# Fluctuations in <p_t> from Polyakov loops

A. Dumitru (Frankfurt) & RDP (BNL & NBI)
also: A. Dumitru, J. Lenaghan (Virginia), O. Scavenius (NBI)

1. Loops => *domains* => fluctuations in <p_t>

   π's vs K's vs p's... y vs θ vs ...

2. Why "extra" Z(3) symmetry?

3. Polyakov loops & Z(3)

4. Polyakov loop model: pressure, Z(3) magnetization...

Single particle spectra: always appear "thermal"
Fluctuations *essential* to test *true* nature of particle prod.

# QGP and Particle Production

*Usually:* Quark-Gluon Plasma => *"nearly"* ideal quarks and gluons

Lattice data + phen. models => probably ok down to 2-3 Tc

We argue: *fails* for Tc => (2-3) Tc: transition region dominated by
*collective* excitations ("Polyakov loops")

For now: merely assume pressure *near* Tc dominated by *some*
collective field

So? Then hadronization is *not:*
recombination of quarks & gluons
"parton-hadron" duality (1 gluon ≈ 1 pion; what about K's?)

Hadronization *is* controlled by the nature of the deconfined phase
*just* above, and below, Tc.

# Domain Picture of Particle Production

*Assume:* particles produced by

domains ≈ 1 fm in size

in each domain, *large* fluctuations in <p_t>, ≈ 10%.

domains gluonic; i.e., flavor blind;
production uncorrelated between different domains.

In the Polyakov loop model:

domain size = 1/(mass of loop at T_c)

by construction, loop is gluonic, so flavor blind

Loop field decays into pions, kaons... because
it is only light at T_c, gets heavy above and below T_c

causality => uncorrelated domains

# Fluctuations in Pion <p_t> from Domains

*Attempt* to give model "independent" analysis of fluc.'s in <p_t> from domain model. Always: explicit parameters taken from loop model; these *could* be different, but not vastly.

Basic parameters:

Scale factor "a" at $T_c$:
longitudinal length in beam direction = $a(T_c)$ x rapidity window
Bjorken expansion: $a \sim \tau$ = proper time.

$dN/dy \sim$ (density π's at $T_c$) $\pi R^2 a(T_c)$

RHIC: $a(T_c) \sim 10$ fm, $R(T_c) \sim 10$ fm.

# domains = $\pi R^2 a(T_c)$/(size each domain) ≈ 300 domains

Fluc.'s in <p_t> = fluc.'s in each domain/√# domains ≈ .6 %

# Fluctuations in <p_t> from domains

## Fluctuations in <p_t> *increase* as # domains *decrease*

total fluc.'s ~ $1/\sqrt{\#}$ domains.

Fluctuations increase with finer bins:

smaller width in rapidity: for 1/4 unit rapidity, fluc.'s x 2.

could also bin in azimuthal angle, $\varphi$.

(moments in $\varphi$?)

vs centrality: fewer domains in peripheral => bigger fluc.'s

$dN/dy$ = # domains => fluc.'s ~ $\sqrt{dN/dy}$.

Model does *not* apply for very peripheral (ie, pp) collisions.

# Kaon Fluctuations

No detailed calculations, so make general comments:

In pp collisions, K/π ~ 10%; K/π ~ 15% for most central coll's @ RHIC
Large increase in K <p_t>, ~ increase in transverse flow

Assume condensate field produces hadrons:

Domains with larger K/π ratio should have more energetic K's;
domains with smaller K/π, less energetic K's.

Correlations between fluctuations in K/π, <p_t> for different species,
tell us *very* detailed properties of particle production.

Need sufficient statistics to compute fluctuations in *many* variables.

Using smaller bins (in rapidity, angle, etc) will help enhance fluc.'s

# Dynamical Kaon Production

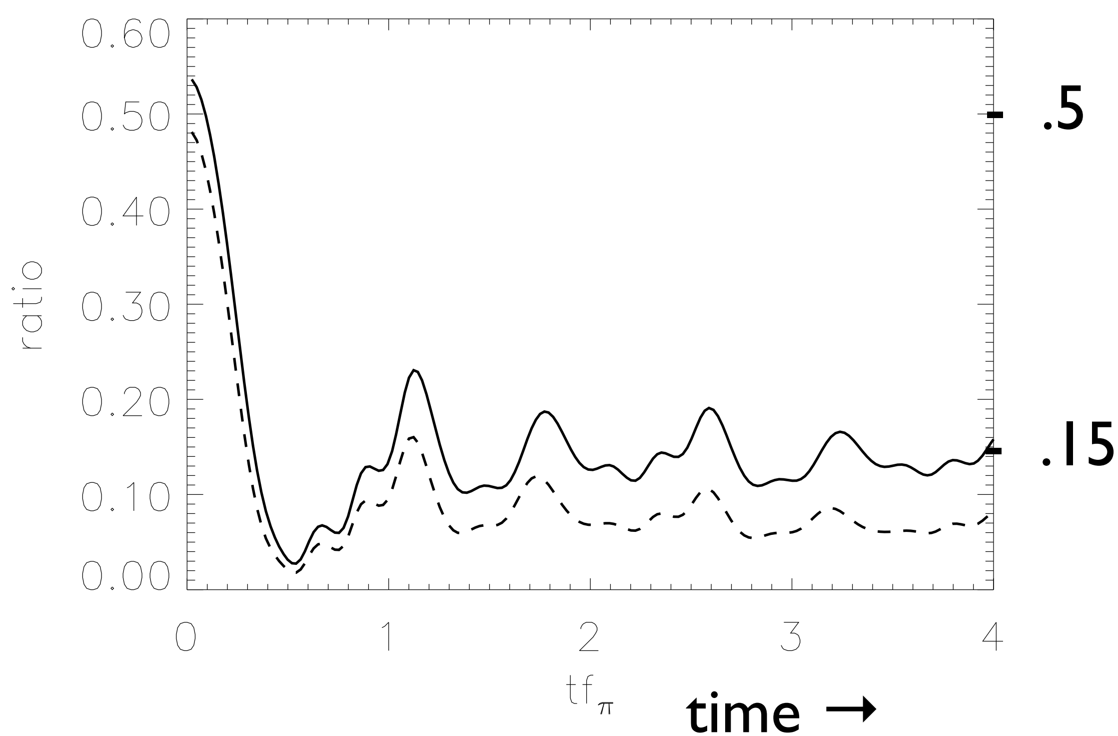
Scavenius, Dumitru, & Lenaghan '01

Semiclassical production of pions, kaons... by coupling to loop.

Originally, K/π ratio large, then decreases due to kaon mass:

K/π ratio ↑
(solid line)

η/π ratio
(dashed line)




Different domains will exist with spread in K/π ratio, K <p_t>, etc.

# Approximate symmetries

Why we know there is chiral symmetry: pions (K's...) are *light*.

Usual manifestation of approximate symmetry, when the symmetry is *broken* in the ground state.

Chiral symmetry broken in the low temperature phase, so pions... remain light until the symmetry is restored, $T < T_c$.

Z(3) gluonic symmetry: the symmetry is only broken in the *deconfined* phase, $T > T_c$, and not in the confined phase.

Hence not apparent in the spectrum of confined particles; one has to go near the transition.

About the transition, and only there, the field for the Polyakov loop is light. Unlike most broken sym.'s.

# Z(3) symmetry

Consider gauge theory with *out* dynamical quarks.

Add "test" quarks. For each, additive quantum number.

Confinement => states are neutral under this new quantum #

+1 for each quark, -1 for each anti-quark.

Meson: +1 - 1 = 0, so possible state.

Baryon = 3 (+1) = 3. So define quantum number modulo 3.

Then baryon charge 0, possible state.

Easier way: each test quark has phase $e^{2\pi i/3}$

Meson: $e^{-2\pi i/3}e^{2\pi i/3} = 1$ Baryon: $\left(e^{2\pi i/3}\right)^3 = 1$

Confinement => only states with phase = 1 can propagate.

# Global Z(3) from Local SU(3)

These phases form a group of Z(3).

't Hooft ('79): this global Z(3) is *part* of a *local* SU(3) (c/o quarks!)

Take gauge transformation $\Omega = \exp(2\pi i/3)$

Perfectly fine gauge transformation for SU(3) gauge theory:

$$\Omega^\dagger \Omega = \mathbf{1} \quad , \quad \det(\Omega) = 1$$

N.B.: det = 1 is same condition as baryon is neutral

Only 3 phases possible: transf. must be same *everywhere* => *global* sym.

Gluons don't change! $A_\mu \rightarrow \Omega^\dagger A_\mu \Omega = \exp(-2\pi i/3) A_\mu \exp(2\pi i/3) = A_\mu$

Test quarks do: $q_{test} \rightarrow \exp(2\pi i/3) q_{test}$

# Test Quarks

Even though we have a theory with*out* dynamical quarks, we can still speak of test quarks.

Suppose one puts, by hand, an *infinitely* massive quark at some point x. All it can do is propagate up in time (= imaginary time at T ≠ 0)

This *test* quark still carries color, though, which it can exchange with the medium. Thus we can use it to probe how the system responds to an external source.

Wilson line = color Aharonov-Bohm phase = *propagator* of test quark:

$$\mathbf{L} = \mathcal{P} \exp \left( ig \int_0^{1/T} A_0 \, d\tau \right)$$

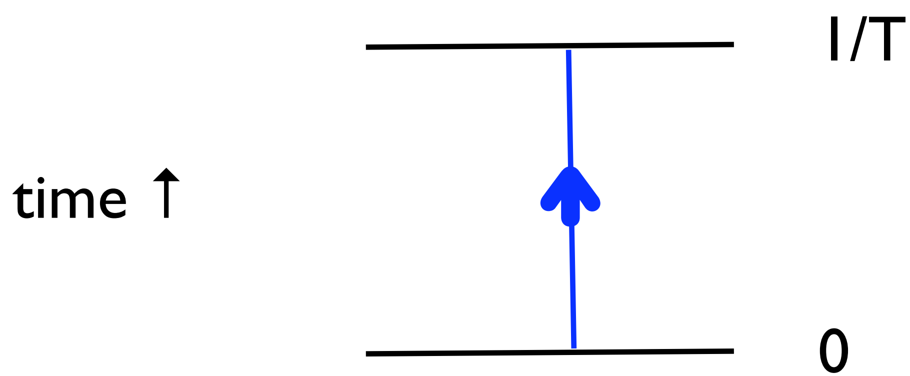
# Polyakov Loops

Wilson line = color matrix, so cannot be gauge invariant.

To form gauge invariant quantity, take color trace =

Polyakov loop: $\ell = \dfrac{1}{3}\,\mathrm{tr}\,\mathbf{L}$

This is the *trace* of the propagator for the test quark.

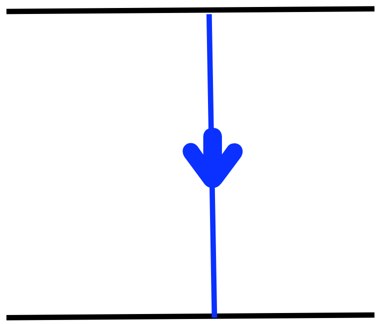



It is a loop, because in (imaginary) time, you start and end at the same place (periodic boundary conditions in imag. time for bosons)

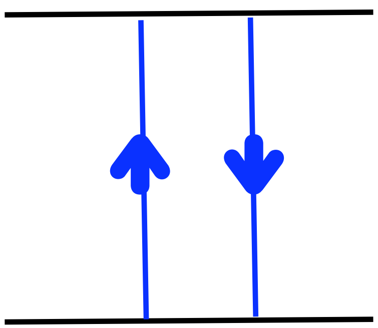
# Test Quarks and Z(3)

test anti-quark = test quark going back in (imag.) time

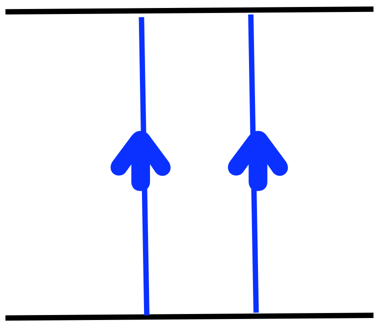
$$= \mathbf{L}^\dagger$$



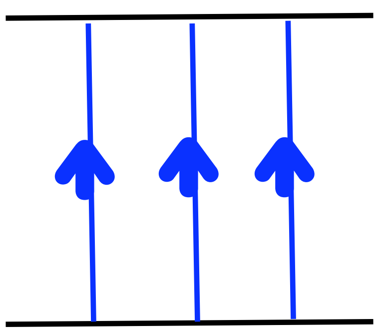
test meson = test quark + test anti-qk.



test di-quark = two test quarks



test baryon = three test quarks



and so on. group theory = ways of combining test quarks & anti-quarks

# Test Quarks, Loops, and Z(3)

Under the global Z(3), each test quark transforms like *one* Z(3) factor:

$$\mathbf{L} \rightarrow e^{2\pi i/3}\ \mathbf{L}$$

Test anti-quarks must (of course) transform in the opposite way, as

$$\mathbf{L}^{\dagger} \rightarrow e^{-2\pi i/3}\ \mathbf{L}^{\dagger}$$

Loops are just traces, so don't change the Z(3) charges:

$$\ell_{qk} \rightarrow e^{2\pi i/3} \ell_{qk} \qquad \ell_{\overline{qk}} \rightarrow e^{-2\pi i/3} \ell_{\overline{qk}}$$

$$\Updownarrow$$

$$\ell_{di-qk} \rightarrow e^{4\pi i/3} \ell_{di-qk} = e^{-2\pi i/3} \ell_{di-qk}$$

*Test* mesons and baryons have no Z(3) charge, so don't change:

$$\ell_{meson} \rightarrow \ell_{meson} \qquad \ell_{baryon} \rightarrow \ell_{baryon}$$

# Confinement and Z(3)

Confinement => quarks don't propagate. So:

$$\langle \ell \rangle = 0 \quad , \quad T < T_{deconf}$$

That is, the expectation value of the (triplet) loop is an order parameter!

$T_{deconf}$ = temperature for the deconfining phase transition.

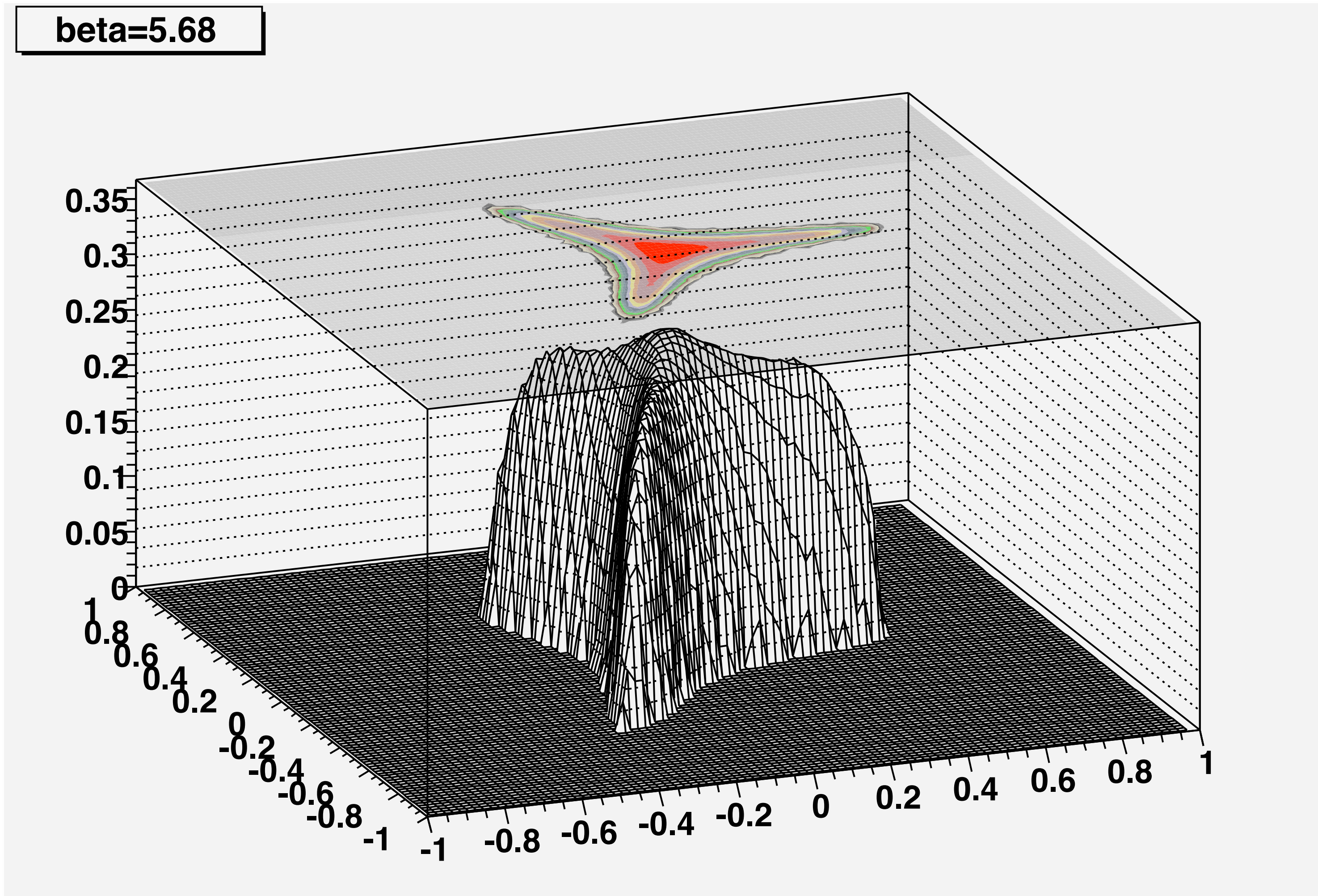
Conversely, deconfinement => quarks do propagate:

$$\langle \ell \rangle \neq 0 \quad , \quad T > T_{deconf}$$

Loops for test anti-quarks, and test di-quarks, are also zero below T_d.

Loops for test mesons and baryons can be non-zero at any temperature, at least in principle.

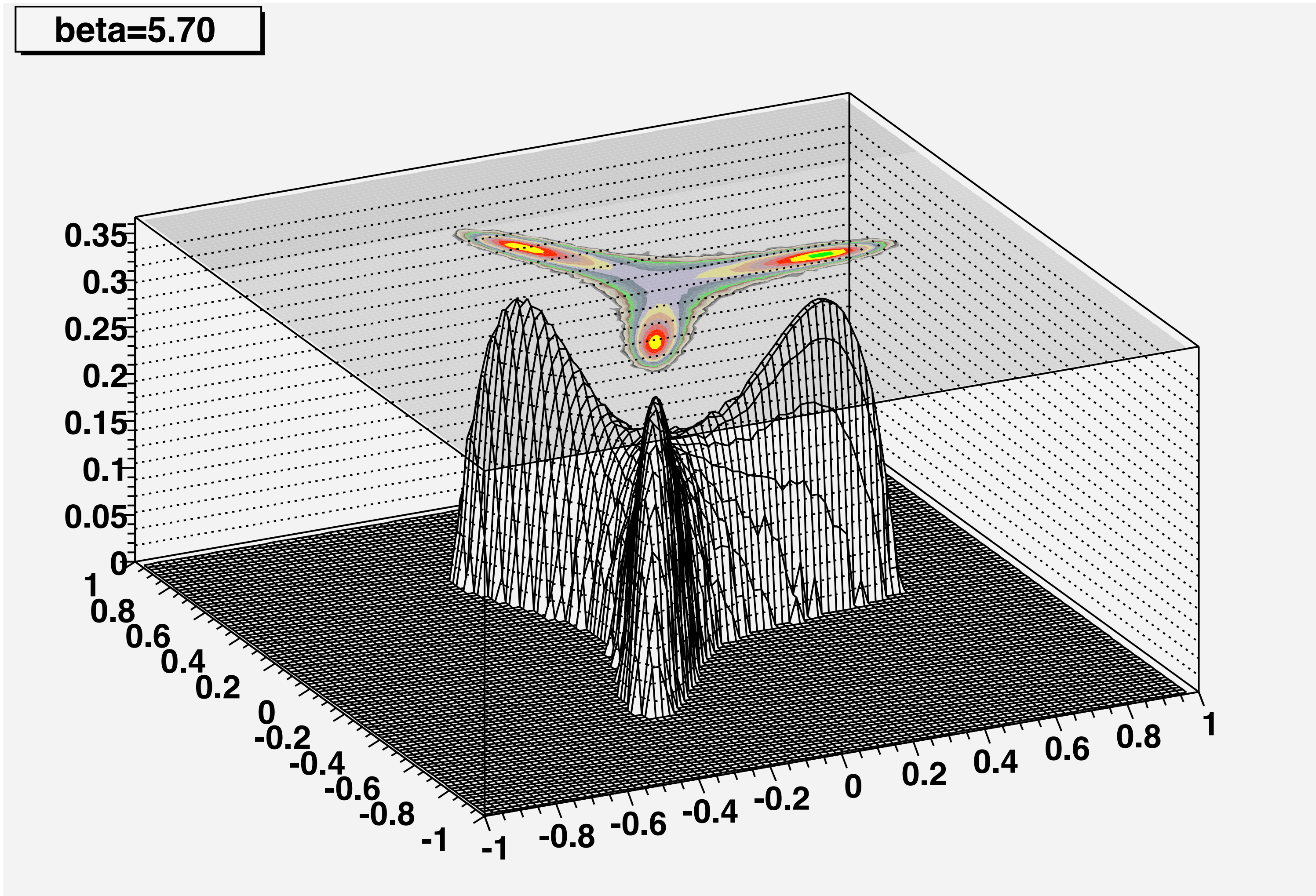
# Histograms of Loops: Confined Phase




Confined phase: expectation of loop = 0.

(Axes real and imaginary parts of loop; height ~ probability.)

# Histogram of Loops: Deconfined Phase




Deconfined phase: *three* degenerate vacua for broken Z(3) symmetry.

# From Bare to Renormalized Loops

Even infinitely massive (test) quarks have mass renormalization ~1/a,
a = lattice spacing. Still, can extract *renormalized* loops from bare:

(Dumitru, Lenaghan, Hatta, Orginos, & RP '03)

Measured following loops for three colors, NO dyn. quarks:

test quark = triplet; test anti-quark = anti-triplet

test di-quark = sextet

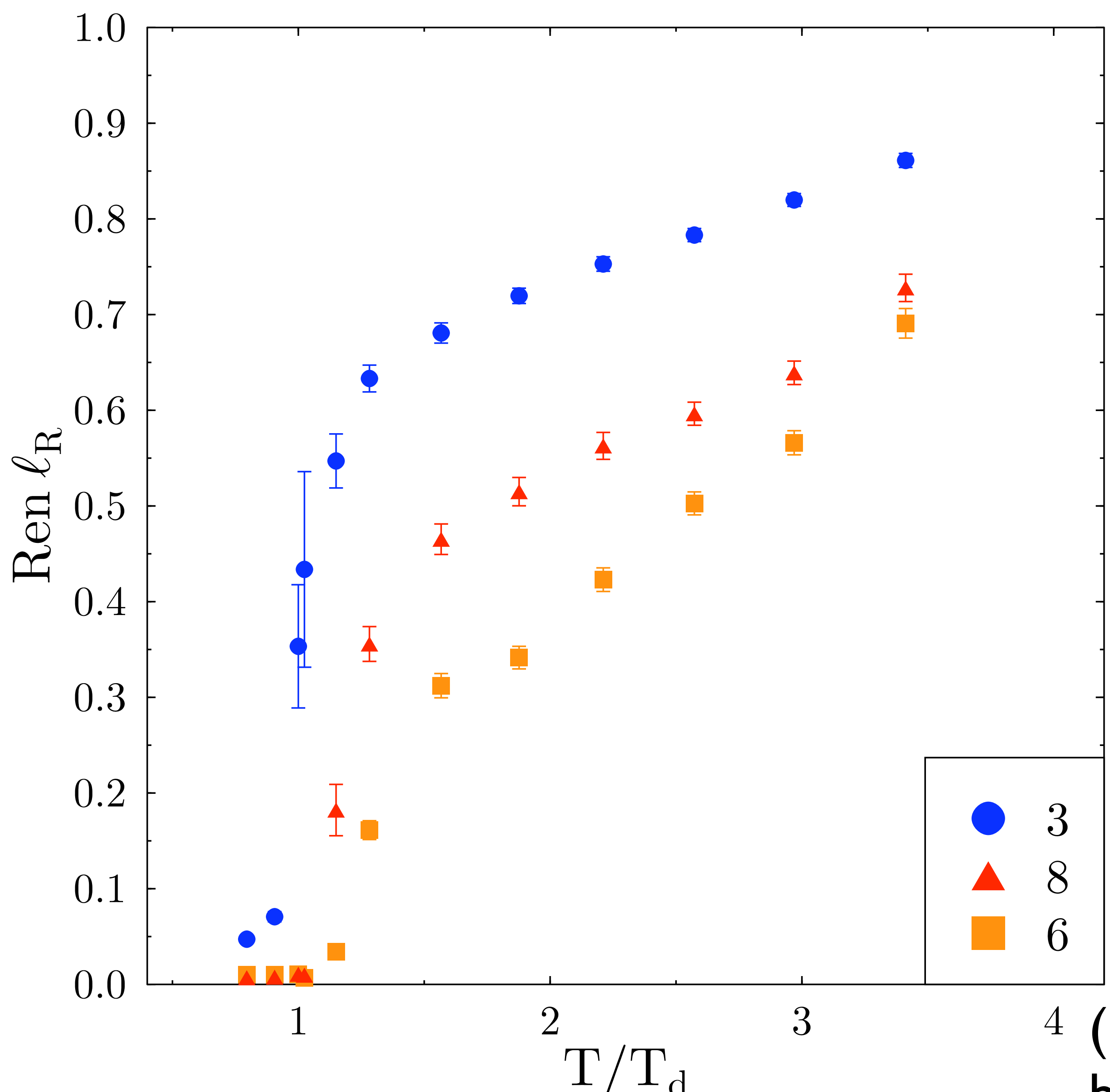
test meson = octet test baryon = decuplet

*Long* song and dance. Relatively simple understanding of the results.

(Ren.'d triplet loop similar, not identical, to Bielefeld prescription.)

# Renormalized Loops from the Lattice

Ren.'d ↑
Loops




test quark
= triplet

test meson
= octet

test di-quark
= sextet

(Looked for test baryon, too small for tech. reasons

# Lattice Ren.'d Loops: cont.'d

See *no* signal for "test meson" *below* T_d:

Polyakov loops appear to dominate for *all* temperatures

Phen.'y: coupling of Polyakov loops to mesons, baryons, dominate particle production (*with* dynamical quarks)

Technical details: find sextet, octet loops ≈ triplet loop squared.

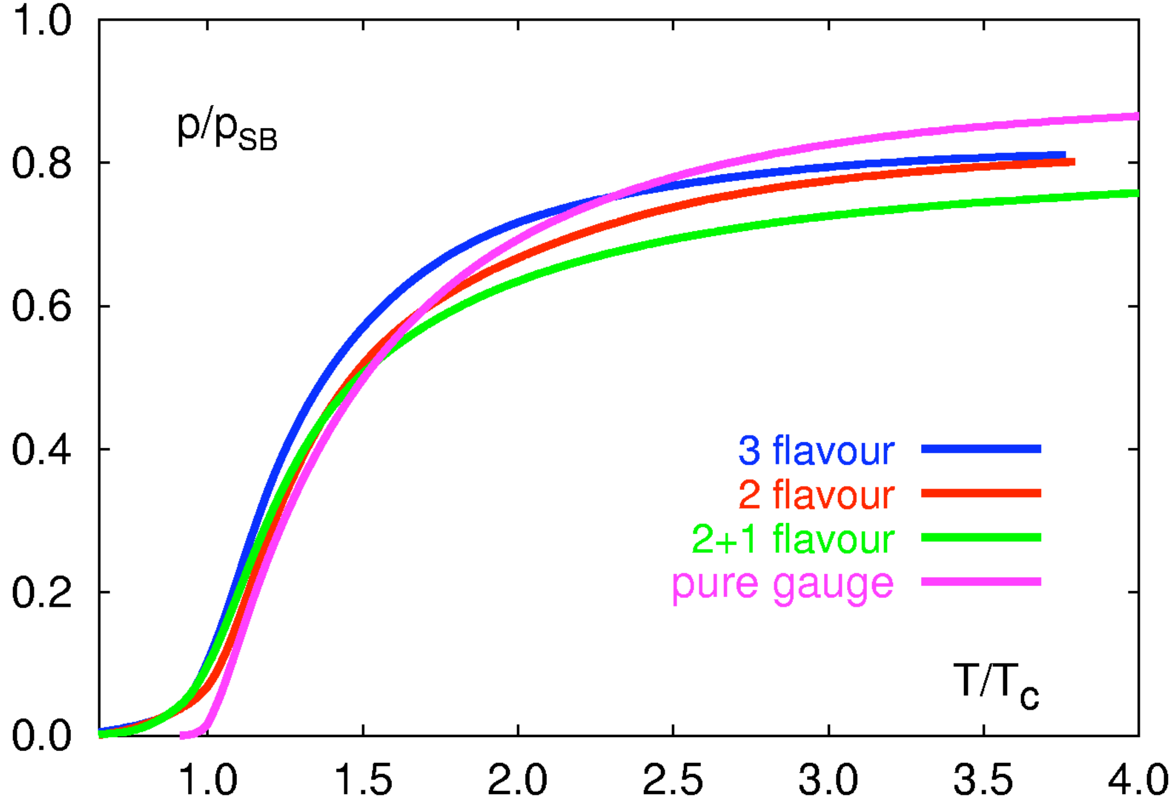
Gives *qualitative* measure that three colors is close to an infinite number, in terms of 1/N expansion (N = # colors).

Also shows that an effective theory with triplet + small admixture of sextet loop is a very good approximation.

# What about dynamical quarks?

Lattice finds remarkable result: $p/p_{ideal}(T/T_c) \approx universal$

pressure/
ideal pressure




Bielefeld

T/T_c =>

Flavor independence: pressure *with* dynamical quarks ~ that without

Due to dominance by Polyakov loops? Need *ren.'d* loops *with* dynamical qks!