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ANL-HEP-CP-98-121

SOLVING QCD

VIA

MULTI-REGGE THEORY

To solve QCD at high-energy we must simultaneously find the hadronic states and the exchanged pomeron (IP) giving UNITARY scattering amplitudes.

Experimentally, the IP $\sim$ a Regge pole at small Q^2 and a single gluon at larger Q^2. (F_2^D - H1, dijets - ZEUS)

In the "solution" which I will describe, these "non-perturbative" properties of the IP are directly related to the non-perturbative confinement and chiral symmetry breaking properties of hadrons.

(See *Phys. Rev.* **D58**, 074008 for more details.)

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Outline

1. The central idea.
2. Preliminaries:

Renormalons and non-perturbative condensates, avoiding the vacuum - light-cone quantization, massive reggeized gluons and complimentarity.

3. Multi-Regge Theory:

Angular variables, partial-wave expansions, multi-Regge limits, asymptotic dispersion relations, Froissart-Gribov continuations, Sommerfeld-Watson representations, multiparticle t-channel unitarity, reggeon unitarity.

4. Pomeron Reggeon Field Theory:

Formulation, the critical pomeron, the super-critical pomeron phase.

5. Reggeon diagrams for QCD:

Description of known results, reggeon diagrams for maximal helicity-pole limits, reggeon helicity-flip vertices, non-commuting infra-red limits.

6. The Infra-red Anomaly in Helicity-Flip Vertices

Anomalous color parity - the anomalous odderon, ultra-violet divergences and Pauli-Villars fermions, the infra-red divergence.

7. SU(2) Symmetry and Confinement

Divergent diagrams, the wee-parton condensate and confinement, the parton model, the pomeron as a reggeized gluon, chiral symmetry breaking.

8. Supercritical $\rightarrow$ Critical IP and SU(2) $\rightarrow$ SU(3)

Supercritical features, the critical $\Lambda_{\perp c}$, IP $\leftrightarrow C_c = -1$, diffractive DIS. $\Lambda_{\perp c} = \infty$ $\leftrightarrow$ extra quark sector $\leftrightarrow$ electroweak symmetry breaking ?

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Of the fluctuation quantities (susceptibilities), the most accessible is the "magnetic" susceptibility

$$\chi_\sigma = \frac{1}{V}[\langle(\sum_x \sigma(x))^2\rangle - \langle(\sum_x \sigma(x))\rangle^2] \tag{6}$$

which scales as

$$\chi_\sigma = const(\beta - \beta_c)^{-\gamma_m}. \tag{7}$$

3. Lattice simulations and preliminary results

Our simulations are being carried out using hybrid molecular dynamics with noisy fermions to accommodate $N_f = 2$. Because of the exact flavour $U(1)_{axial}$ symmetry at $m = 0$, the direction of symmetry breaking in the $(\langle\bar\psi\psi\rangle, i\langle\bar\psi\gamma_5\xi_5\psi\rangle)$ space (or (σ,π) space is not determined. On a finite lattice, this direction rotates during the run, forcing us to use $\sqrt{\langle\bar\psi\psi\rangle^2 - \langle\bar\psi\gamma_5\xi_5\psi\rangle^2}$ or $\sqrt{\langle\sigma\rangle^2 + \langle\pi\rangle^2}$ as our order parameter on each configuration. (Here $\langle\rangle$ should be taken to mean a lattice average, not an ensemble average.) This estimate differs from the true value by $\mathcal{O}(1/\sqrt{V})$, which can only be removed by working at more than 1 spatial volume for each N_t.

We are currently running on $8^3 \times 4$, $12^2 \times 24 \times 4$, $12^3 \times 6$, and $18^3 \times 6$ lattices at $\gamma = 20$, and on a $12^3 \times 6$ at $\gamma = 10$.

Whereas our earlier simulations at $N_t = 4$ and $\gamma = 10$ showed a first order transition, all $N_t = 6$ combinations above show evidence for the expected second order transition. $\langle\bar\psi\psi\rangle$ and the Wilson line show a sharp, but not discontinuous, transition with no sign of metastability, unlike the previous case. Figure 1 shows the β dependence of the chiral condensate for $N_t = 6$ and $\gamma = 20$. In addition, close to the transition, observables show clear signs of critical slowing down with large fluctuations over many thousands of time units. (We have simulated for as many as 39,000 time units at a single β value.) Such a time evolution for the chiral condensate close to the transition is shown in figure 2. The $N_t = 4$, $\gamma = 20$ runs show signs of critical fluctuations, but the transition occurs over a very narrow range and it will require more statistics to tell if it has become second order or remains first order.

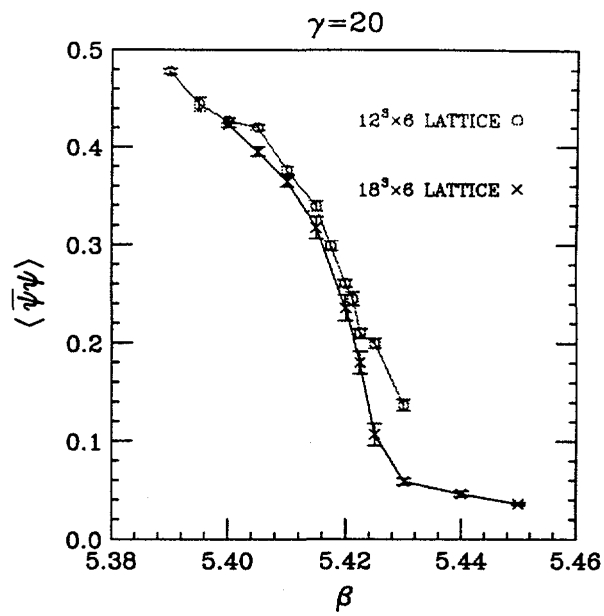

Figure 1. $\langle\bar\psi\psi\rangle$ as a function of β for $N_t = 6$ and $\gamma = 20$.

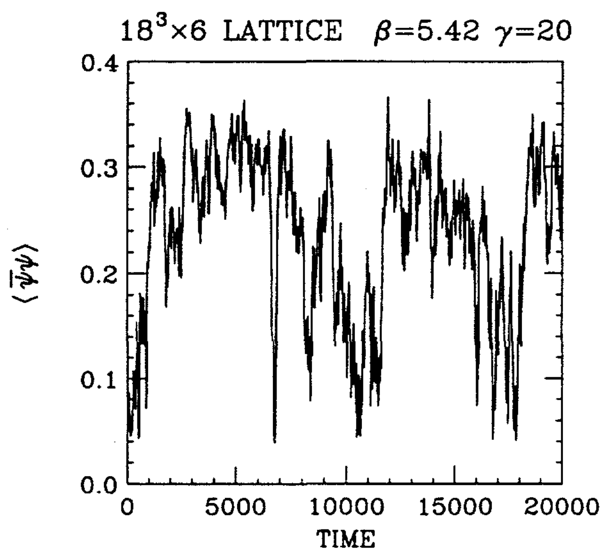

Figure 2. Time evolution of $\langle\bar\psi\psi\rangle$ at $\beta = 5.42$ on an $18^3 \times 6$ lattice at $\gamma = 20$.

It is clear that we will need to extend our runs close to the phase transition. This is a consequence of the critical slowing down close to the second order transition. This currently limits our ability to extract accurate critical exponents due in part to the fact that our errors are poorly determined and partly because it prevents accurate extrapolation to infinite volume. In addition, the scaling window could be very narrow requiring us to consider more β values close to the transition. Despite this the $\langle\bar{\psi}\psi\rangle$ data looks promising, and suggests a critical exponent $\beta_m \sim 0.3$, however, this is on the basis of statistically poor fits. The $N_t = 6$, $\gamma = 20$ data shows relatively modest finite volume effects.

For $N_t = 4$, $\gamma = 20$, we find $\beta_c \approx 5.288$. For $N_t = 6$, $\gamma = 10$, $\beta_c \approx 5.466$, while for $N_t = 6$, $\gamma = 20$, $\beta_c \approx 5.424$.

Figure 3 shows the σ and π screening masses for the $18^3 \times 6$, $\gamma = 20$ simulations. The σ screening mass shows the correct behaviour, decreasing to zero as β is increased through the transition, and increasing from zero, degenerate with the π above the transition. Below the transition, the pion mass is consistent with zero. It appears doubtful that these masses can be determined accurately enough to obtain a good estimate for γ_m. The δ mass can be calculated, but even assuming it remains distinct from the σ/π mass above the transition, it will be difficult to tell how much of this is due to the explicit $U(1)_{axial}$ symmetry breaking provided by the 4-fermion interaction.

4. Summary

$N_f = 2$ lattice QCD with massless quarks and a weak 4-fermion interaction appears to have the expected second order transition, at least for $N_t \geq 6$. More work is needed to clarify the $N_t = 4$ case.

With more statistics the $N_t = 6$ simulations should produce an accurate determination of the critical exponent β_m. Moving to finite mass at $\beta = \beta_c$ should allow an accurate determination of δ.

Hadronic screening masses need further analysis. Other order parameters remain to be analysed.

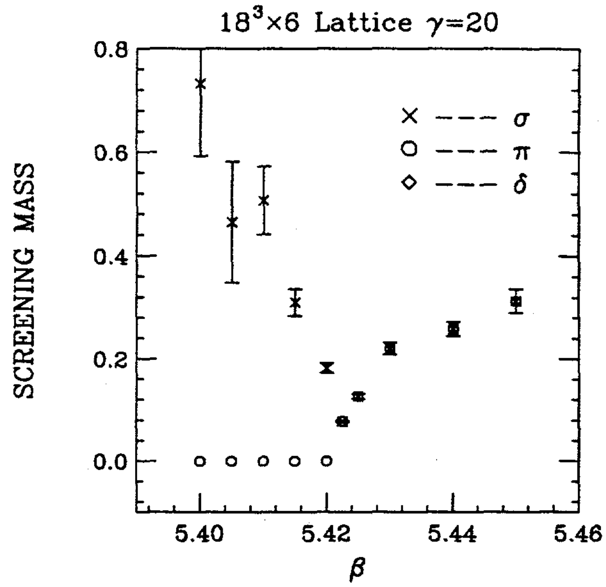

Figure 3. σ and π screening masses on an $18^3 \times 6$ lattice at $\gamma = 20$.

Unfortunately, there is no obvious way to include 4-fermion interactions with full $SU(2) \times SU(2)$ chiral flavour symmetry.

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