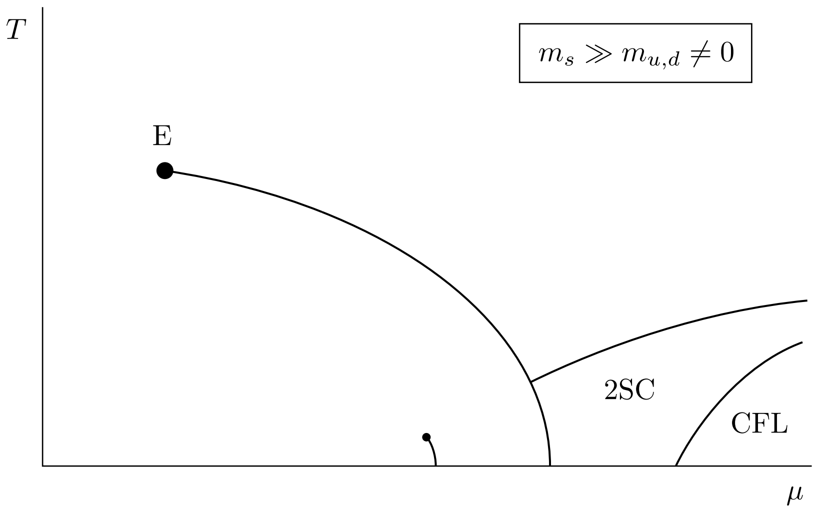

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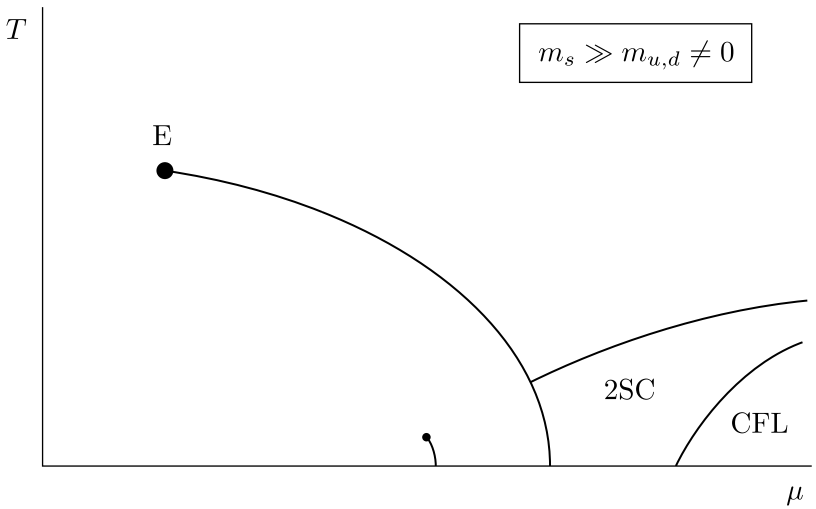

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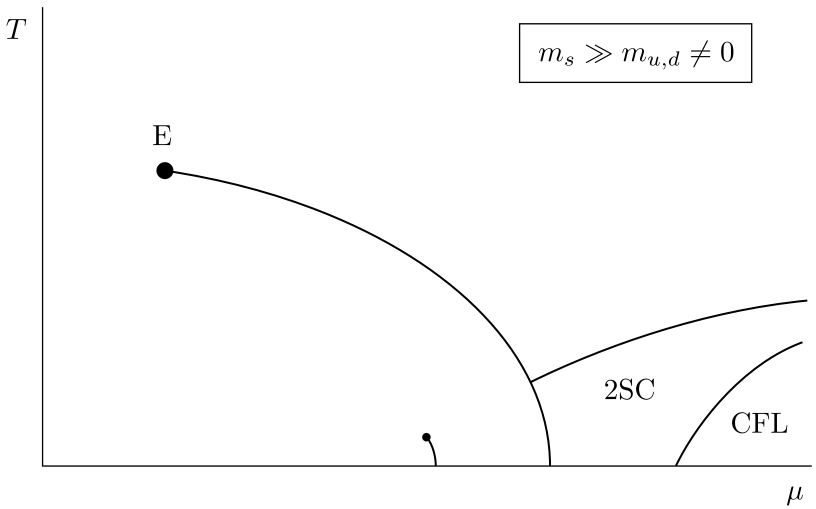

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- Quark-Gluon Plasma, such a new phase, expected in Heavy ion Collisions.

Expected QCD Phase Diagram and Lattice Approaches to unravel it.

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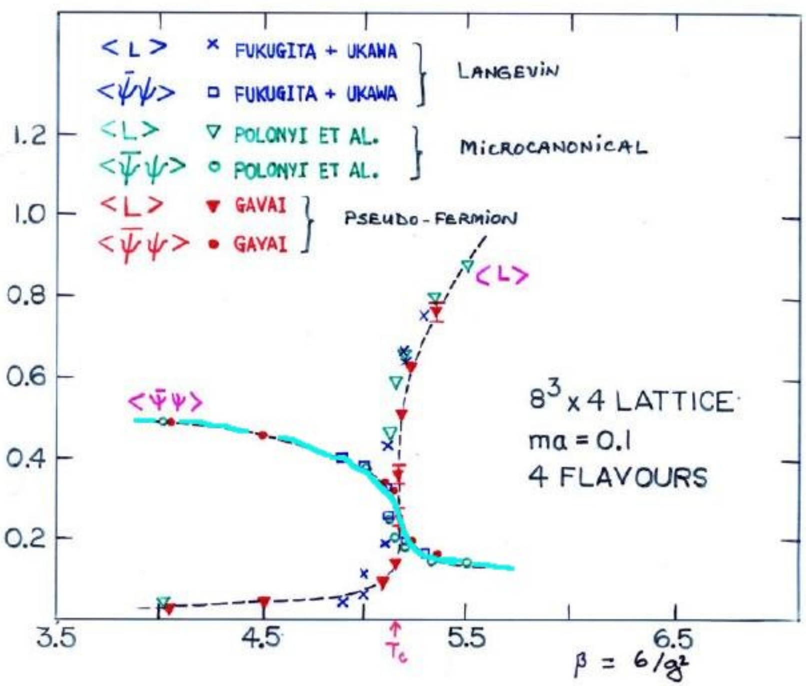

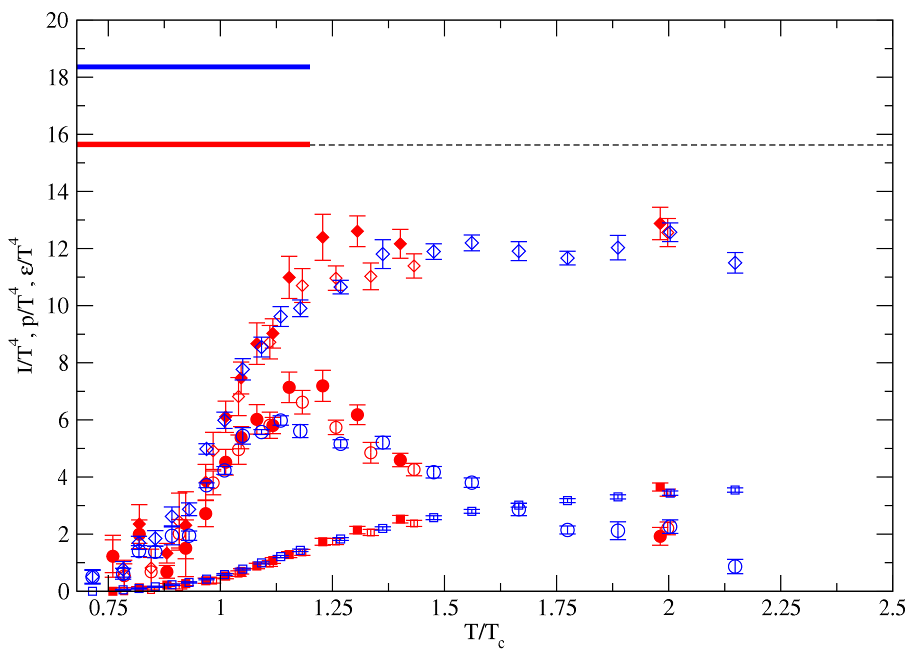

Bernard et al., MILC hep-lat/0509053.

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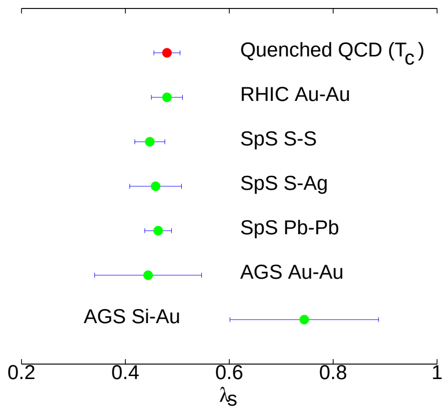

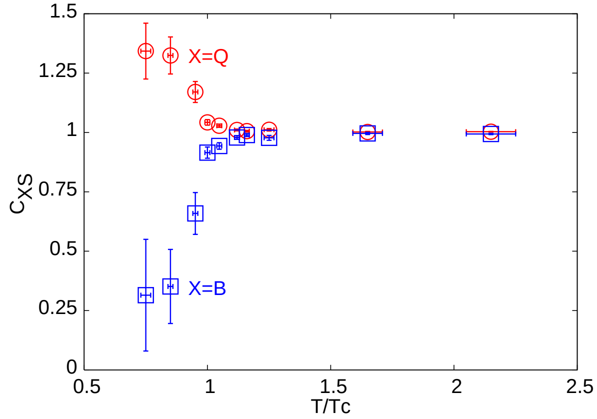

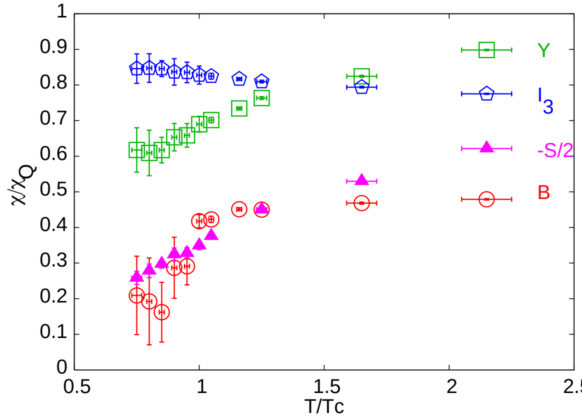

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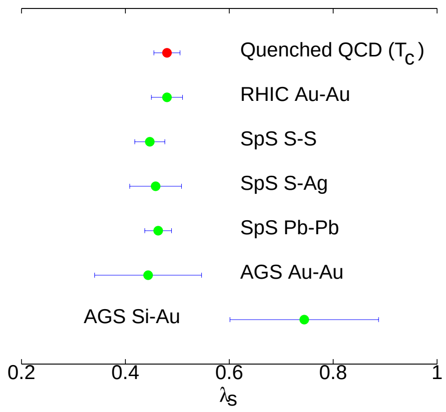

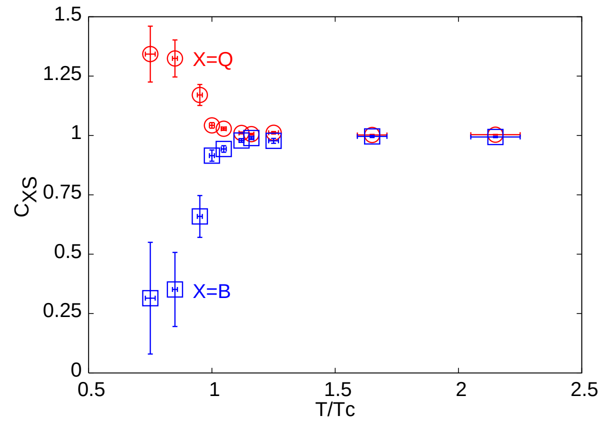

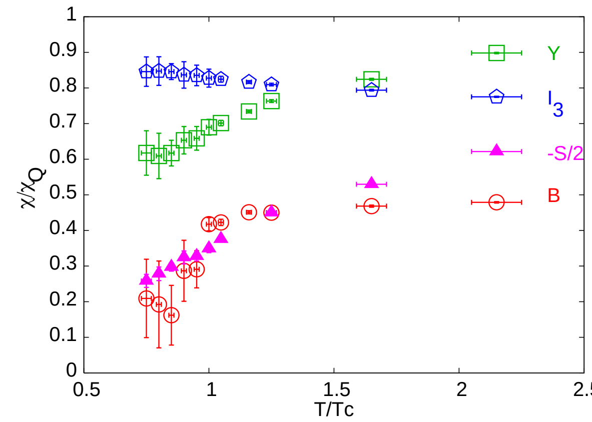

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• λ_s — Measure of Production of strange quark-antiquark pairs; Expts agree with estimates from the new state Quark-Gluon Plasma.
— Lattice QCD suggests that strangeness carried by quark-like objects
— Robust correlations like BQ are better observables.

- Host of new results now on T-μ phase diagram and more complex observables such as J/ψ-dissolution/persistence, dileptons, speed of sound, transport coefficients... etc.

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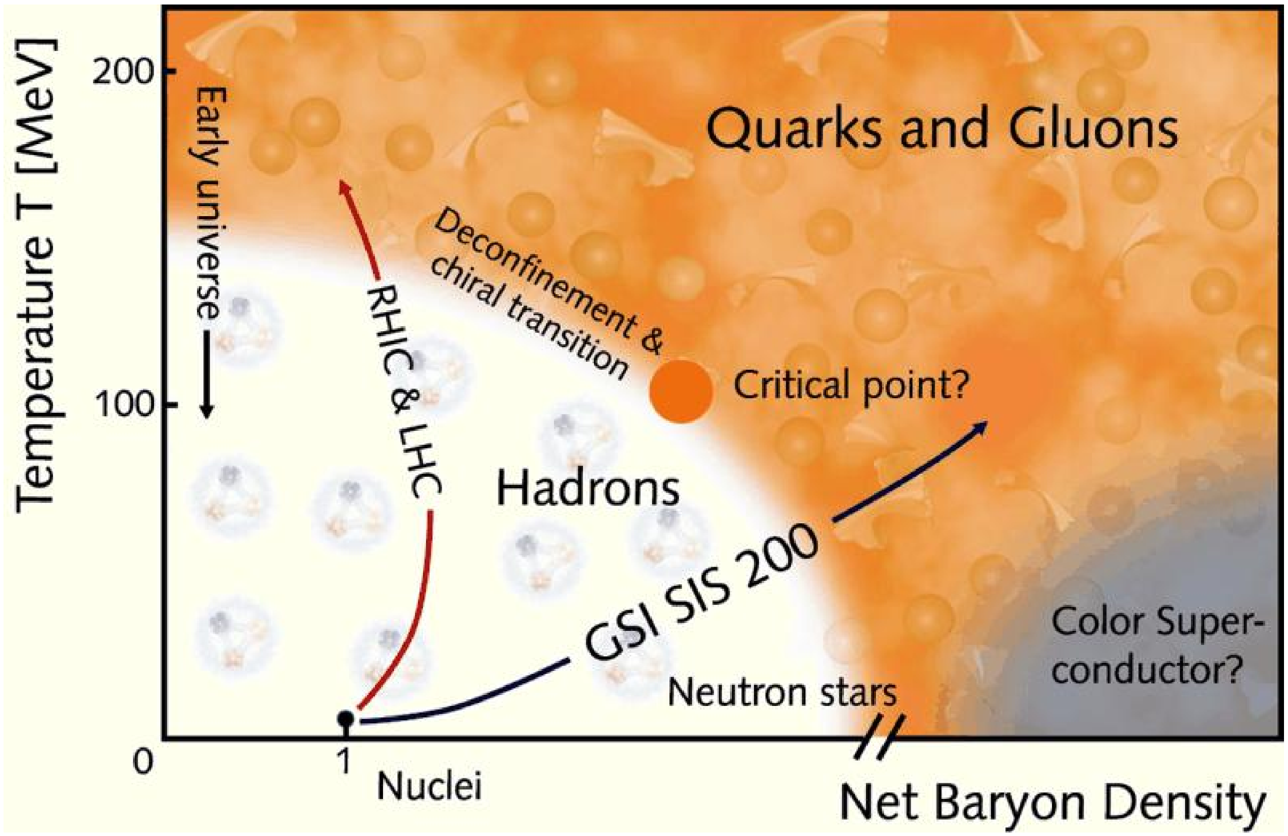

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  - Taylor Expansion (C. Allton et al., PR D66 (2002) 074507 & D68 (2003) 014507; R.V. Gavai and S. Gupta, PR D68 (2003) 034506).

Why Taylor series expansion?

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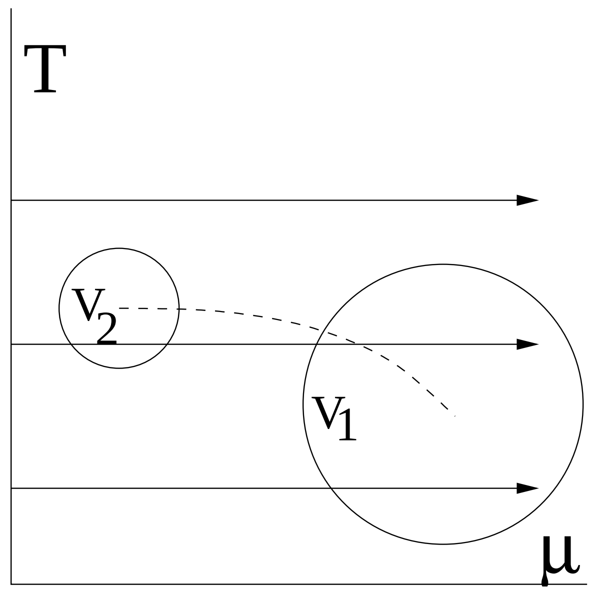

We study volume dependence at several T to i) bracket the critical region and then to ii) track its change as a function of volume.

How Do We Do This Expansion?

Assuming N_f flavours of quarks, and denoting by μ_f the corresponding chemical potentials, the QCD partition function is

$$\mathcal{Z} = \int DU \exp(-S_G) \prod_f \mathrm{Det}\ M(m_f, \mu_f) \quad .$$

Canonical definitions then yield various number densities and susceptibilities :

$$n_i = \frac{T}{V}\frac{\partial \ln \mathcal{Z}}{\partial \mu_i} \text{ and } \qquad \chi_{ij} = \frac{T}{V}\frac{\partial^2 \ln \mathcal{Z}}{\partial \mu_i \partial \mu_j} \quad .$$

Denoting higher order susceptibilities by χ_{n_u,n_d}, the pressure P has the expansion in μ:

$$\frac{\Delta P}{T^4} \equiv \frac{P(\mu,T)}{T^4} - \frac{P(0,T)}{T^4} = \sum_{n_u,n_d} \chi_{n_u,n_d} \frac{1}{n_u!} \left(\frac{\mu_u}{T}\right)^{n_u} \frac{1}{n_d!} \left(\frac{\mu_d}{T}\right)^{n_d} \qquad (2)$$

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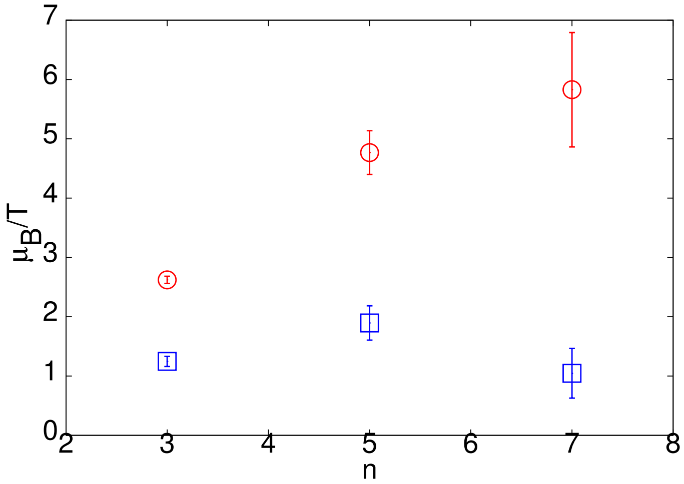
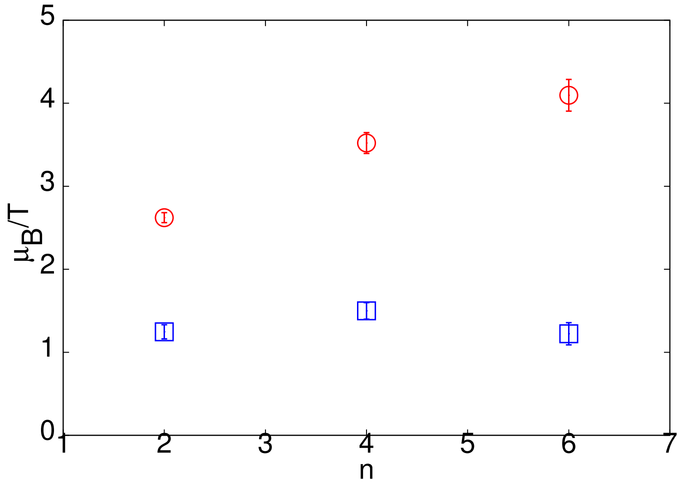
- From this expansion, a series for baryonic susceptibility can be constructed. Its radius of convergence gives the nearest critical point.

- Successive estimates for the radius of convergence can be obtained from these using $\sqrt{\frac{\chi_B^n}{\chi_B^{n+2}}}$ or $\sqrt{\frac{\chi_B^0}{\chi_B^n}}$. We use terms up to 8th order in μ, i.e., estimates from 2/4, 4/6 and 6/8 terms.

R. V. Gavai and Sourendu Gupta, Phys Rev. D 71, 114014 (2005).





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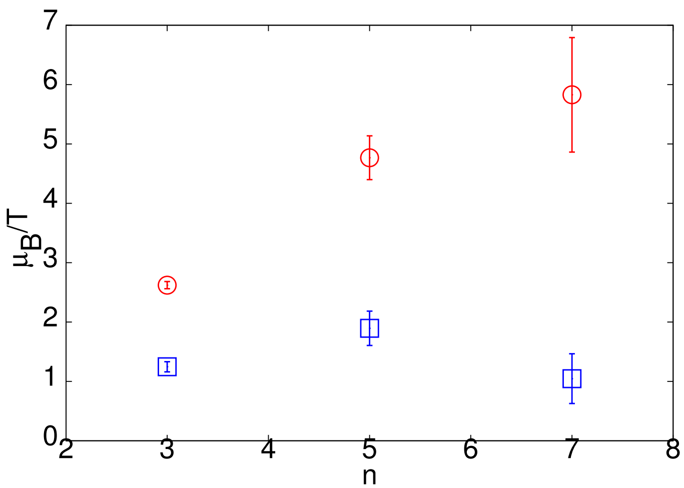

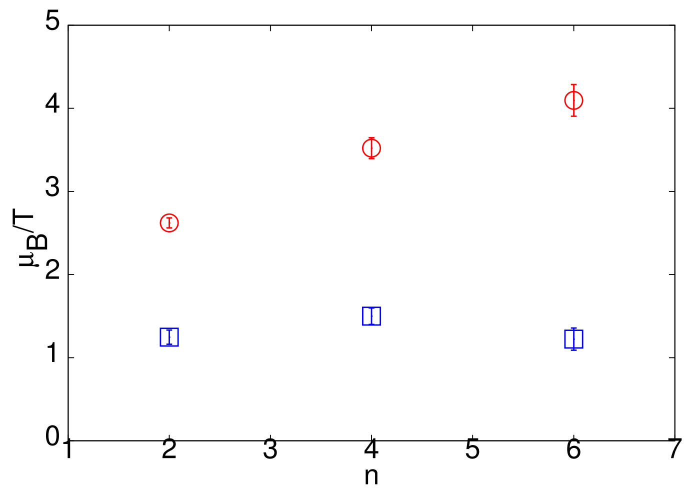

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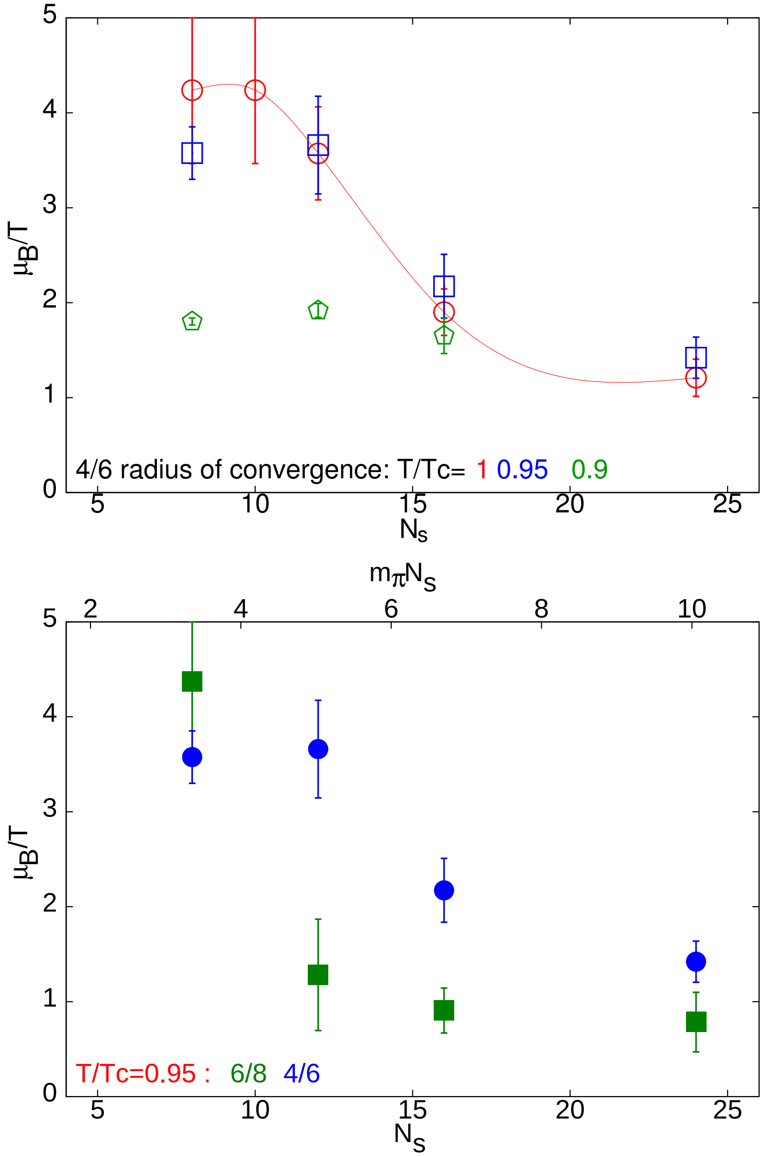
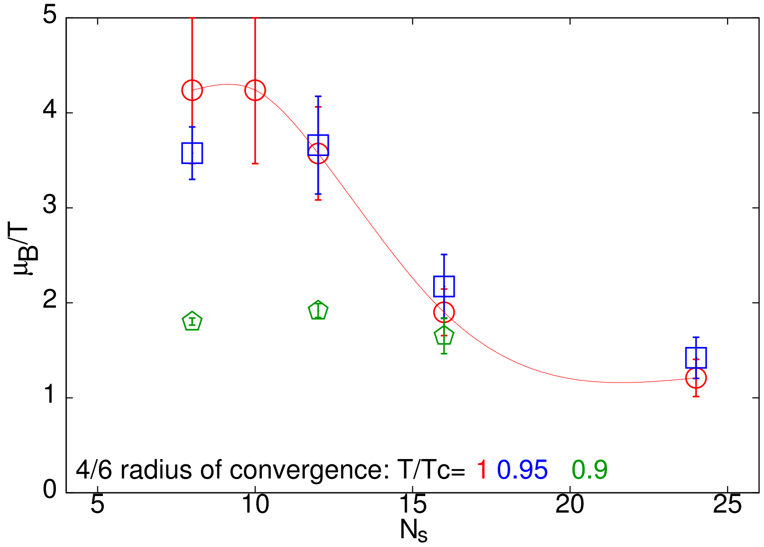
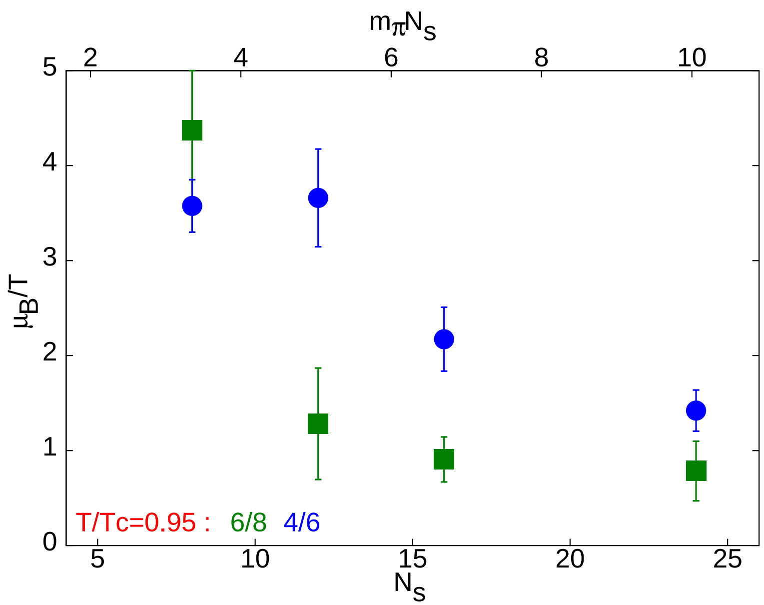
CRAY X1 of I L G T I , T I F R, Mumbai

More on our Results



4/6 radius of convergence: T/Tc= 1 0.95 0.9
μB/T
NS
mπNS
T/Tc=0.95 : 6/8 4/6





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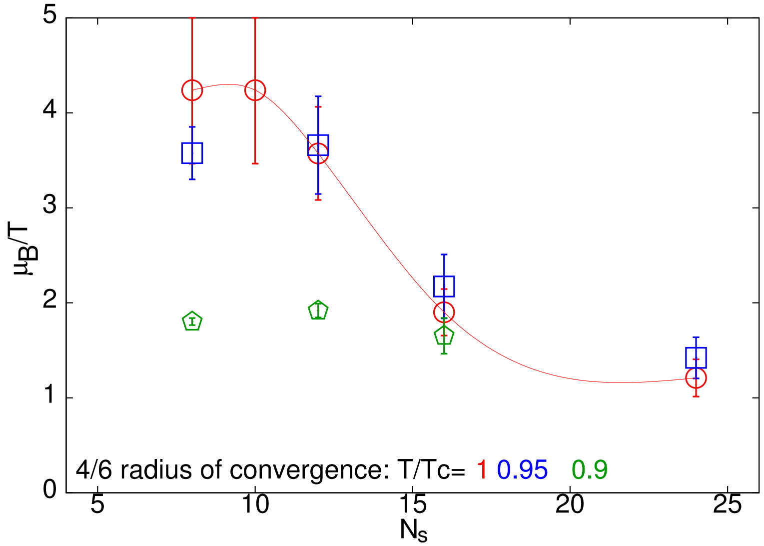
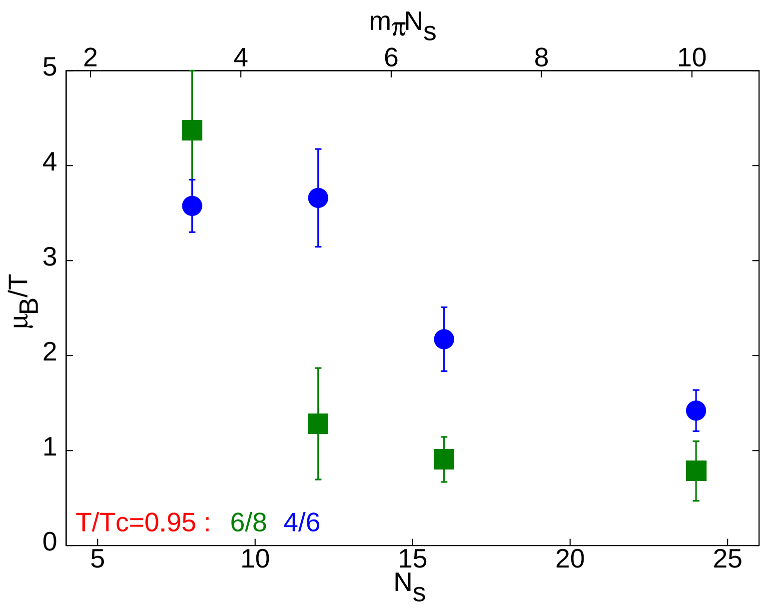
- Our estimate consistent with Fodor & Katz (2002) [$m_\pi/m_\rho = 0.31$ and $N_s m_\pi \sim$ 3-4].





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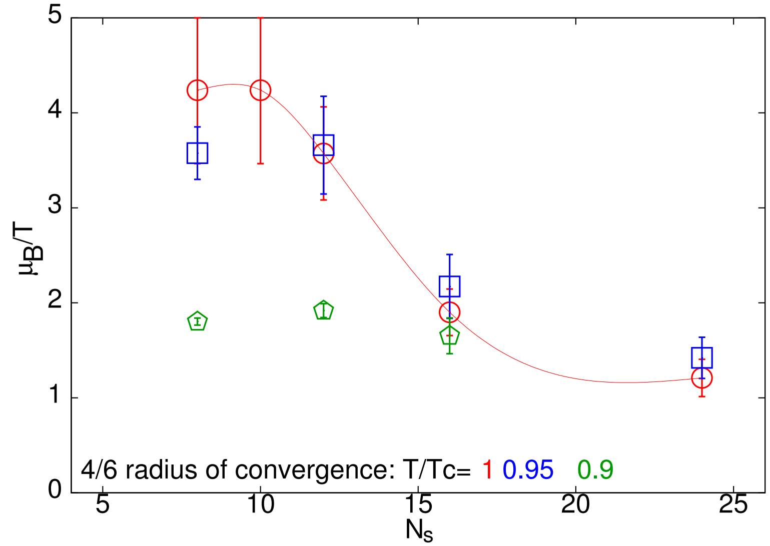

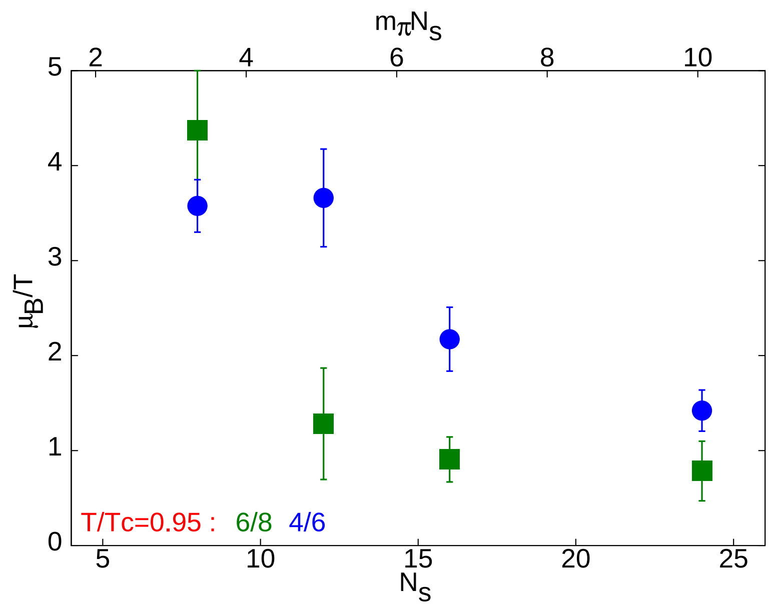

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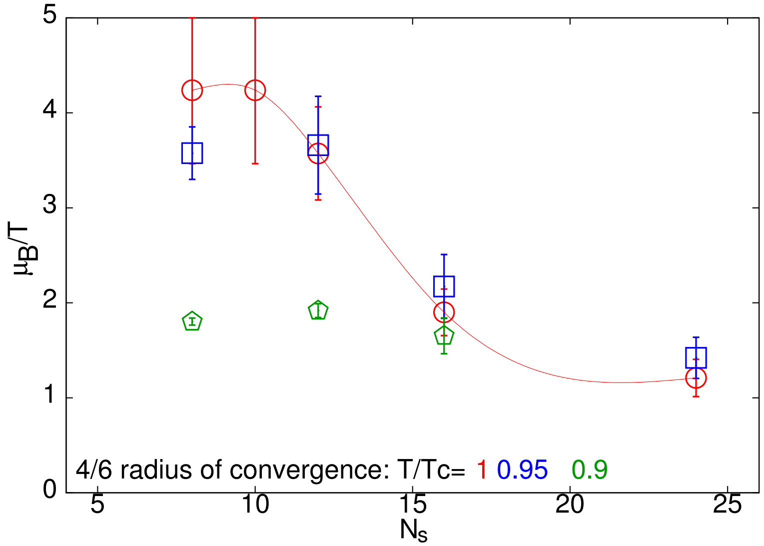

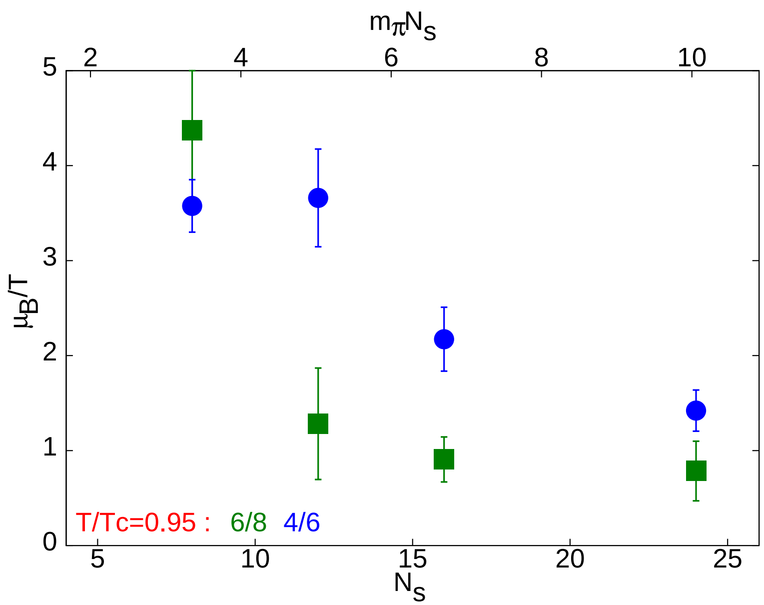

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- Bielefeld-Swansea results (hep-lat/0501030) up to 6th order. They use $N_s m_\pi \sim 15$ but have a large $m_\pi/m_\rho \sim 0.7$.

Heavy Ion Collisions

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- Quark-Gluon Plasma can be, and may **indeed** have been, produced in Heavy Ion Collisions in CERN, Geneva and BNL, New York.
- Necessary Conditions for QGP production :
  - High Energy Density, $\approx$ 1-3 GeV/fm^3.
  - Large System Size, $L \gg \Lambda_{QCD}^{-1}$.
  - Many particles

$\Longrightarrow$ Heavy Ion Collisions at 99.5-99.995 % Velocity of Light.

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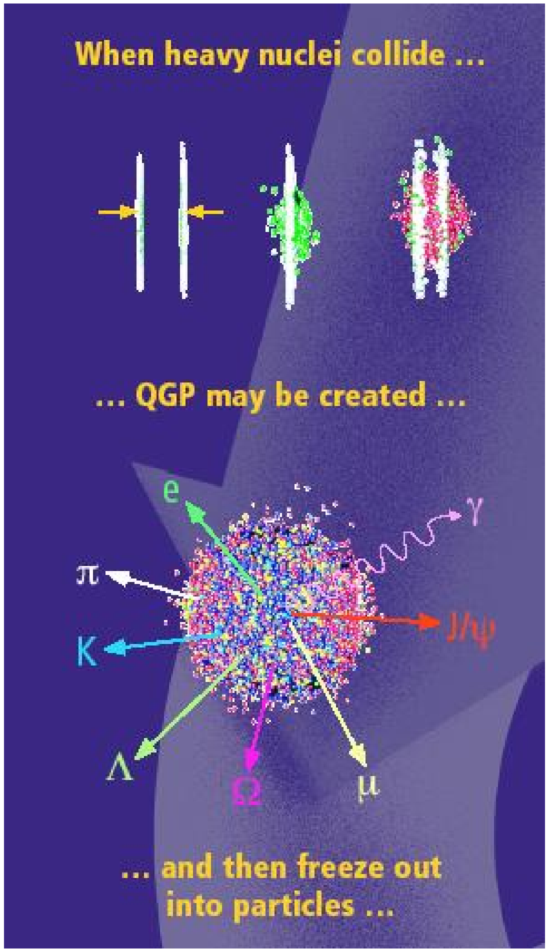

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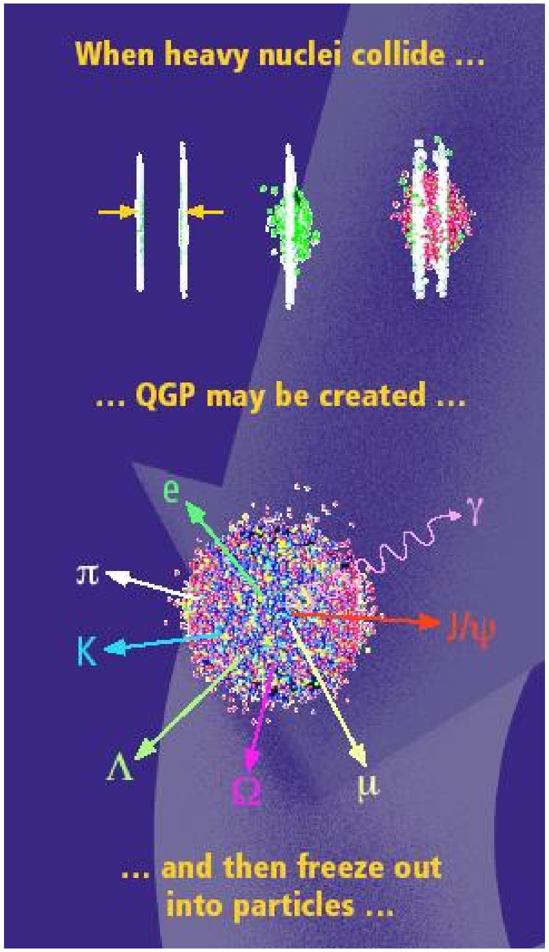

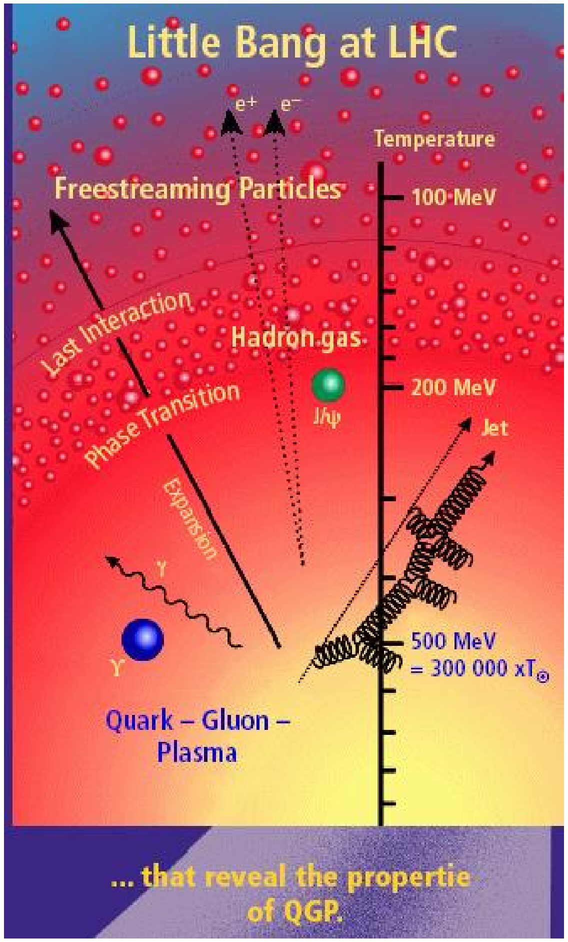

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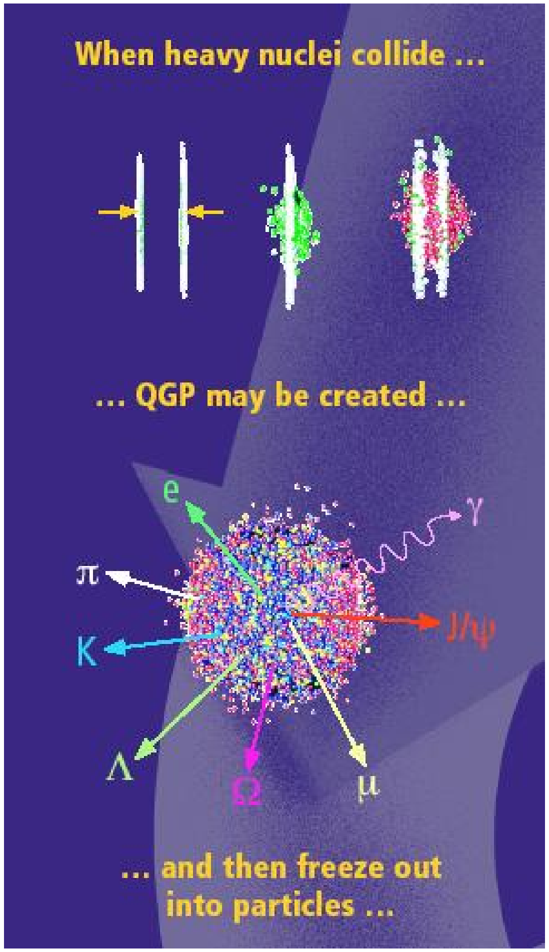
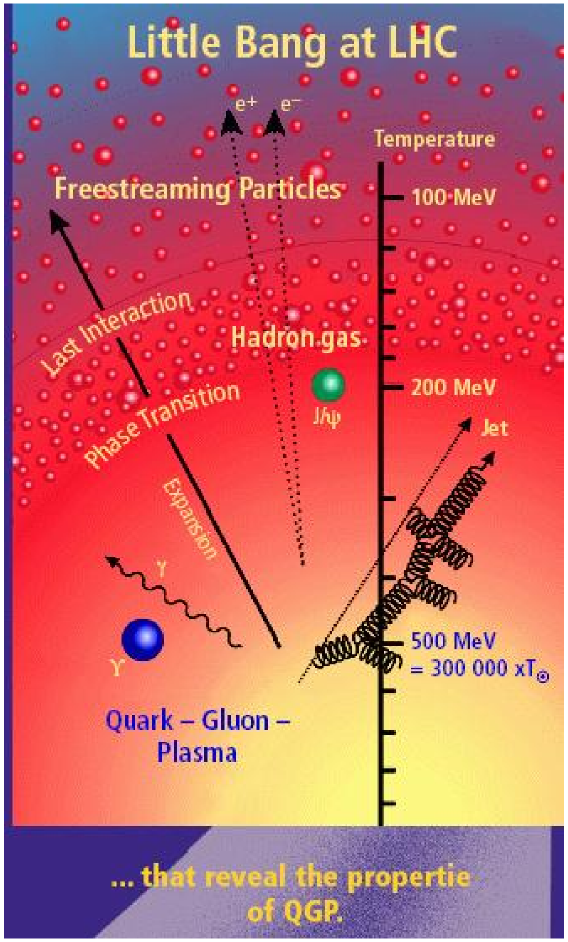
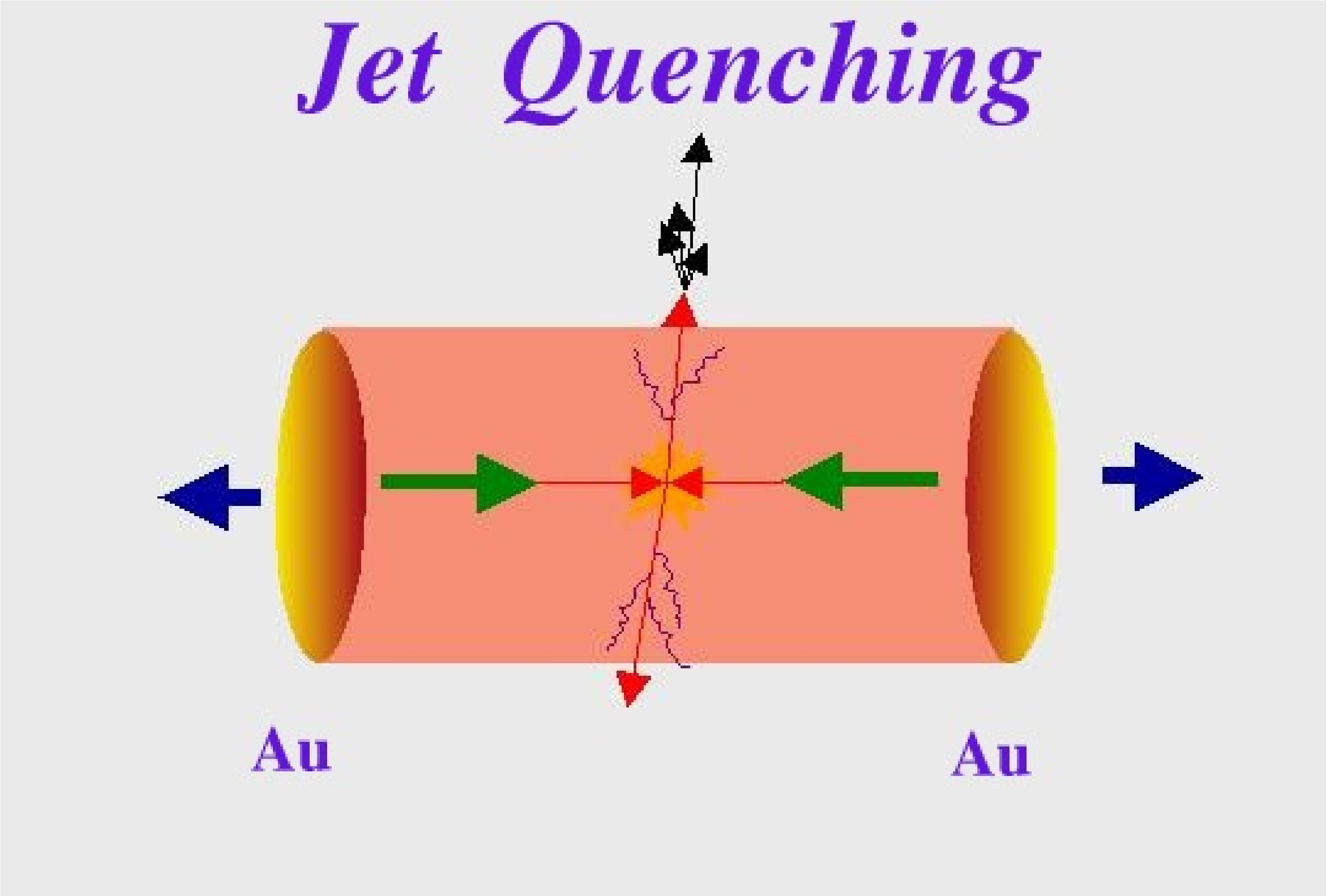




Fireball of QGP condenses into hadrons in $\approx 10^{-23}$ seconds.


Jet Quenching
Au
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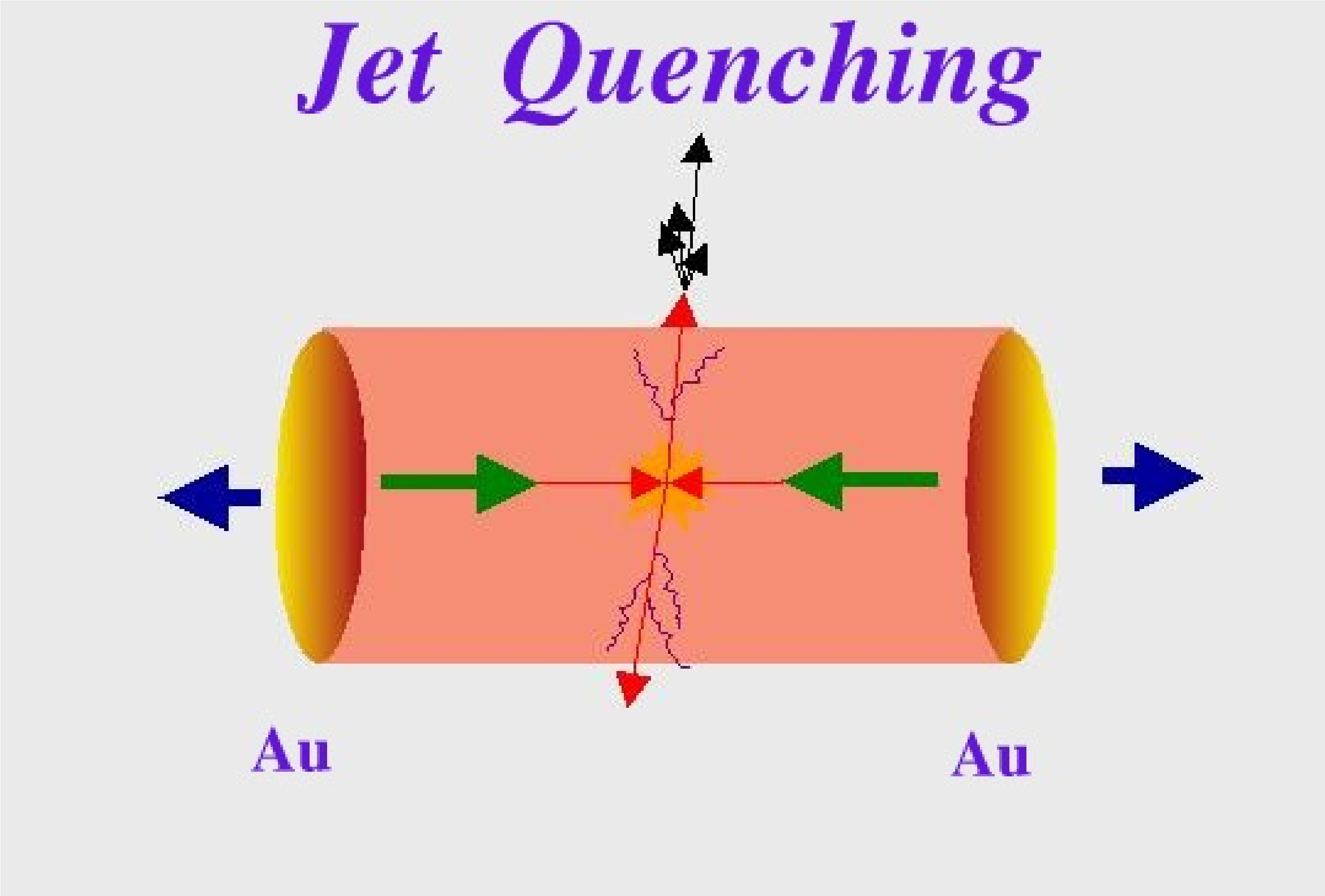

- Rare, Highly Energetic Scatterings produce jets of particles : $g + g \to g + g$.

- Quark-Gluon Plasma, any medium in general, interacts with a jet, causing it to lose energy – Jet Quenching.

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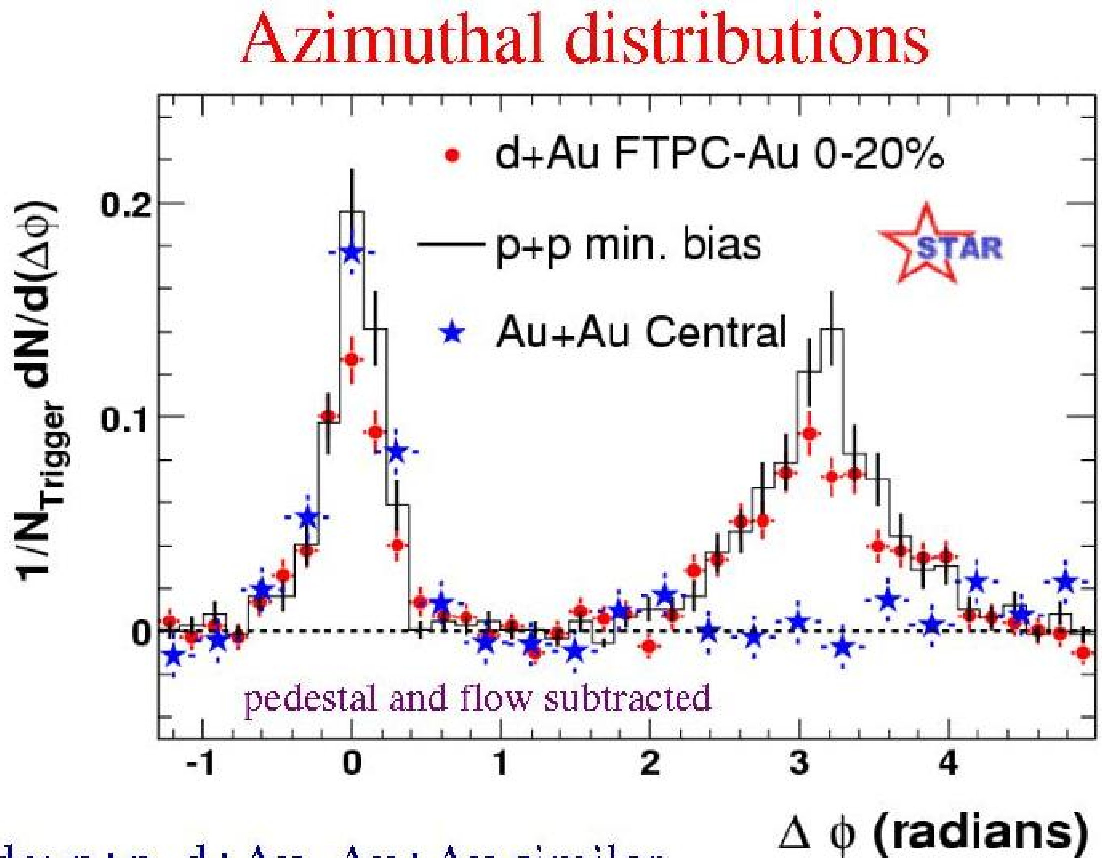


Near- side: p+p, d+Au, Au+Au similar

Back- to- back: Au+Au strongly suppressed relative to p+p and d+Au

Anomalous J/ψ Suppression : CERN NA50 results

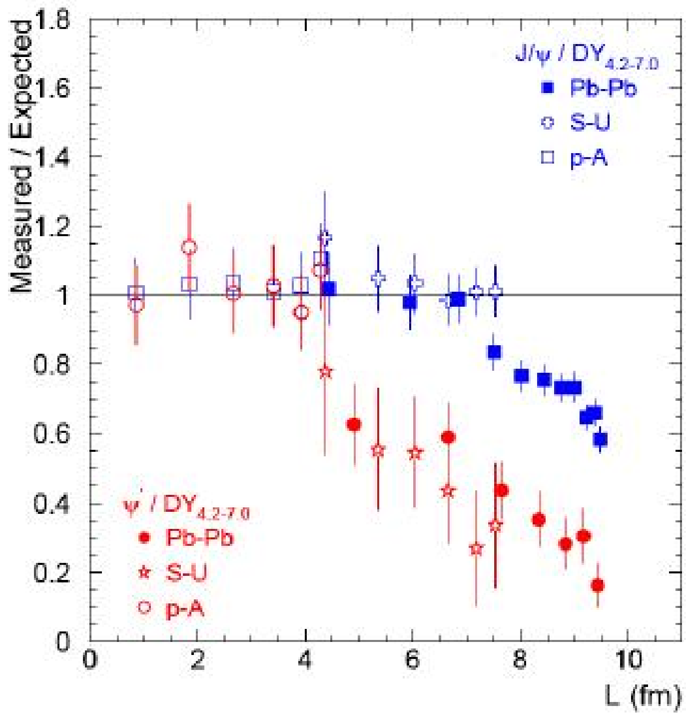
♠ Matsui-Satz idea — J/ψ suppression as a signal of QGP.
♠ Deconfinement $\rightsquigarrow$ Screening of coloured quarks,
which cannot bind.

Anomalous J/ψ Suppression : CERN NA50 results

Expected = Glauber absorption model

$\sigma_{abs}(J/\psi) = 4.18 \pm 0.35$ mb

$\sigma_{abs}(\psi') = 7.60 \pm 1.12$ mb



- **S-U** and **peripheral Pb-Pb (J/ψ)/DY** results follow the absorption curve extrapolated from p-A measurements.
- **Pb-Pb central** collisions show an **anomalous (J/ψ)/DY suppression** with respect to p-A behaviour.
- **ψ'/DY** behaviour is the same in **S-U** and **Pb-Pb** interactions and not compatible with the one observed in p-A collisions.
- **ψ' anomalous suppression** sets in earlier than the J/ψ one.

J/ψ Suppression

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- Original Matsui-Satz idea — Based on Quarkonium potential model calculations and an Ansatz for temperature dependence $\rightsquigarrow$ dissolution of J/ψ and χ_c by $1.1T_c$.

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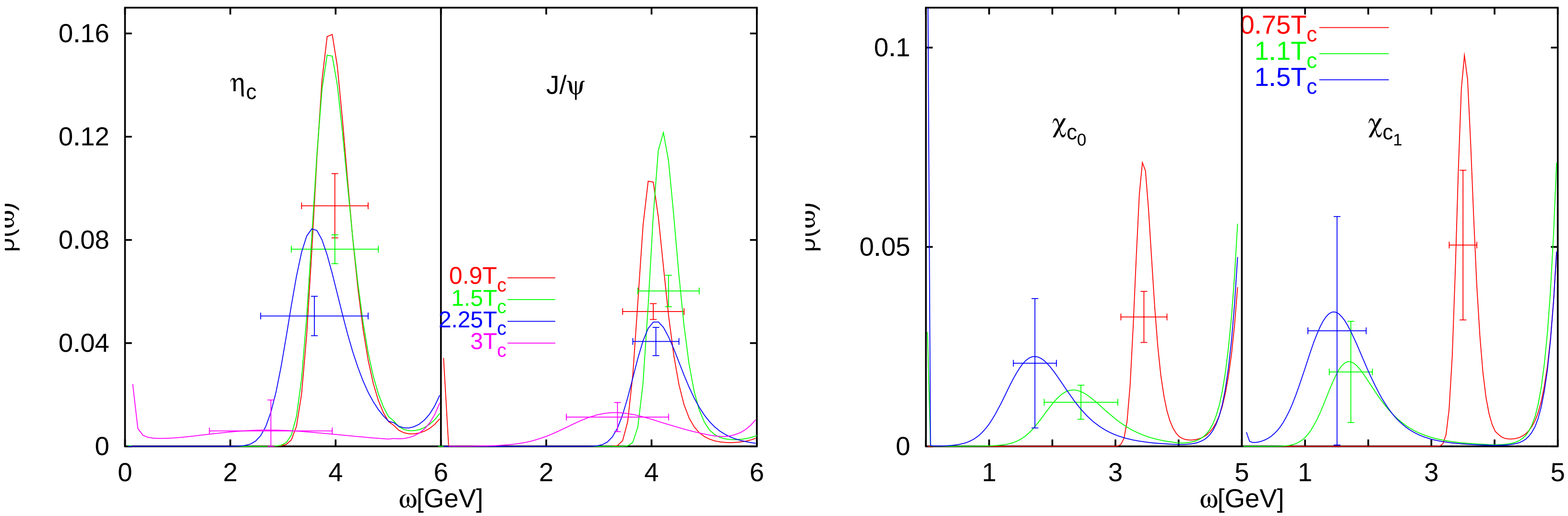
- Caution : nonzero temperature obtained by making temporal lattices shorter.



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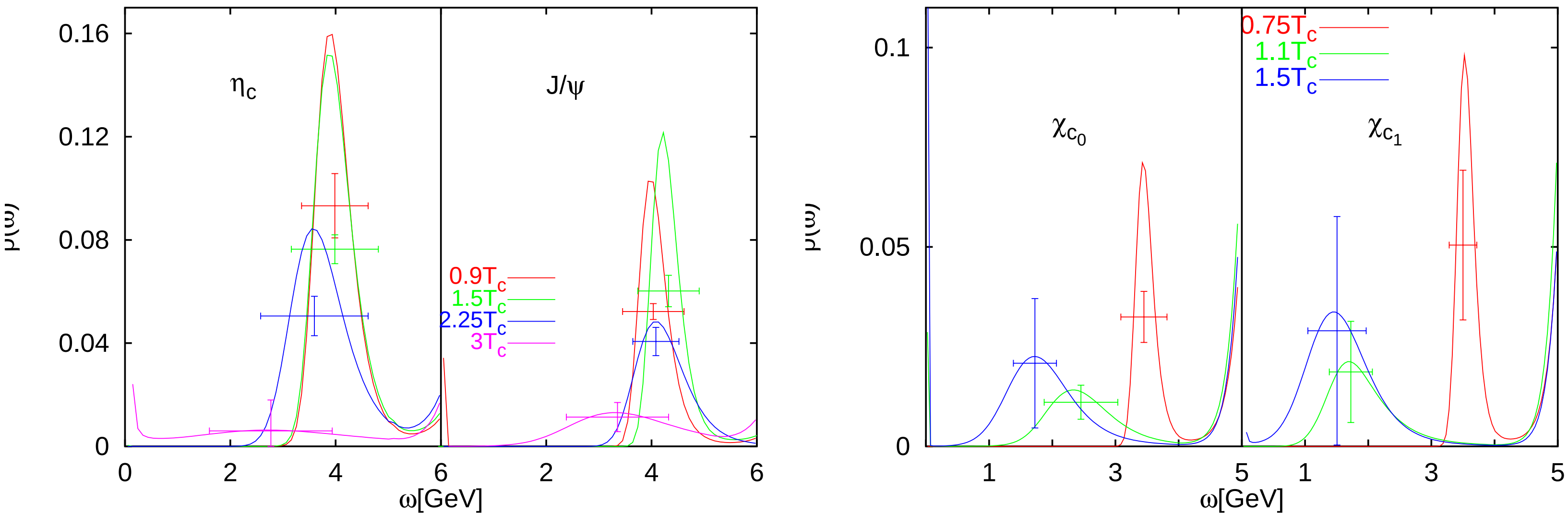

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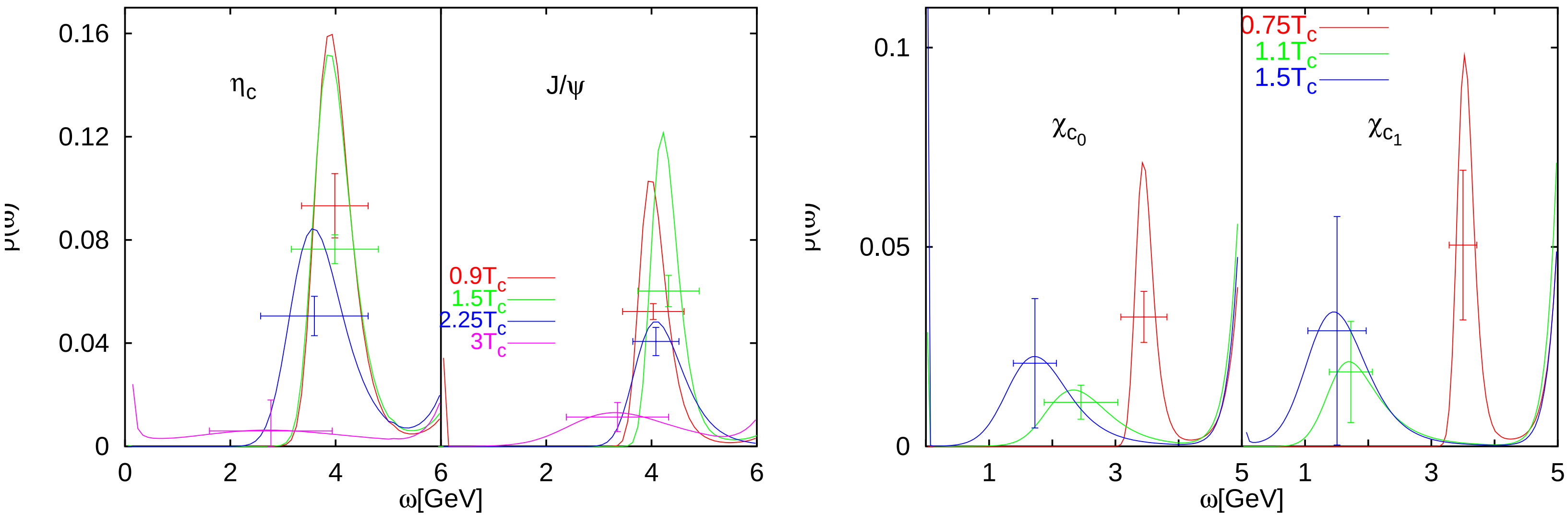

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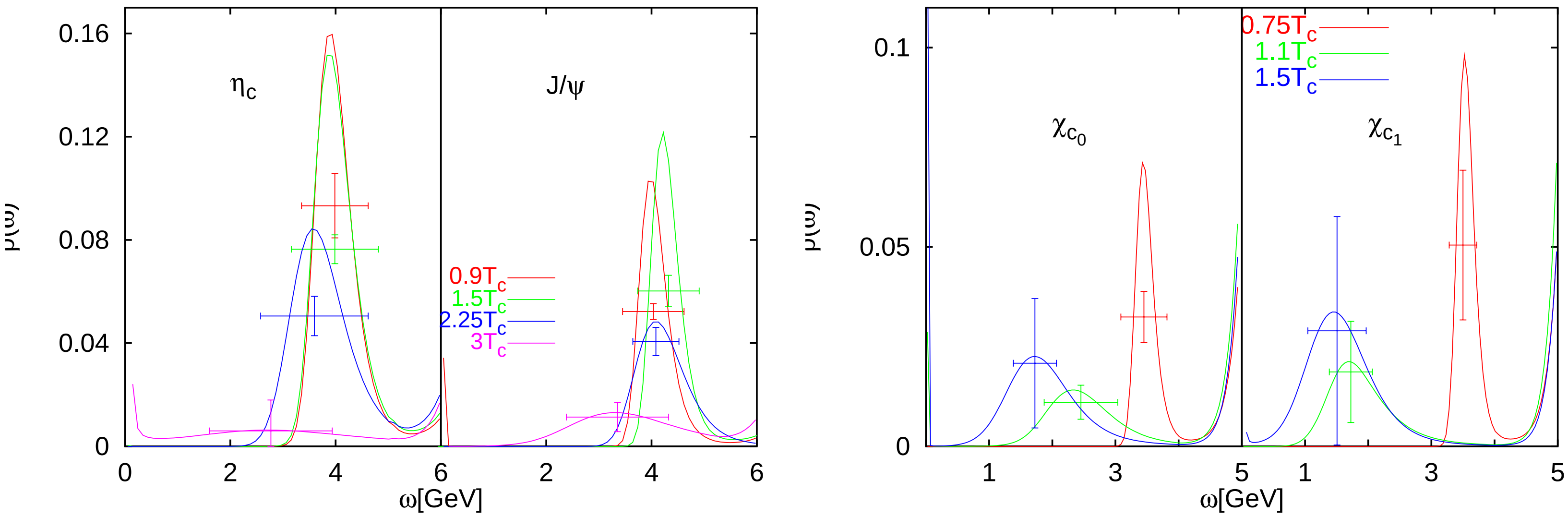

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♠ Effect of inclusion of dynamical fermions ?

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- C_v – Event-by-event temperature/p_T fluctuations.
- Can be obtained from $\ln Z$ by taking appropriate derivatives which relate it to the temperature derivative of anomaly measure Δ/ϵ.

  (RVG, S. Gupta and S. Mukherjee, hep-lat/0412036)
- New method to obtain these differentially without getting negative pressure. Introducing a parameter 't', t=1 used in earlier Bielefeld studies, we use t = 0.

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

- Using lattices with 8, 10, and 12 temporal sites ($38^3 \times 12$ and 38^4 lattices) and with statistics of 0.5-1 million iterations, ϵ, P, s, C_s^2 and C_v obtained in continuum.

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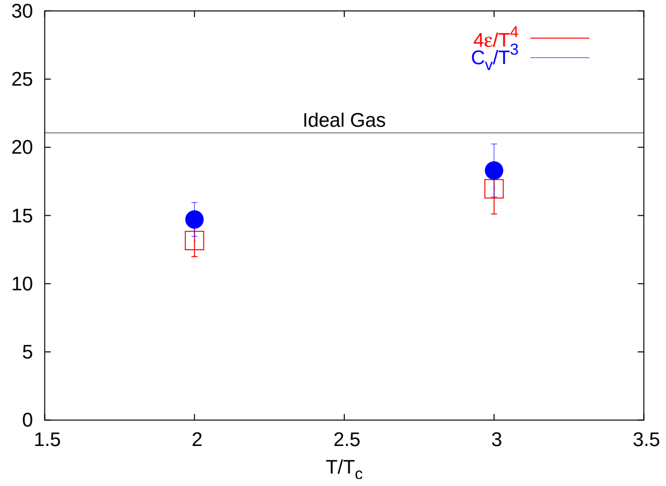
- Entropy agrees with strong coupling SYM prediction

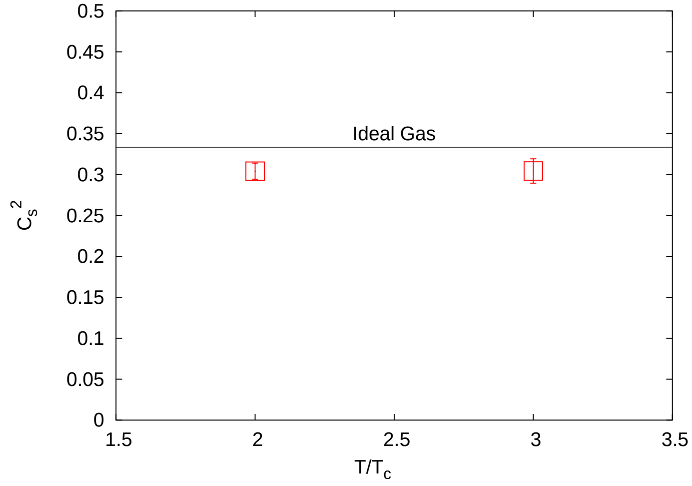
(Gubser, Klebanov & Tseytlin, NPB '98, 202)

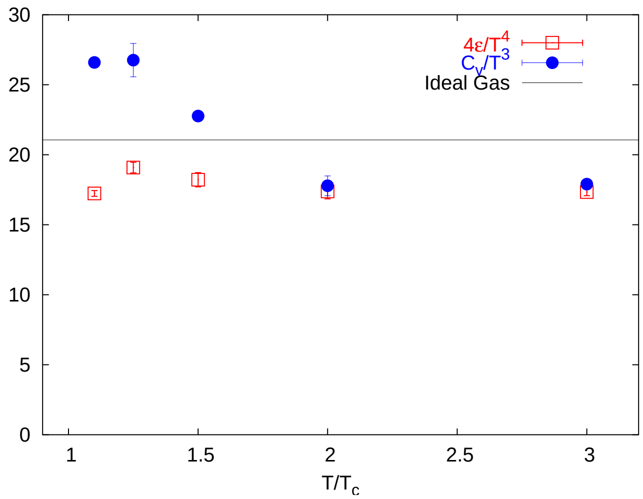
$$\begin{aligned} \frac{s}{s_0} &= f(g^2 N_c), \quad \text{where} \\ f(x) &= \frac{3}{4} + \frac{45}{32}\zeta(3)(2x^{-3/2}) + \cdots \quad \text{and} \\ s_0 &= \frac{2}{3}\pi^2 N_c^2 T^3, \end{aligned} \tag{3}$$

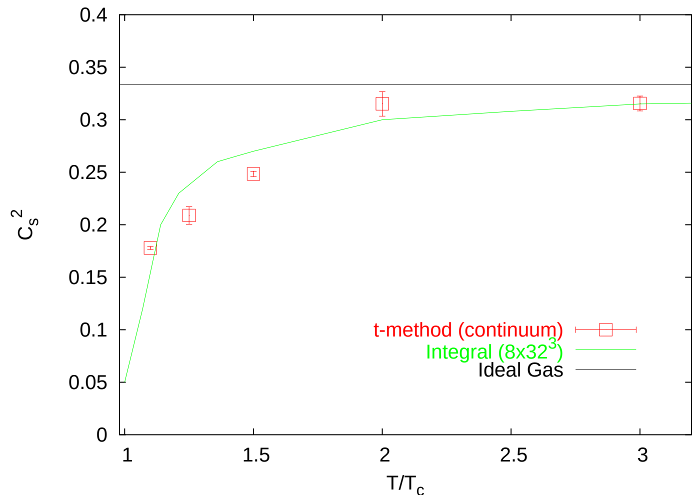
for $T = 3T_c$ but fails at $2T_c$, as do various weak coupling schemes.

Results for t = 1 and 0 respectively:









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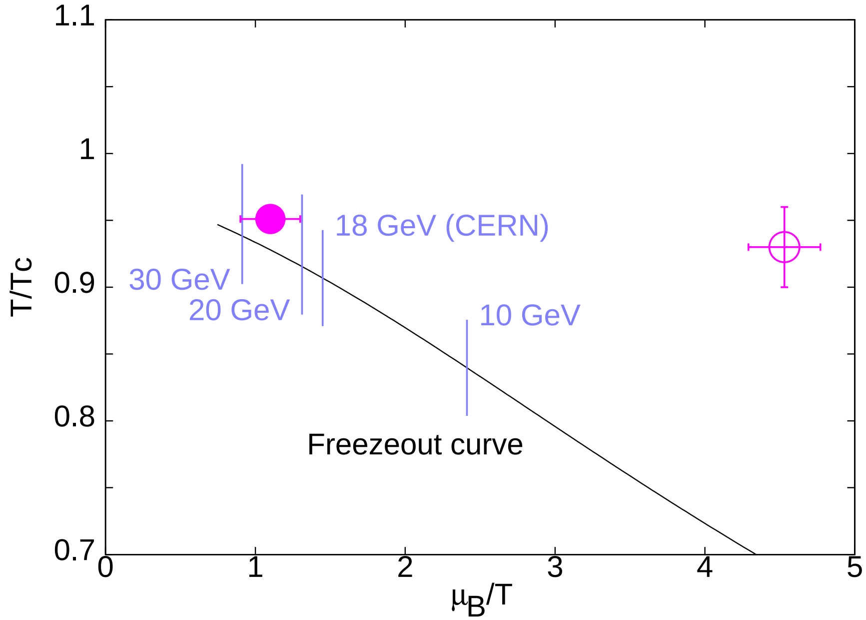

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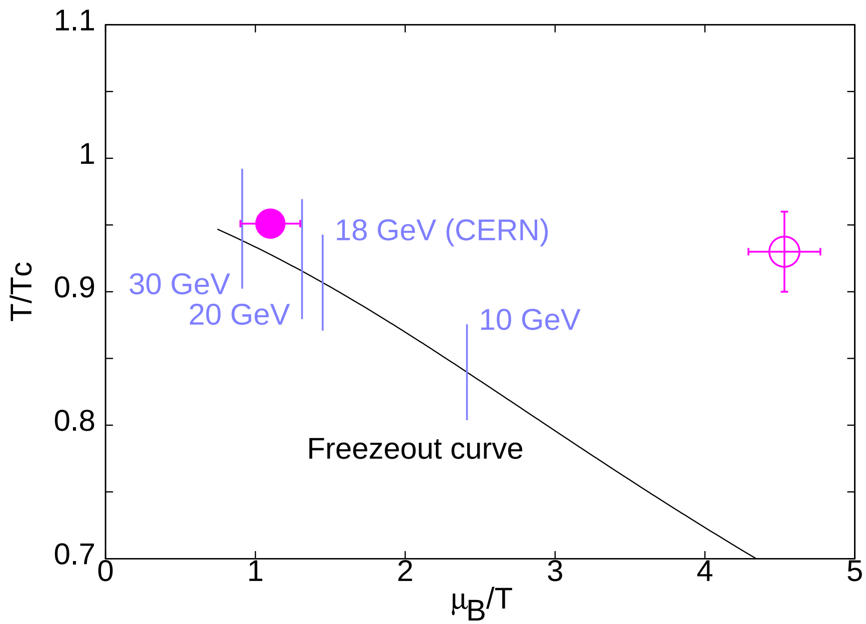

Heavy Ion Collisions in CERN Geneva, and BNL, New York, have seen tell-tale signs of QGP : Many surprises already and more excitement likely to come.