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Long Range Force and Y-Bosonic strings in Baryons

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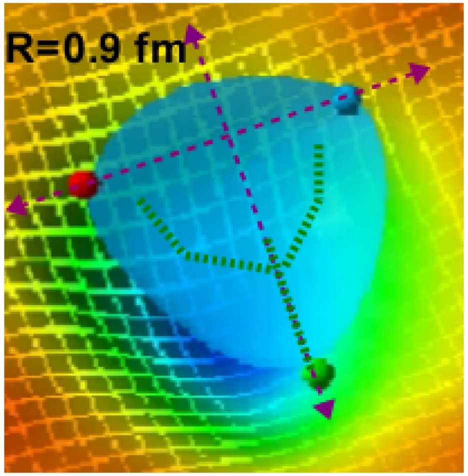

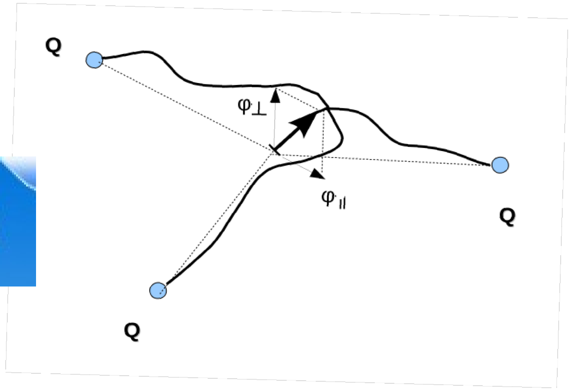

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Abstract:

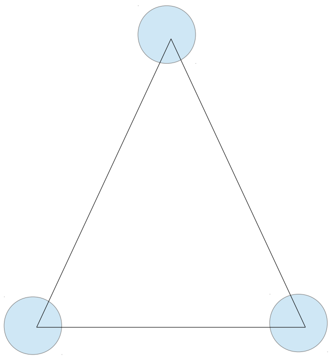
The potential due to system of a three static quark (3Q) is studied using SU(3) lattice QCD at finite T. The (3Q) potential is calculated in pure SU(3) Yang-Mills lattice gauge theory at finite temperature with Polyakov loops operators. In this work, we focus on the relation between the parametrization ansatz of the (3Q) potential and the observed form of the strings in the baryon. The interesting result is that, although the gluonic pattern is a Δ-shaped, the lattice data for the potential fits well to a Y -shaped string pattern. Moreover, we found that the fit to the Y -law reproduces the quark anti-quark string tension provided a Dedekind η function accounting for string fluctuation, with leading Luscher-like corrections, is included in the fit ansatz.

We look further into the signatures of the effective Y-bosonic strings in the gluonic energy profile . The analysis of the density unveils a filled-Δ distribution. However, we found that these Δ-shaped density profiles are structured from three Y-shaped Gaussian-like tubes. The geometry of the Y-shaped Gaussian strings changes according to the quark configuration and temperature such that an angle of 2pi/3 is always kept between the strings. The lattice data for the mean-square width of the gluonic action density have been compared to the corresponding width calculated based on the string model at finite temperature. We assume Y-string configuration with minimal length. The growth pattern of the action density of the gluonic field fits to junction fluctuations of the Y-baryonic string model for large quark separation at the considered temperatures.

Our results promote for a new lattice picture of the baryonic strings: The energy profile is always a Δ shape type, however, the baryonic potential is consistent with a Y-law describing a system of fluctuating strings and giving rise to a Δ flux, at large distances.

Lattice QCD findings regarding the 3-quark potential are settled about a confining potential that admits two possible models depending on the inter-quark separation distances.

$$V_{qqq}(\vec{r}_1, \vec{r}_2, \vec{r}_3) \approx \frac{1}{2} \sum_{i<j} V_{q\bar{q}}(r_{ij})$$



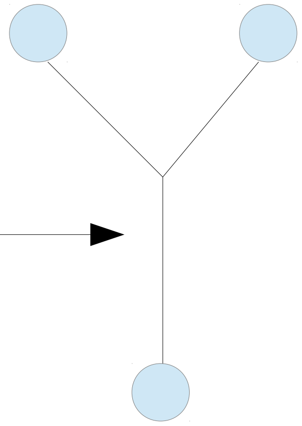
The so-called Delta parametrization for small quark separation distances of R<0.7 fm and the Y-ansatz for R >0.7 fm.

C. Alexandrou, P. de Forcrand, and O. Jahn, Nucl. Phys. Proc. Suppl. 119, 667 (2003), hep-lat/0209062.

T. T. Takahashi, H. Suganuma, Y. Nemoto, and H. Matsufuru, Phys. Rev. D 65, 114509 (2002).

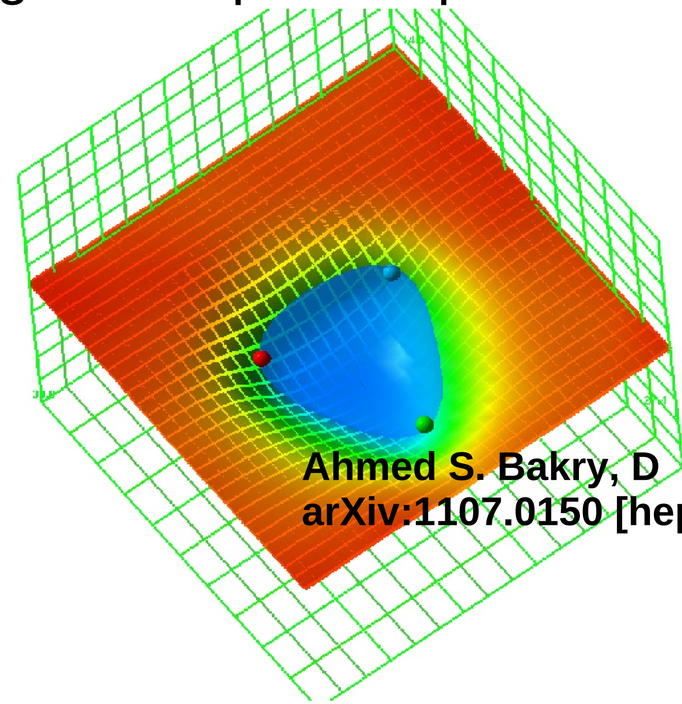
$$V_{3\mathrm{Q}} = -A_{3\mathrm{Q}} \sum_{i<j} \frac{1}{|\mathbf{r}_i - \mathbf{r}_j|} + \sigma_{3\mathrm{Q}} L_{\min} + C_{3\mathrm{Q}},$$

Genuine three-body force



N. Brambilla, J. Ghiglieri, and A. Vairo, Phys.Rev. D81,054031 (2010), 0911.3541. (Perturbative calculations)

- Unexpected filled Δ-shaped flux arrangement surprisingly persists to large inter-quark separations.



Ahmed S. Bakry, D Leinweber, Tony Williams, Phys Rev D91, 094512(2015)
arXiv:1107.0150 [hep-lat]

- A baryonic string model indicates Lüscher-like terms that has been addressed in 3 Potts model.

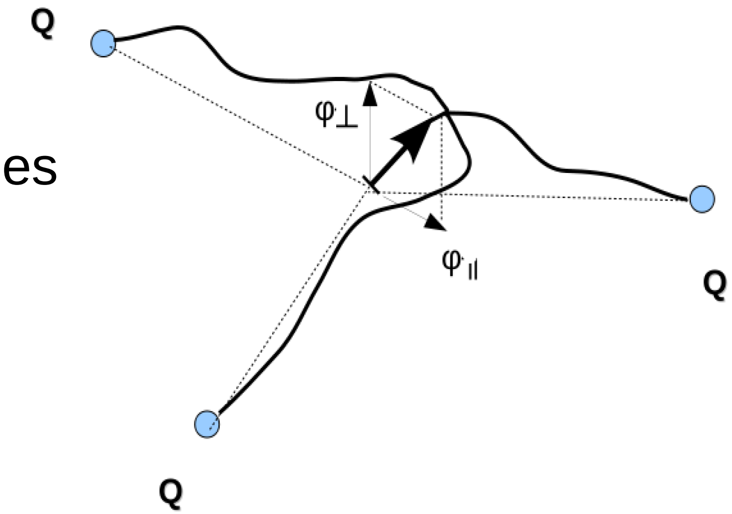
O Jahn and Ph. Deforcrand, hep-lat/0209062, Ph. De Forcrand and O. Jahn, N phys A 755(2005)

Baryonic String Picture

Model assumptions

The elementary constituents of hadronic matter (quarks) are confined together due to formation of very thin flux tubes.

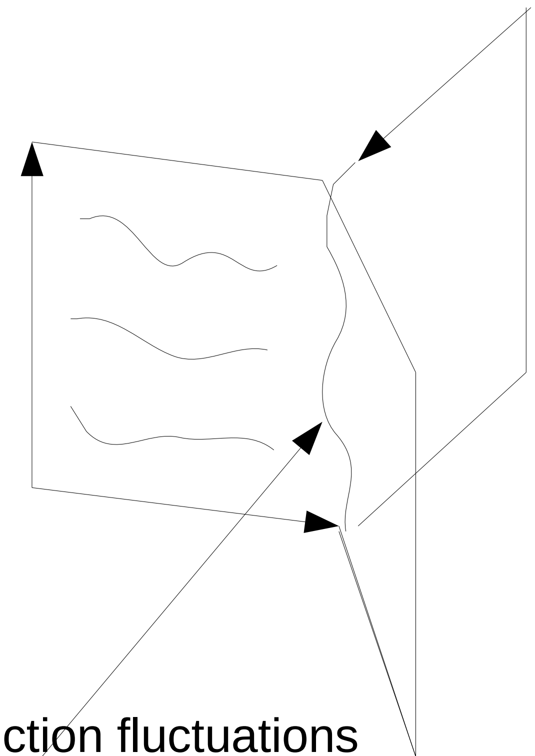
In the Y-baryonic string model. The quarks are connected by three strings that meet at a junction.



The classical configuration is the one that minimizes the area of the string world sheets.

The position of the junction is determined
by the requirement of minimal total string length.

- The most natural choice for the string action S is the Nambu–Goto action which is proportional to the surface area of the world sheet.



$$S[X] = \sigma \int d\zeta_1 \int d\zeta_2 \sqrt{g},$$

$g_{\alpha\beta}$ is the two dimensional induced metric on the blade world sheet embedded in the background R4.

$$g_{\alpha\beta} = \frac{\partial X}{\partial \zeta_\alpha} \cdot \frac{\partial X}{\partial \zeta_\beta}, \quad (\alpha, \beta = 1, 2),$$

$$g = \det(g_{\alpha\beta}).$$

The string partition function is a Gaussian integral over the junction fluctuations

$$Z = e^{-(\sigma L_Y + m) L_T} \int D\varphi \ \exp\left(-\frac{m}{2} \int dt \, |\dot{\varphi}|^2\right) \prod_{i=1}^{3} Z_i(\varphi),$$

$$Z_i(\varphi) = \int_\varphi D\xi_i \ \exp\left(-\frac{\sigma}{2} \int |\partial \xi_i|^2\right)$$

The partition function for the fluctuations of a given blade that is bounded by the junction worldline φ(t)

$$\mathrm{V}_{qqq}(L_1, L_2, L_3) = \sigma \sum_i L_i + V_{\|} + V_{\perp} + O(L_i^{-2}) \,,$$

with

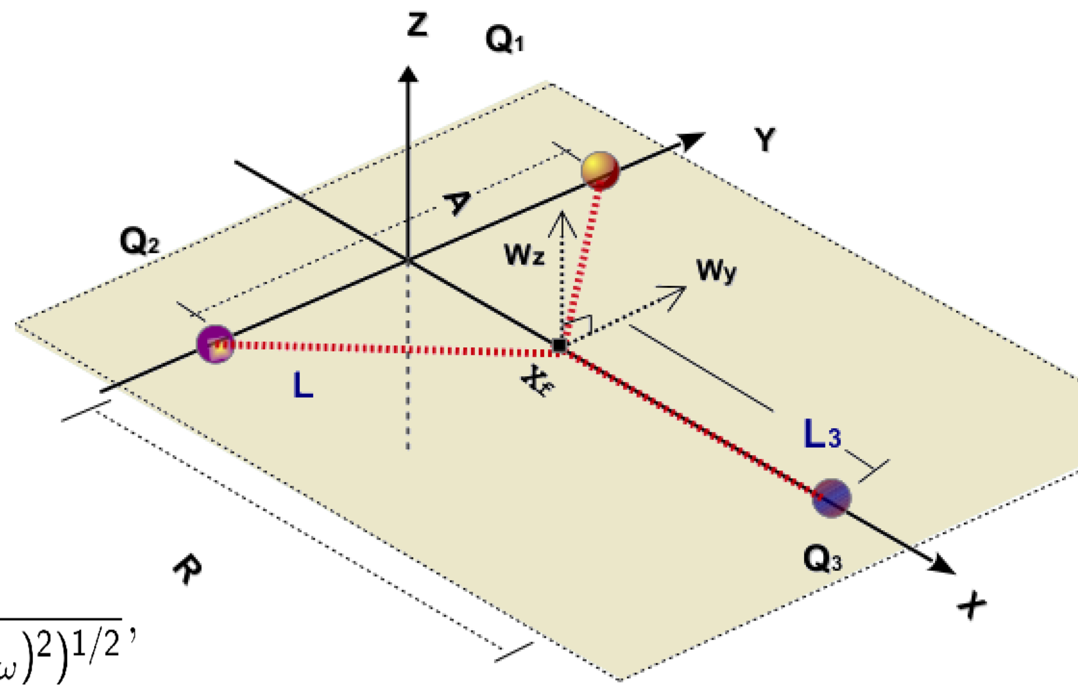
$$V_{\|} = -\frac{\pi}{24} \sum_i \frac{1}{L_i} + \int_0^{\infty} \frac{dw}{2\pi} \ln \left[\frac{1}{3} \sum_{i<j} \coth(wL_i) \coth(wL_j) \right] \,,$$

$$V_{\perp} = -\frac{\pi}{24} \sum_i \frac{1}{L_i} + \int_0^{\infty} \frac{dw}{2\pi} \ln \left[\frac{1}{3} \sum_i \coth(wL_i) \right] \,.$$

The first test of the baryonic string model predictions with LGT at zero temperature has been reported by Deforcrand and Jahn considering 3 Potts model for a three quark potential.

The numerical measurements of the 3-state Potts gauge model are consistent with the predicted Lüscher-like corrections and the formation of a Y-system of three flux tubes.

The junction fluctuations decomposed into perpendicular



$$\langle \phi_z^2 \rangle = \frac{2}{L_T} \sum_{\omega>0} \frac{1}{k\omega^2 + \sigma\omega \sum_i \coth(\omega L_i)\psi(\omega, L_i)}.$$

and parallel fluctuations

$$\langle \phi_x^2 \rangle = \frac{2}{L_T} \sum_{\omega>0} \frac{1}{Q_{x,\omega} + Q_{y,\omega} - (Q_{xy,\omega}^2 + (Q_{x,\omega} - Q_{y,\omega})^2)^{1/2}},$$

$$\langle \phi_y^2 \rangle = \frac{2}{L_T} \sum_{\omega>0} \frac{1}{Q_{x,\omega} + Q_{y,\omega} + (Q_{xy,\omega}^2 + (Q_{x,\omega} - Q_{y,\omega})^2)^{1/2}}.$$

to the 3 quark plane would read as a sum over Fourier modes as above.

$$Q_x = \left(k\omega^2 + \sigma\omega \sum_i \coth(\omega L_i)\psi(\omega, L_i) \right) +$$
$$\left(\frac{\sigma}{2}\omega + \frac{\omega^3}{12\pi} \right) \left[\sum_i \eta_{i,x}^2 \coth(\omega L_i)\psi(\omega, L_i) \right] ,$$

The string fluctuations are smoothed and decoupled to make it more convenient to compare with lattice data at finite temperature.

Simulation set-up

The gauge configurations were generated using the standard Wilson gauge action.

The two lattices employed are of spatial size corresponding to N_s=36, and temporal extents corresponding to N_t=,10, 8.
beta=6.0, lattice spacing a=0.1 fm.

Bins of 20 measurements separated by 70 sweeps of updates.
Each bin of measurements is taken following a 2000 of updating sweeps.

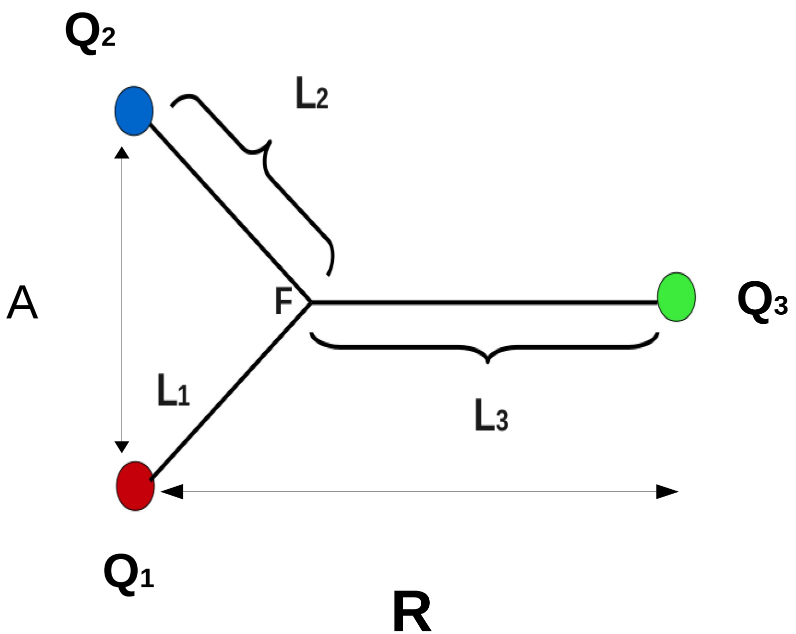
500 bins corresponding to 10,000 measurement at each temperature.

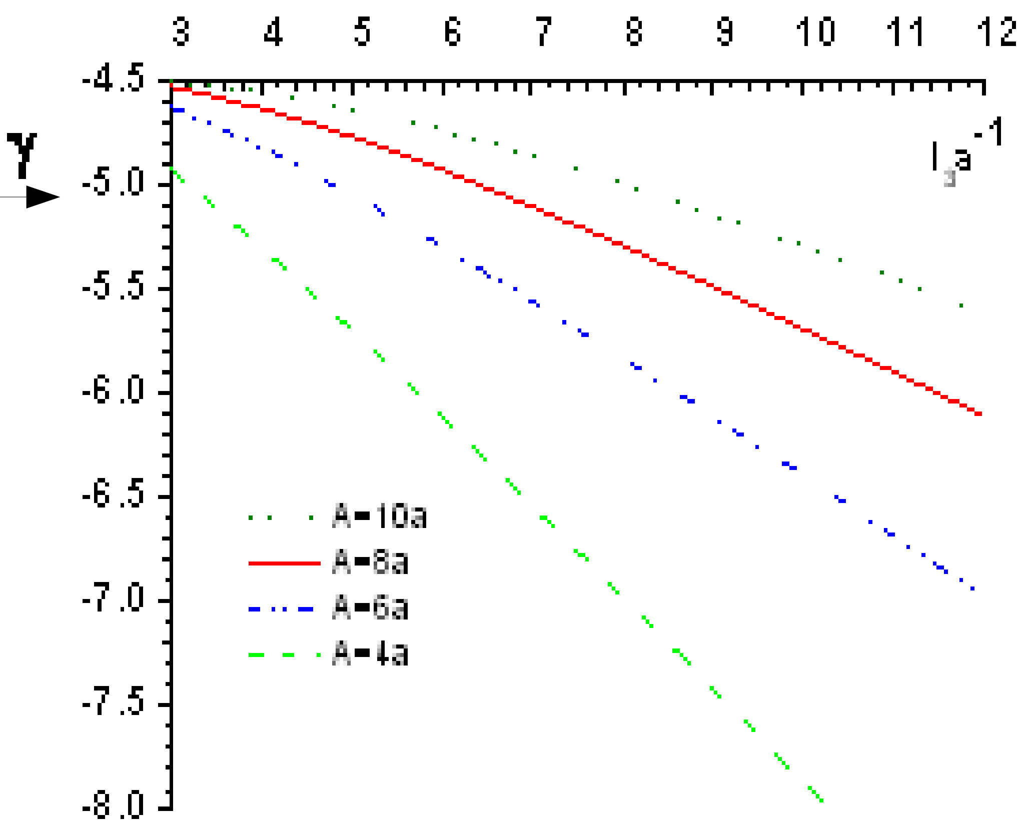
Potential of a Y-string Model at finite temperature

It can be shown that the 3Q potential is given by a sum of term proportional to minimal length of the Y-string in addition to Dedkind eta function accounting for the Gaussian string fluctuations.

$$V_{3Q} = \sigma L_Y - \frac{\gamma}{T}\eta\left(\frac{iT}{2L_Y}\right),$$

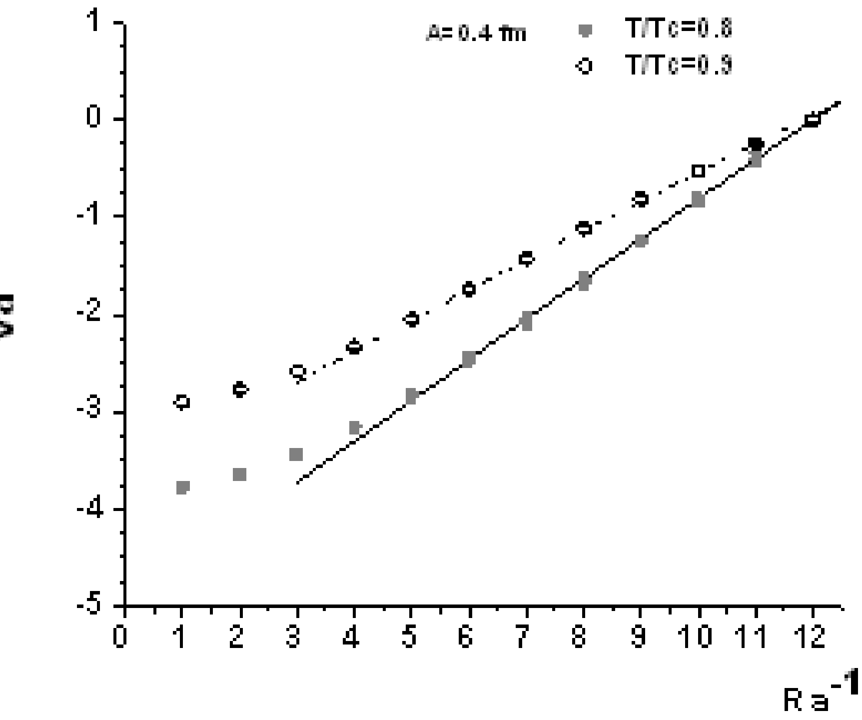
This formula should be distinguished from the the bare Y-ansatz, which does not include the string corrections.

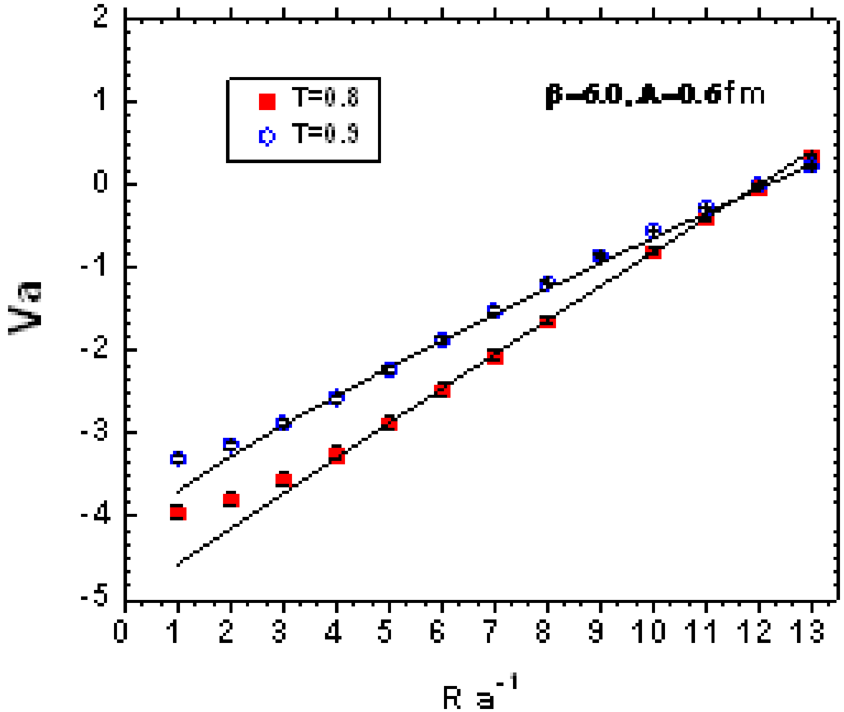




The string model's geometrical factor calculated for four different isosceles bases versus the third string length.

Returned fits of the 3Q potential to Y-string Model





Fits of the lattice 3Q potential to the Y- string potential. The above two figures are for 3Q isosceles triangular configuration with two base length 0.4 fm and 0.6 fm.

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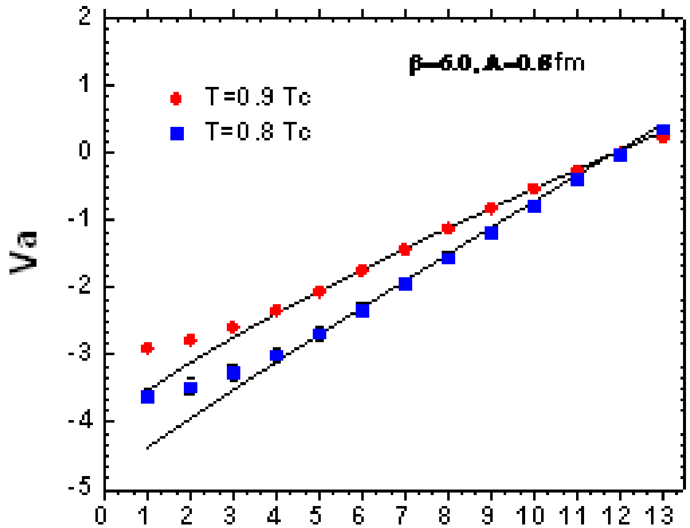
Although the profile of the energy density is a filled Delta, the 3Q potential fits essentially good to the Y-ansatz derived from string model.

The returned fits shows that we obtain the same string tension as QQ, provided that we consider the effects of the string fluctuations in the Gaussian approximation-



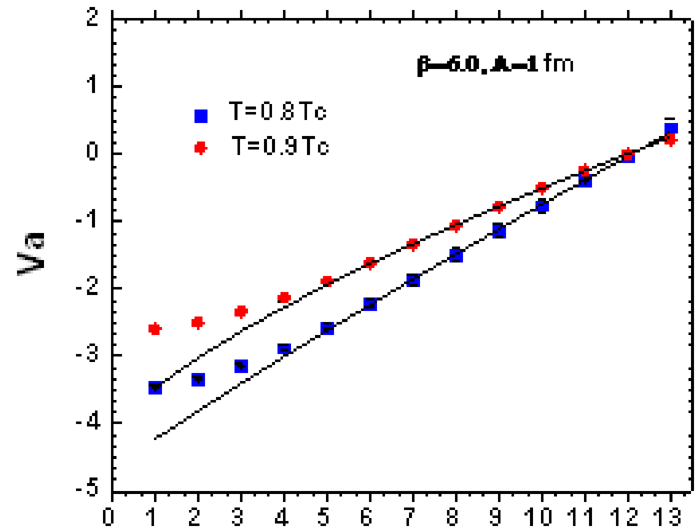


TABLE I: The returned values of the fit parameters in addition to $\chi^2_{\rm dof}(x)$ corresponding to fits to the lattice $3Q$ potential corresponding to the string model formula, the fits are for isosceles triangle quark configuration of base $A = 6\,a$, $A = 8\,a$ and $A = 10\,a$ at $T/T_c = 0.8$.

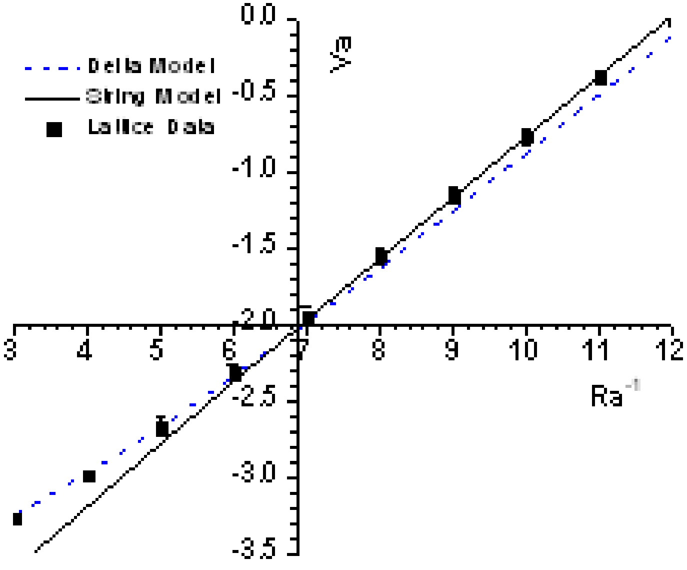
Fit Range	R=4-12			R=6-12			R=8-12		
Fit Parameters	σ	χ^2	C	σ	χ^2	C	σ	χ^2	C
$T/T_c = 0.8$									
$A = 4a$	0.42	2.8	-4.41	0.42	0.4	-4.42	0.42	0.3	-4.42
$A = 6a$	0.416	11.4	-4.15	0.42	1.1	-4.16	0.42	0.4	-4.16
$A = 8a$	0.42	13.7	-3.87	0.42	4.34	-3.88	0.42	2.1	-3.89
$T/T_c = 0.9$									
$A = 4a$	0.32	2.7	-3.17	0.32	1.8	-3.18	0.32	1.8	-3.18
$A = 6a$	0.32	14.4	-3.04	0.32	6.9	-3.03	0.32	1.1	-3.02
$A = 8a$	0.32	7.1	-2.76	0.32	2.3	-2.77	0.32	2.1	-2.77
$A = 10a$	0.32	18.8	-2.46	0.32	8.2	-2.47	0.32	3.5	-2.98

The Y-string quantum fluctuations at high temperature are encoded in the Dedkind eta function whose leading order expansion is the so-called Luscher-like terms

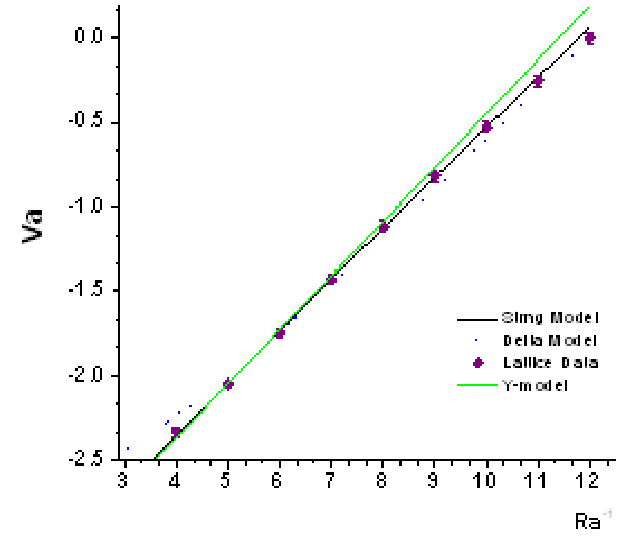
Y-string model versus Delta model and bare Y-model

The adjacent plot shows the success
of Y-string model in accounting for the 3Q
potential at large distances compared to
The Delta model-(two body force)-

At small distances, however, it seems that
a Delta ansatz is better than string model
at T/Tc=0.8.



The second plot is at higher temperature T/Tc=0.9
It even shows that a bare Y-ansatz without
string fluctuations terms poorly describes
the long distance range of the potential.



Summary of the results for the 3Q potential

- We discussed an extension to Y-string model at finite temperature.
- We found that the fit to the Y-law reproduces the quark anti-quark string tension provided a Dedekind η function accounting for string fluctuation is included in the fit ansatz.
- Comparison with the fit with the Δ-ansatz and even bare Y-ansatz, in some limits, shows that the Y-string model provides the best fits on the confinement part in the 3Q potential.
- The interesting result is that, although the gluonic pattern is a Δ-shaped, the lattice data for the potential fits well to a Y-shaped string pattern.

Lattice results for the energy density and Y-string model

In the next two section we show an analysis of the lattice data from two points of view.

First, we give a qualitative description of the rendered action density profile and show how the aspects of the distribution are consistent with the stringlike behavior.

Second, we directly compare the width profile of the action density with the string model fluctuations.

b)The Delta-action is a sum of three Y "Gaussian-Like flux tubes"

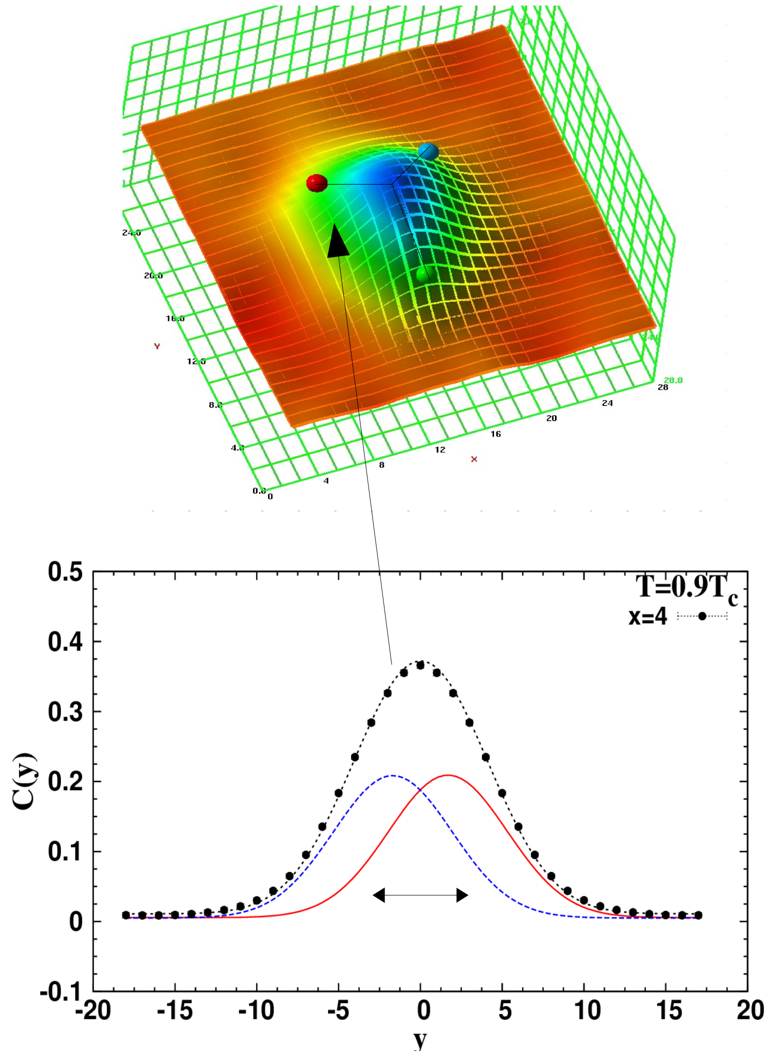
To unravel the configuration of the strings in the baryon, we explore the structure of the gluonic distribution with a general ansatz consisting of a two Gaussians

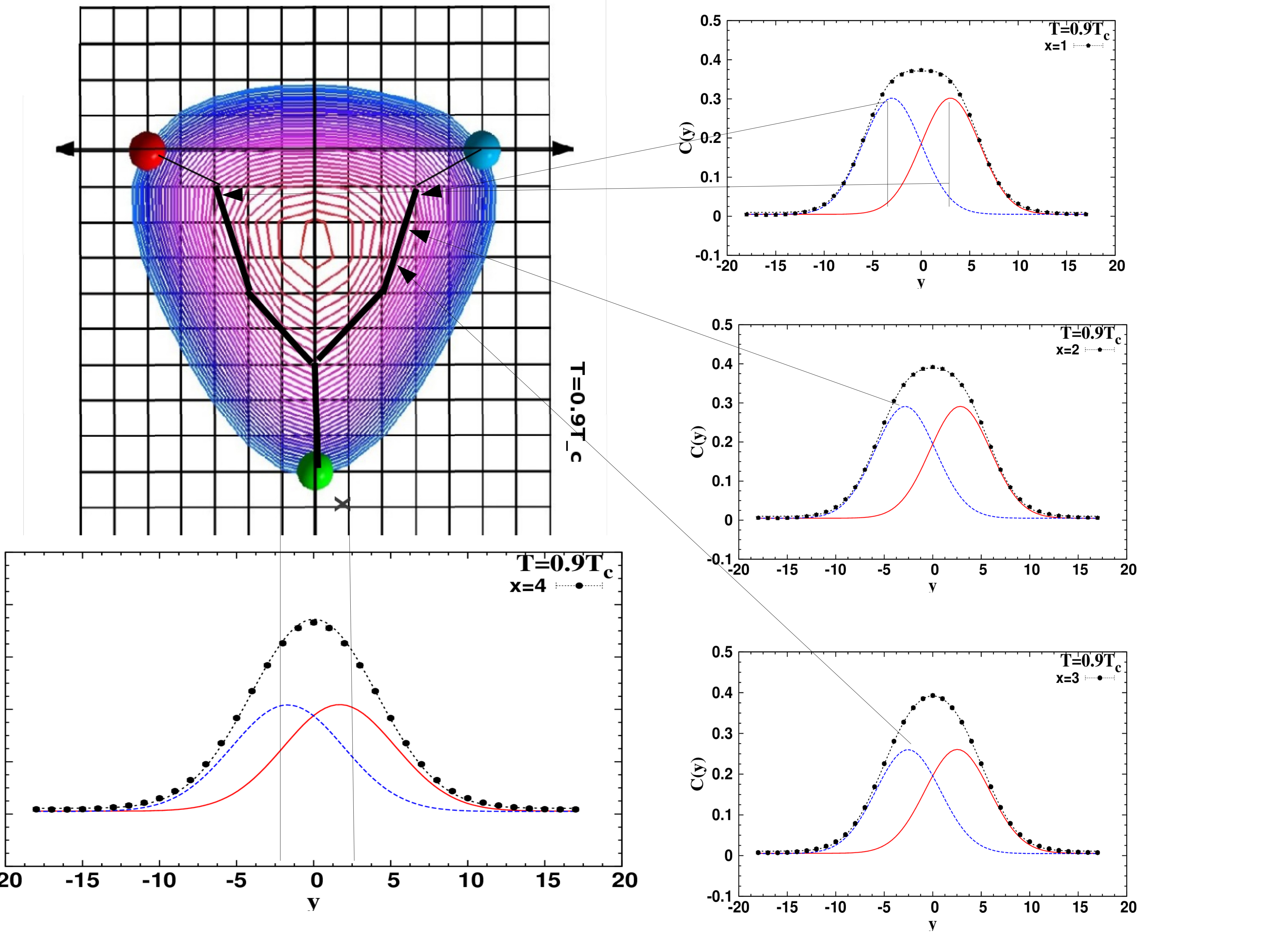
$$G(y; a, w) = A \exp(-(y-u)^2/W^2) + A \exp(-(y+u)^2/W^2).$$

The form assumes a region consisting of a system of two overlapping strings of the same strength A, and mean-square width.

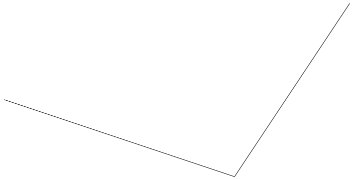
We scan the gluonic domain with the above fit function for all the distances x from the base A connecting the quarks Q1 and Q2 .

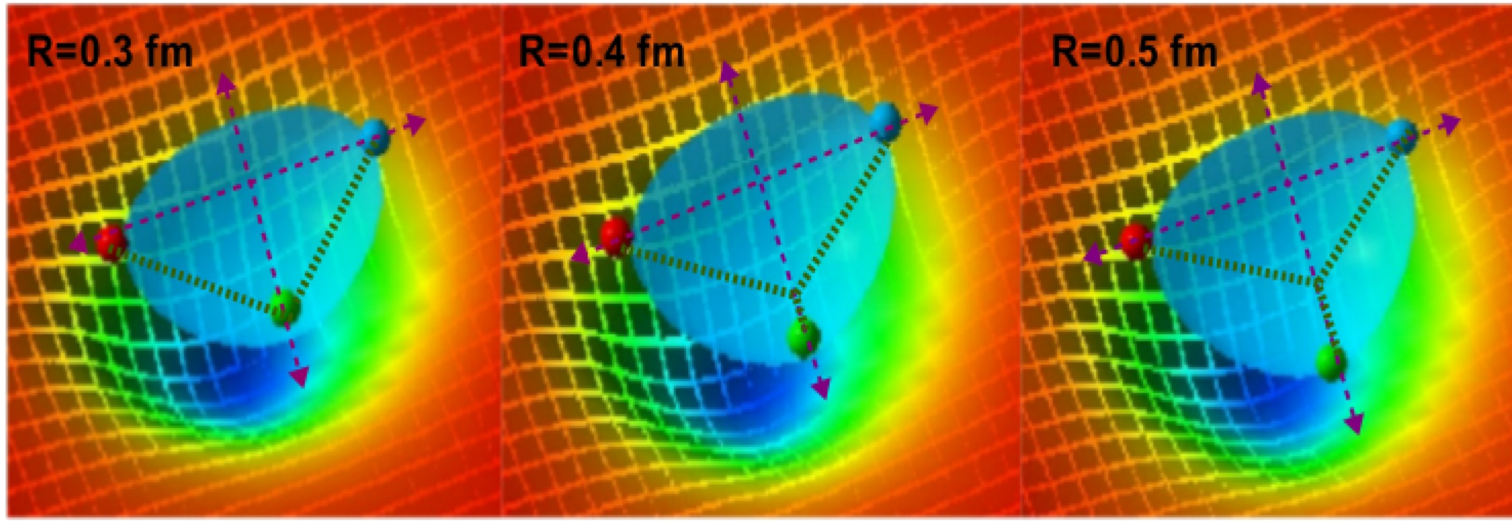
The interesting behavior comes from the returned values of the parameter u.

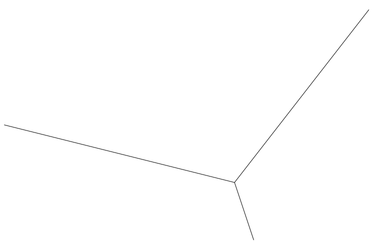




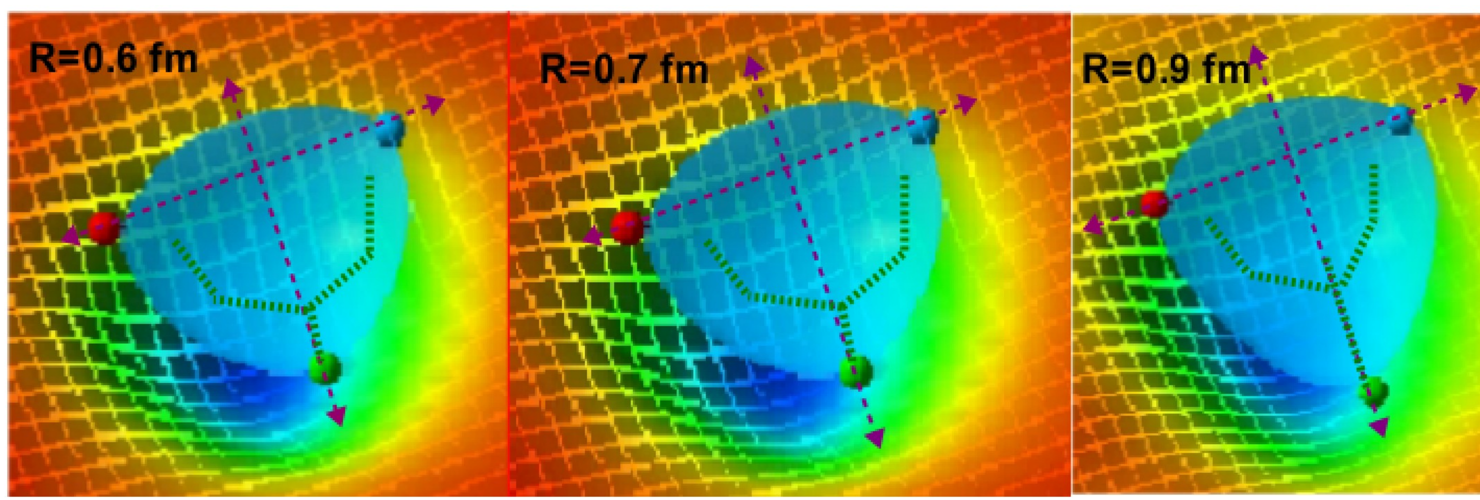
T=0.9T_c
T=0.9T$_c$
x=1
x=2
x=3
x=4
C(y)
y

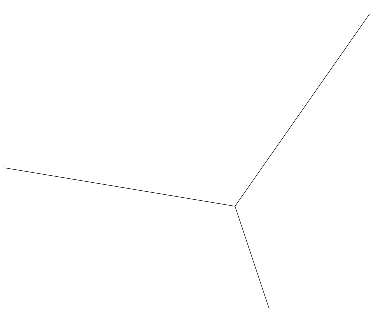






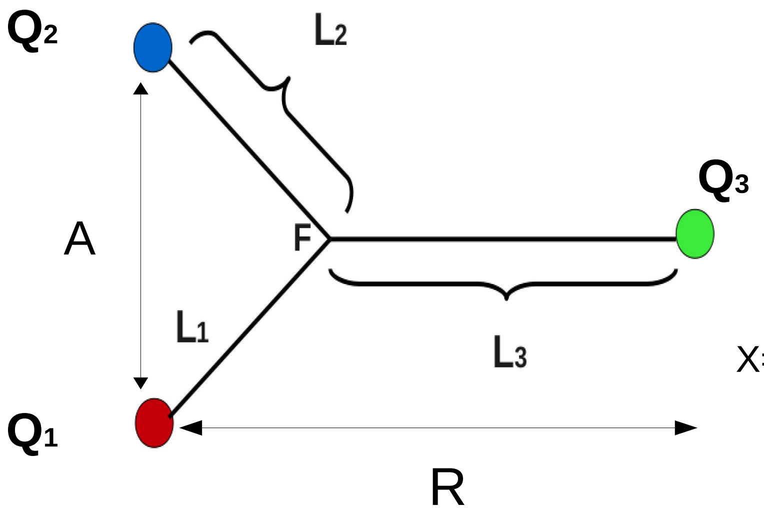
This a schematic plot of the profile of the two Gaussians superimposed over the rendered action density.





Returned fits of the gluon flux to the string width profile

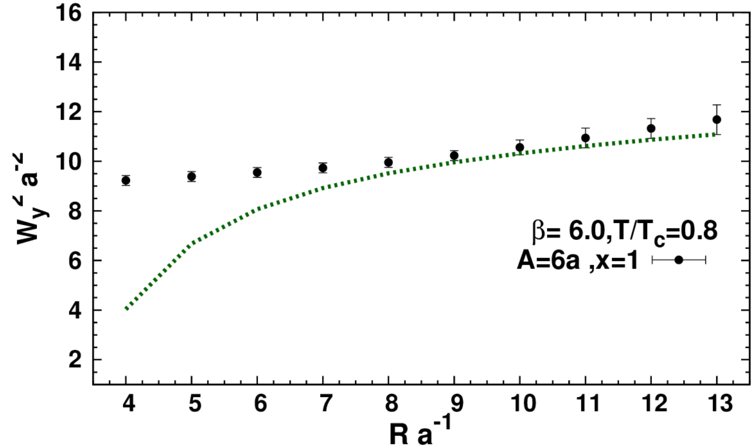
a) In-plane fluctuations



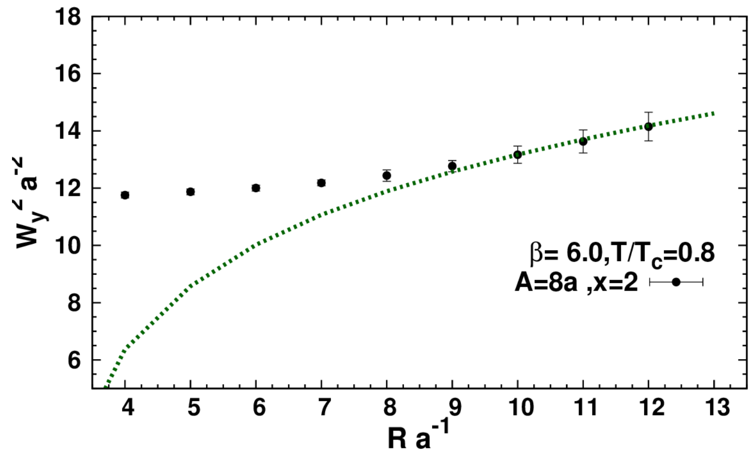
Fits of the junction's profile from string picture to the lattice data.

The broadening of the width versus the third quark separation R.

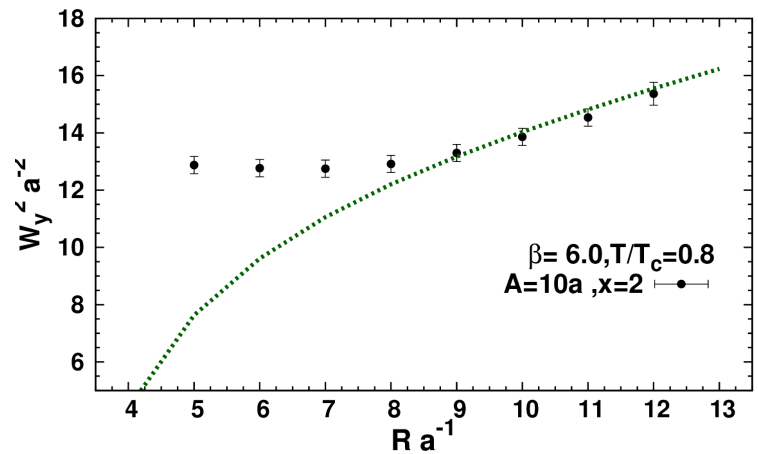
X=1, A=0.6 fm, X_f =1.7



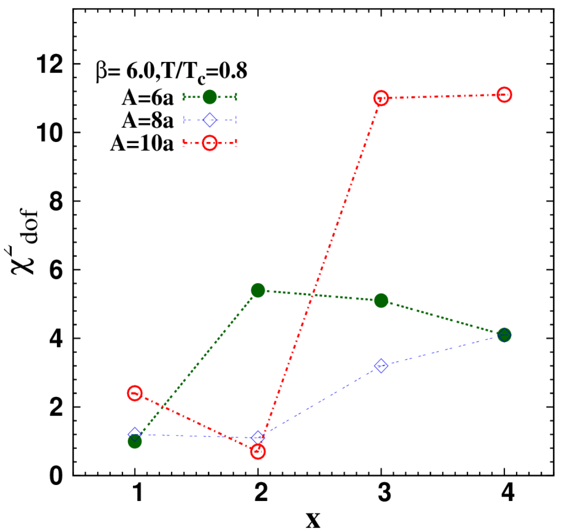
X=2, A=0.8 fm, X_f =2.3

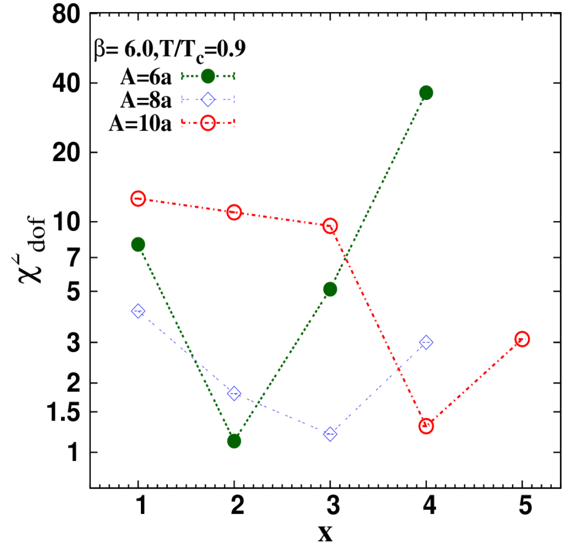


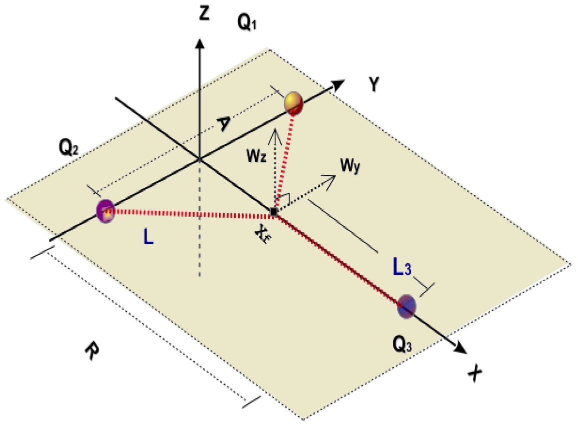
X=2, A=1.0 fm, X_f =2.9



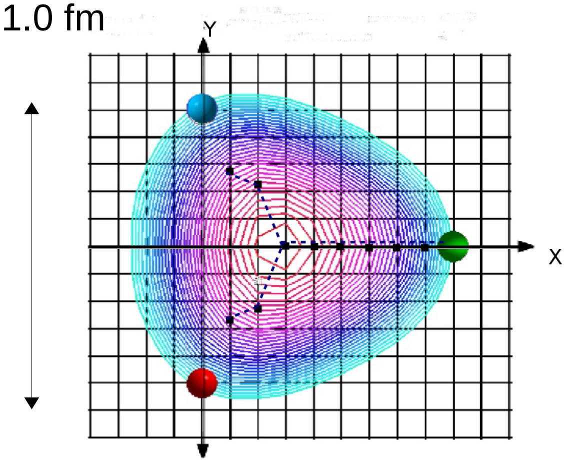
We observe that the planes of best fits manifest in accord with the profile of the two Gaussian shown rather than junction’s classical position at the Fermat point.

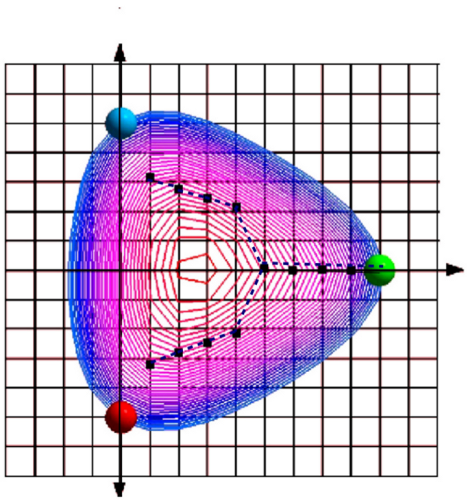






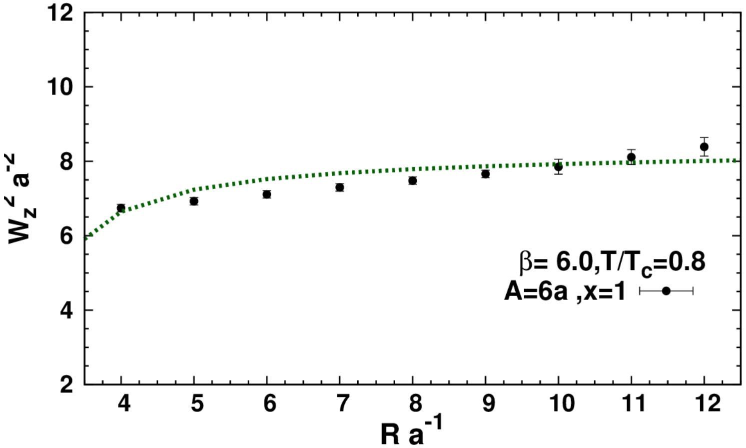
A=1.0 fm

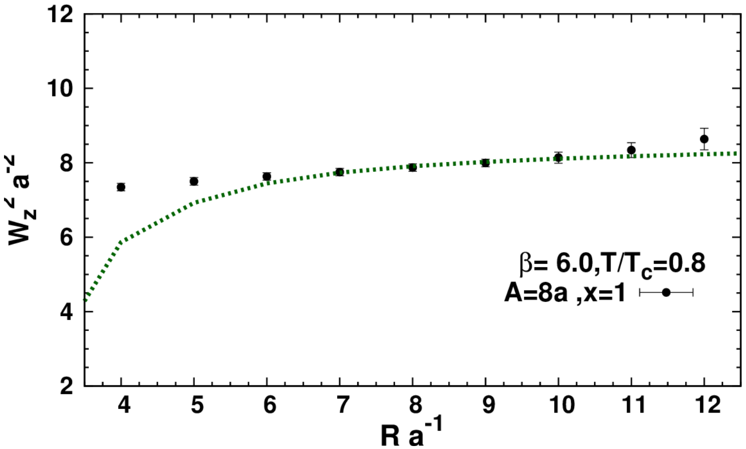


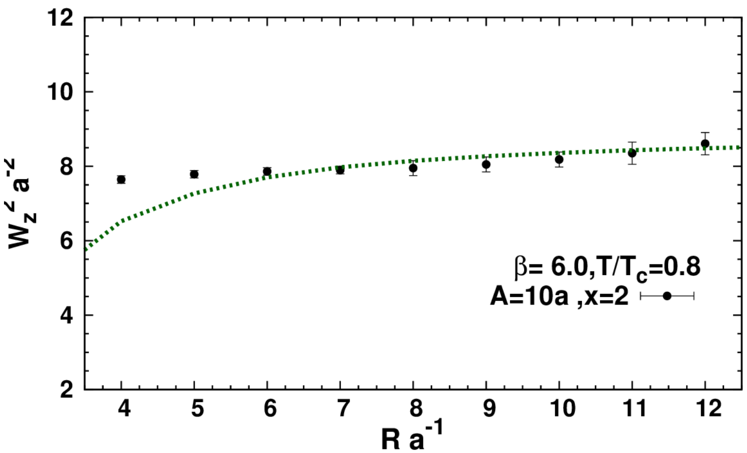


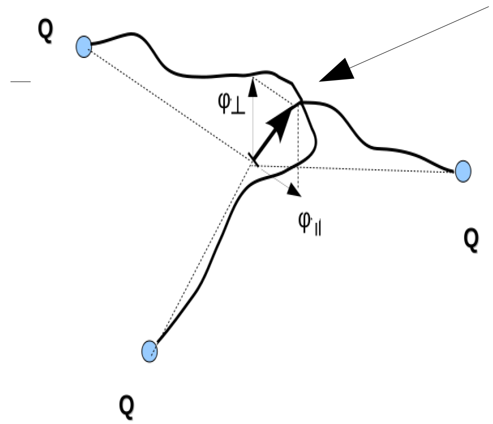
The greatest contribution of the junction appears to be in one lattice spacing immediately before the plane at which $u(x_0) = 0$.

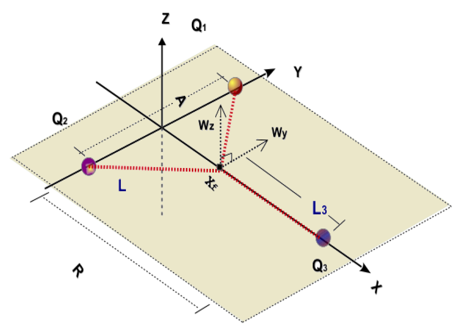
b) Perpendicular Fluctuation

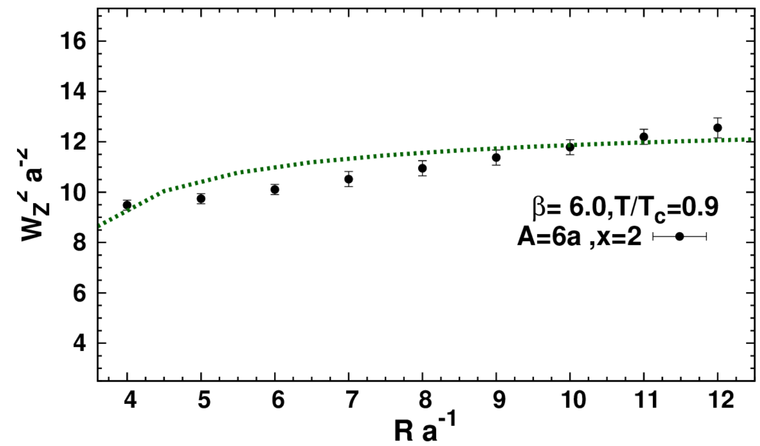


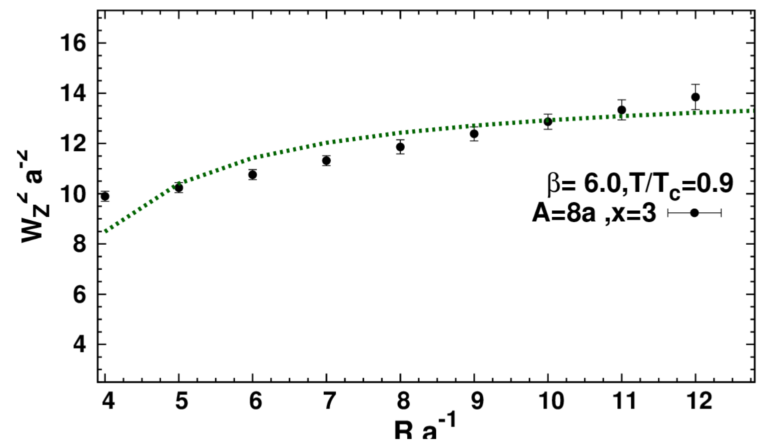


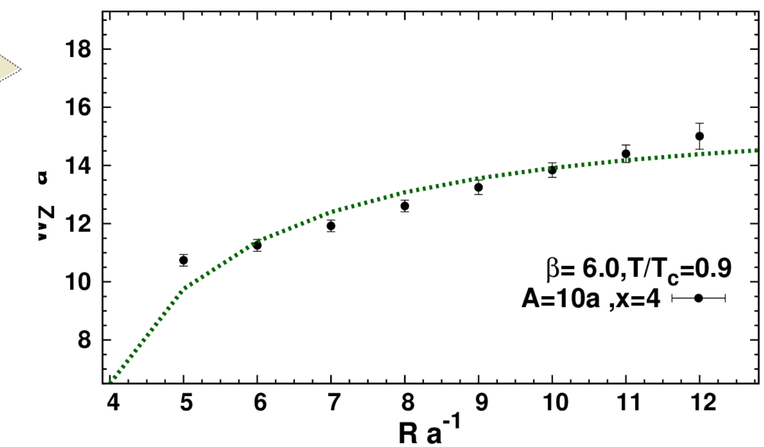












Summary

- The Y-baryonic string model has been discussed at finite temperature for the three quark potential and the width profile of the junction, assuming it's classical position at Fermat point.
- The lattice data for the 3Q potential and mean-square width of the gluonic action density has been compared with the Y-string model prediction.
- We found that the fit to the Y-law reproduces the quark anti-quark string tension provided a Dedekind η function accounting for string fluctuation is included in the fit ansatz.
- Comparison with the fit with the Δ-ansatz and even bare Y-ansatz, in some limits, shows that the Y-string model provides the best fits on the confinement part in the 3Q potential.
- We report a formation of the Y-shaped confining strings in a static baryon at finite T in the action density of Pure SU(3) YM theory for the first time.
- The best fits for the Y-string model for the energy profile are returned for large quark source separation.
- The revealed form of the 3Q potential and strings energy in the baryons at finite temperature introduces a new picture for a static hadron that may prove very relevant at zero temperature.

References

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