QCD Vacuum, Centre Vortices and Flux Tubes

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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

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  - Action and Topological Charge densities

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  - Accurate algorithms required to reveal these configurations
- Centre Vortices
  - What are they? Why are they interesting?
  - What happens if they are removed from QCD?
- Potential Energy between heavy quarks
  - Y versus Δ shape flux-tubes in baryons
  - Emphasize how the nature of the flux tube revolutionizes the concept of a constituent-quark.

CSSM Lattice Collaboration

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Francois Bissey
Sharada Boinepalli
Frederic Bonnet
Patrick Bowman
Fu-Guang Cao
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Wally Melnitchouk
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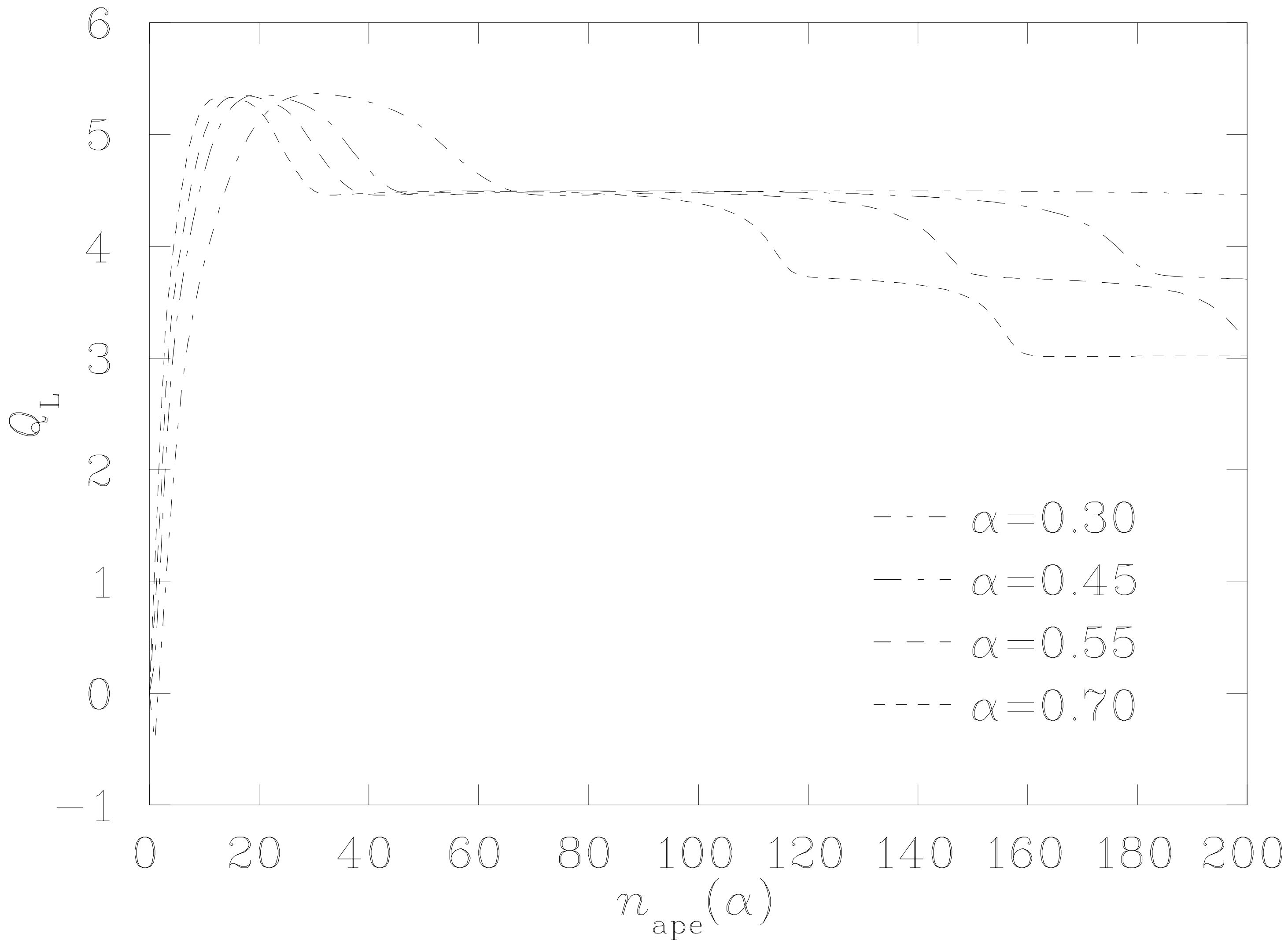
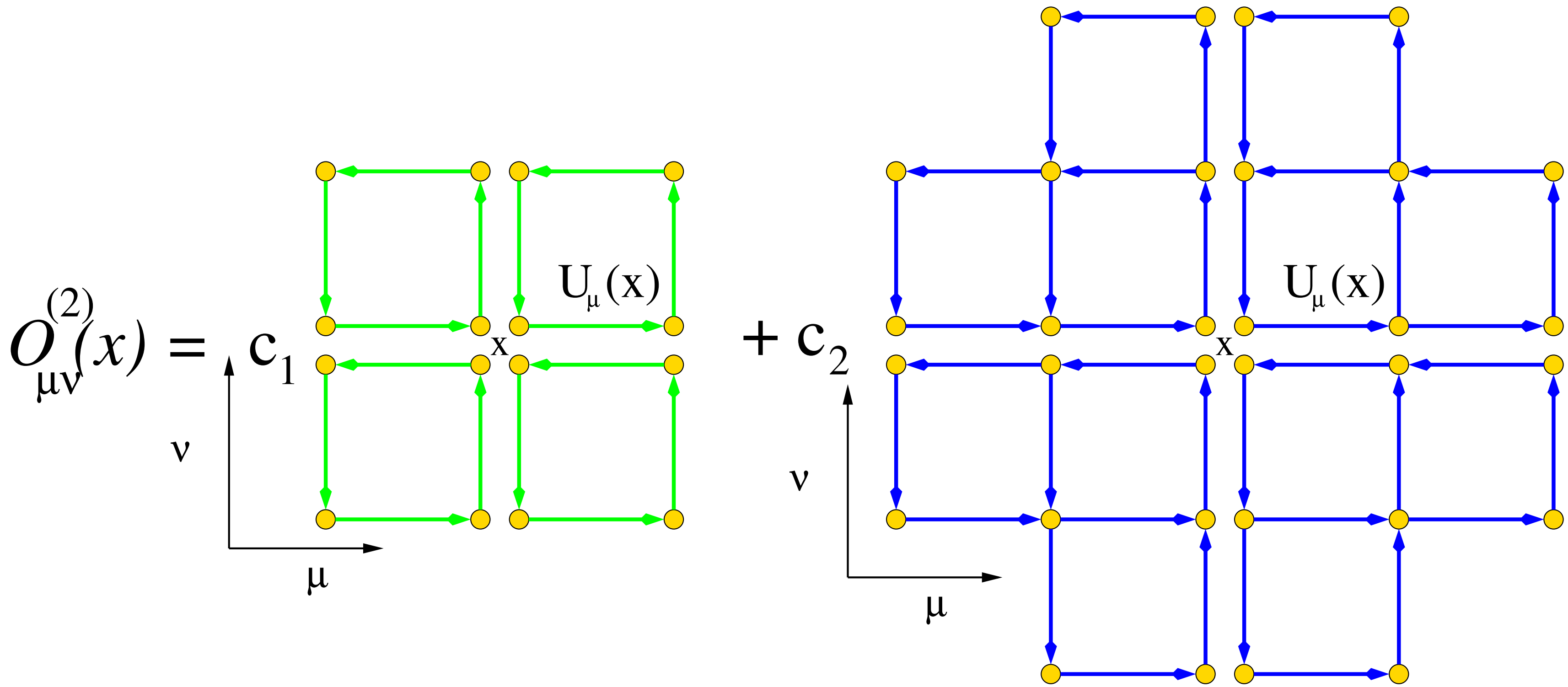
Tony Signal
Lorenz von Smekal
Mark Stanford
Tony Williams
James Zanotti
Jianbo Zhang

One-Loop $F_{\mu\nu}$ F. Bonnet *et.al*, Phys.Rev.D62:094509,2000



Two-loop Improvement



- Generalized to five-loop improvement in
  - S. O. Bilson-Thompson, D. B. Leinweber and A. G. Williams, arXiv:hep-lat/0203008.

Five-Loop Improvement

- An $\mathcal{O}(a^4)$-improved field-strength tensor is given by the following sum of Clover contributions $C^{m\times n}{}_{\mu\nu}$ for $m \times n$ loops:

$$F_{\mu\nu}^{\rm Imp} = k_1\, C_{\mu\nu}^{(1\times 1)} + k_2\, C_{\mu\nu}^{(2\times 2)} + k_3\, C_{\mu\nu}^{(1\times 2)} + k_4\, C_{\mu\nu}^{(1\times 3)} + k_5\, C_{\mu\nu}^{(3\times 3)},$$

where

$$k_1 = 19/9 - 55\, k_5\,, \qquad k_2 = 1/36 - 16\, k_5\,,$$

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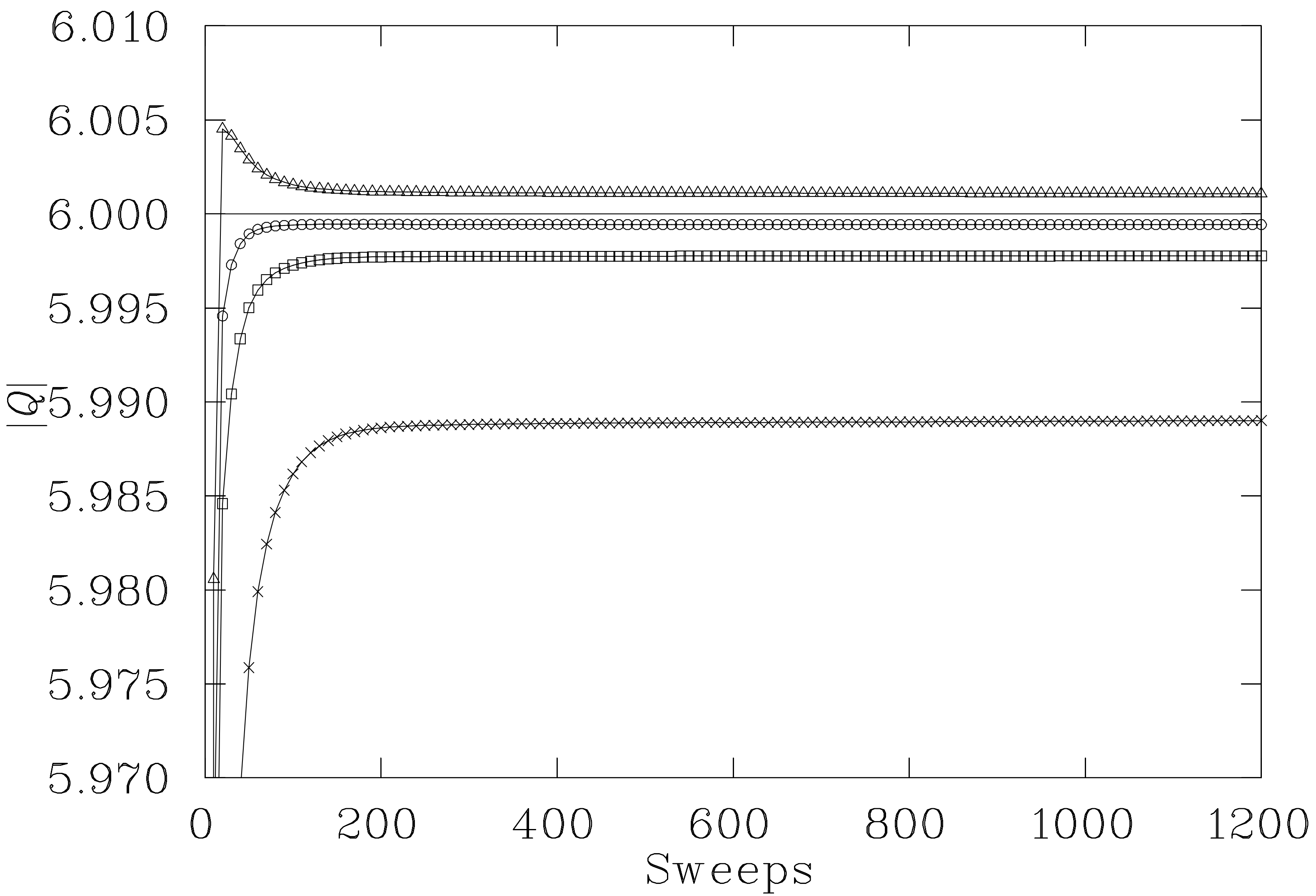
- k_5 is a tunable free parameter.
- Governs $\mathcal{O}(a^6)$ errors.
  - When $k_5 = 1/90$, $k_3 = k_4 = 0$ providing a 3-loop $F_{\mu\nu}$.
  - Setting $k_5 = 0$, provides 4-loop $F_{\mu\nu}$.
  - We consider $k_5 = 1/180$, as the 5-loop $F_{\mu\nu}$.

2, 3, 4 and 5-Loop Improved $F_{\mu\nu}$



Revealing the Structure of Gluon Fields

- Consider the Action density

$$S(x) = \frac{1}{2}\, F^{ab}_{\mu\nu}(x)\, F^{ba}_{\mu\nu}(x)\,.$$

- $S(x)$ is a scalar field in four dimensions.
- Consider a three-dimensional slice of the lattice.

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- Consider a three-dimensional slice of the lattice.
- To view the structure of typical vacuum gluon-field configurations
  - Render areas of intense action density in red.
  - Render areas of moderate action density in blue.
  - Low action-density regions are not rendered to allow us to see into the gluon field.

Exposing Long-Distance Physics

- Short-distance physics in QCD is well understood.
  - Interactions are weak at short distances.
  - Quarks behave as approximately free particles.
  - Corrections may be estimated via perturbation theory.

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  - Process is called “Cooling.”
- Each frame in the animation follows one sweep of Cooling.
  - All links are updated to locally minimize the action.
  - Highly-improved lattice operators are utilized.
  - Both $\mathcal{O}(a^2)$ and $\mathcal{O}(a^4)$ errors are removed
  - $\mathcal{O}(a^6)$ errors tuned to stabilize nonperturbative phenomena

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  - Render areas of positive charge density in red.
  - Render areas of negative charge density in blue.
  - Low charge-density regions are not rendered to allow us to see into the gluon field.

Instanton Facts

- Gluon fields having nontrivial winding represented by the topological charge $Q = \sum_x q(x) = \pm 1$.
- Classical solutions to the QCD equations of motion
- They live in four dimensions.
- They have small finite action, $S_0 = 8\pi^2/g^2$
  - Approximately 10,000 times smaller than the action of a typical field configuration

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- Similarly for the action.
- Revealed in lattice QCD only after extensive cooling.

The Effective Mass of Quarks

- Short-distance physics in QCD is well understood.
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  - Quarks behave as approximately free particles.
  - Corrections may be estimated via perturbation theory.
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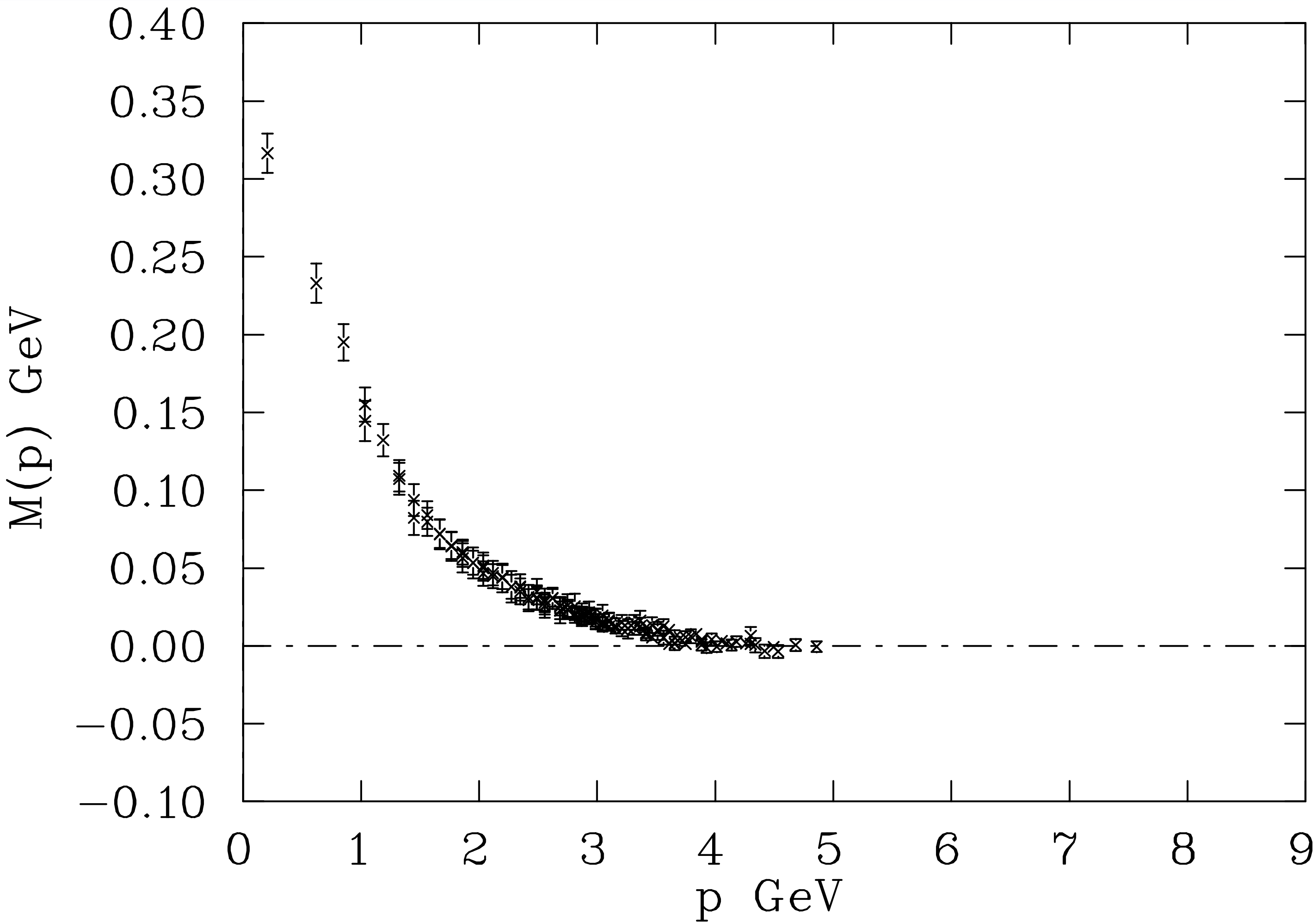
- At long distances, a rich structure in the QCD vacuum is revealed.
- Quarks and gluons do not propagate as free particles.
- The quark acquires an effective mass due to its interaction with the QCD vacuum.

Massless Quarks in the QCD Vacuum



Propagator Spectral Representation

- Eigenmodes of the Dirac Operator are defined by

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- For small quark masses (like the u or d quarks in nature)
  - Eigenmodes having small eigenvalues, λ_i, dominate the nature of how quarks propagate in the QCD vacuum.

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$$S = \frac{1}{\not{D} + m_q} = \sum_i | \, \psi_i \, \rangle \, \frac{1}{\lambda_i + m} \langle \, \psi_i \, | \, .$$

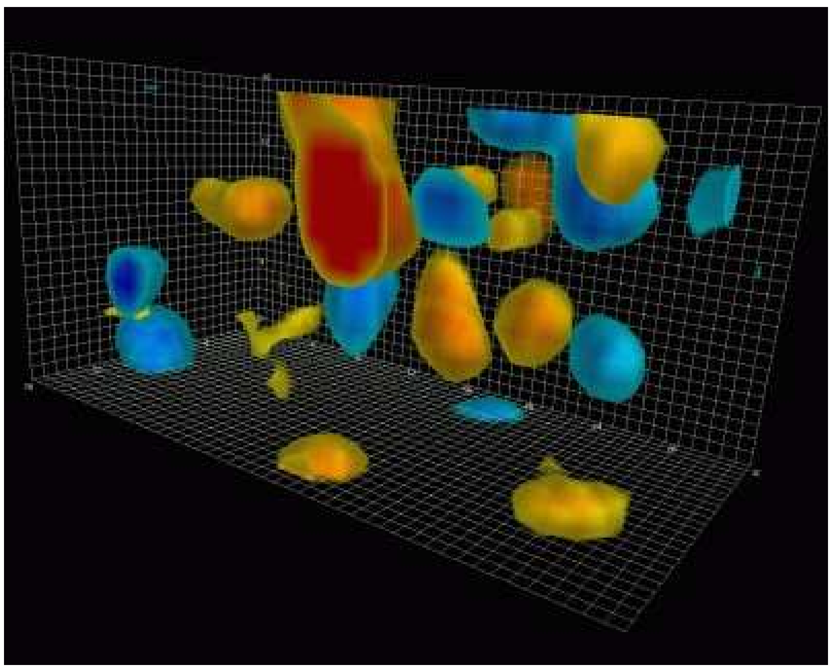
- For λ_i small, the real scalar field

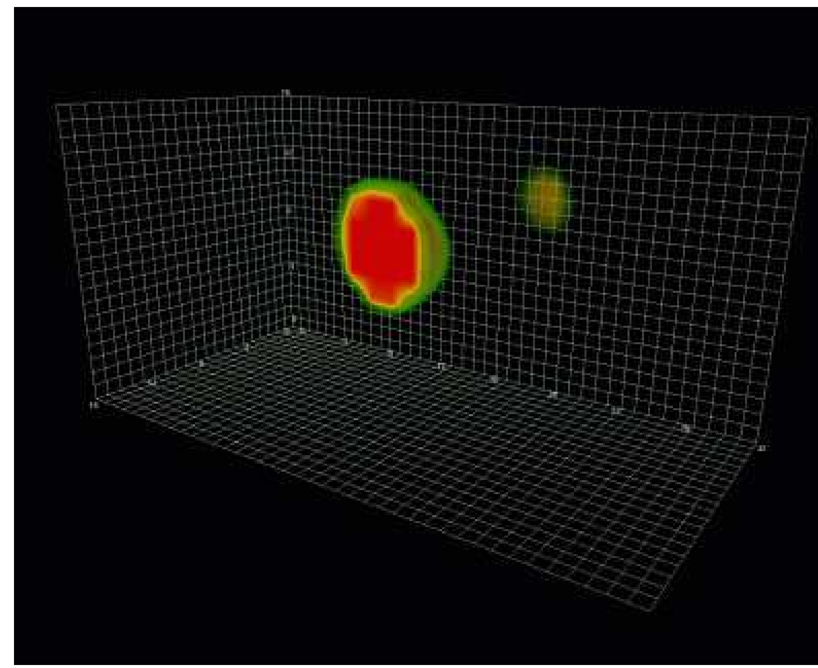
$$P_i(x) = \langle \, x \, | \, \psi_i \, \rangle \langle \, \psi_i \, | \, x \, \rangle = \psi(x) \, \psi^\dagger(x) \, ,$$

describes the probable locations of the quarks in the vacuum as they propagate.

Low-lying Eigenmode Density

- Low-lying eigenmodes of the Dirac operator are located on the topological structures giving rise to them.





- Each low-lying nondegenerate mode is associated with a single topological structure.

What are Centre Vortices?

1. Gauge fix gluon configurations to Maximal Centre Gauge
   - Bring the links $U_\mu(x)$ close to the centre elements of $SU(3)$

$$Z = \exp\left(2\pi i \, \frac{m}{3}\right) \mathbf{I} \,, \text{ with } m = -1, 0, 1$$

   - On the lattice, search for the gauge transformation Ω

$$\sum_{x,\mu} \left| \mathrm{tr} \, U_\mu{}^\Omega(x) \right|^2 \xrightarrow{\Omega} \max$$

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1. Gauge fix gluon configurations to Maximal Centre Gauge
2. Project the gluon field to the centre phase

$$U_\mu(x) \to Z_\mu(x) \text{ where } Z_\mu(x) = \exp\left(2\pi i \, \frac{m_\mu(x)}{3}\right), \quad m_\mu(x) = -1, 0, 1$$

- Implemented by

$$\frac{1}{3}\mathrm{tr}\, {U_\mu}^{\Omega}(x) = \underbrace{r_\mu(x)}_{\text{real}} \; \underbrace{\exp\Big(i\varphi_\mu(x)\Big)}_{\text{phase}} ,$$

$$\cos \underbrace{\left(\varphi_\mu(x) - \frac{2\pi}{3} m_\mu(x)\right)}_{\text{close to zero}} \xrightarrow{m_\mu} \max .$$

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3. Vortices are identified by the centre charge

$$z = \prod_\square Z_\mu(x) = \exp\left(2\pi i \, \frac{n}{3}\right)$$

- If $\mathrm{mod}(n, 3) = 0$ no vortex pierces the plaquette
- If $\mathrm{mod}(n, 3) = -1,$ or 1 a vortex with charge z pierces the plaquette

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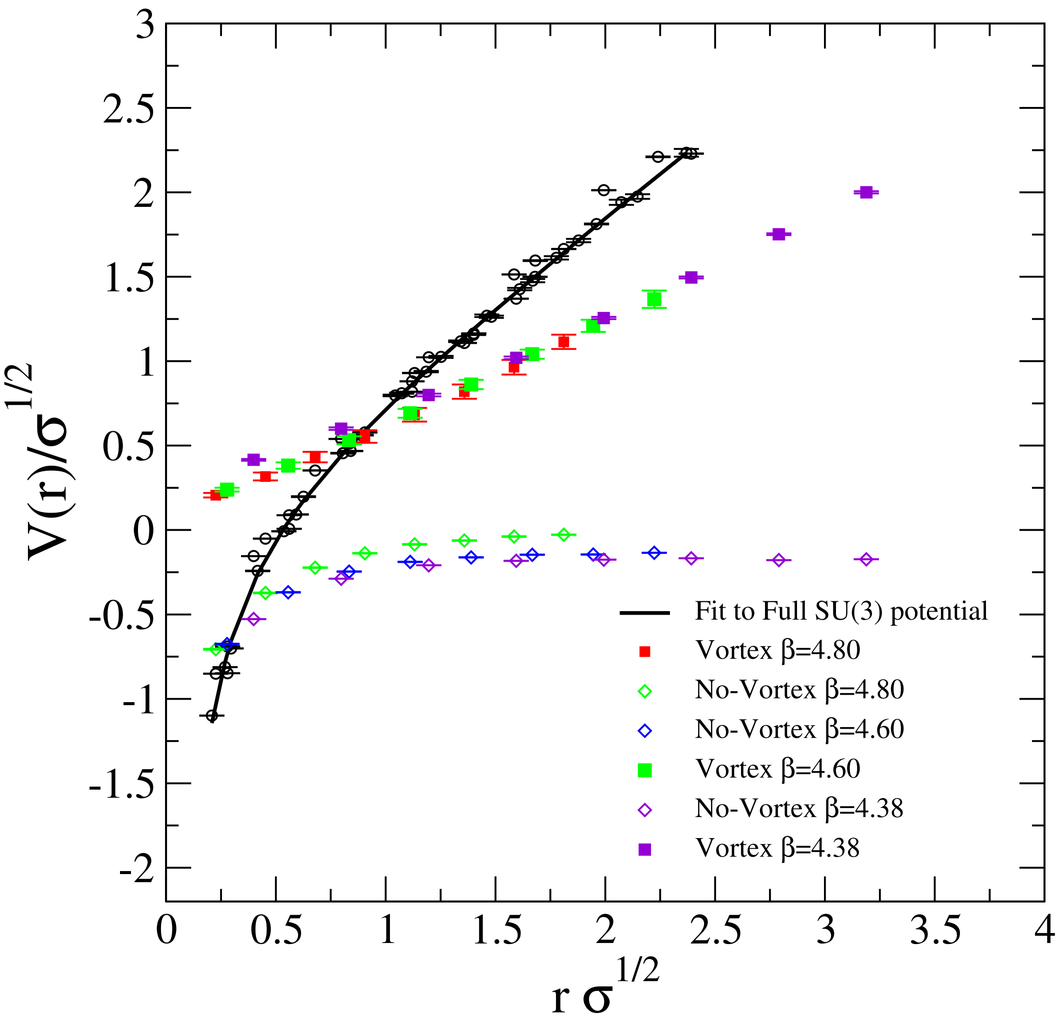
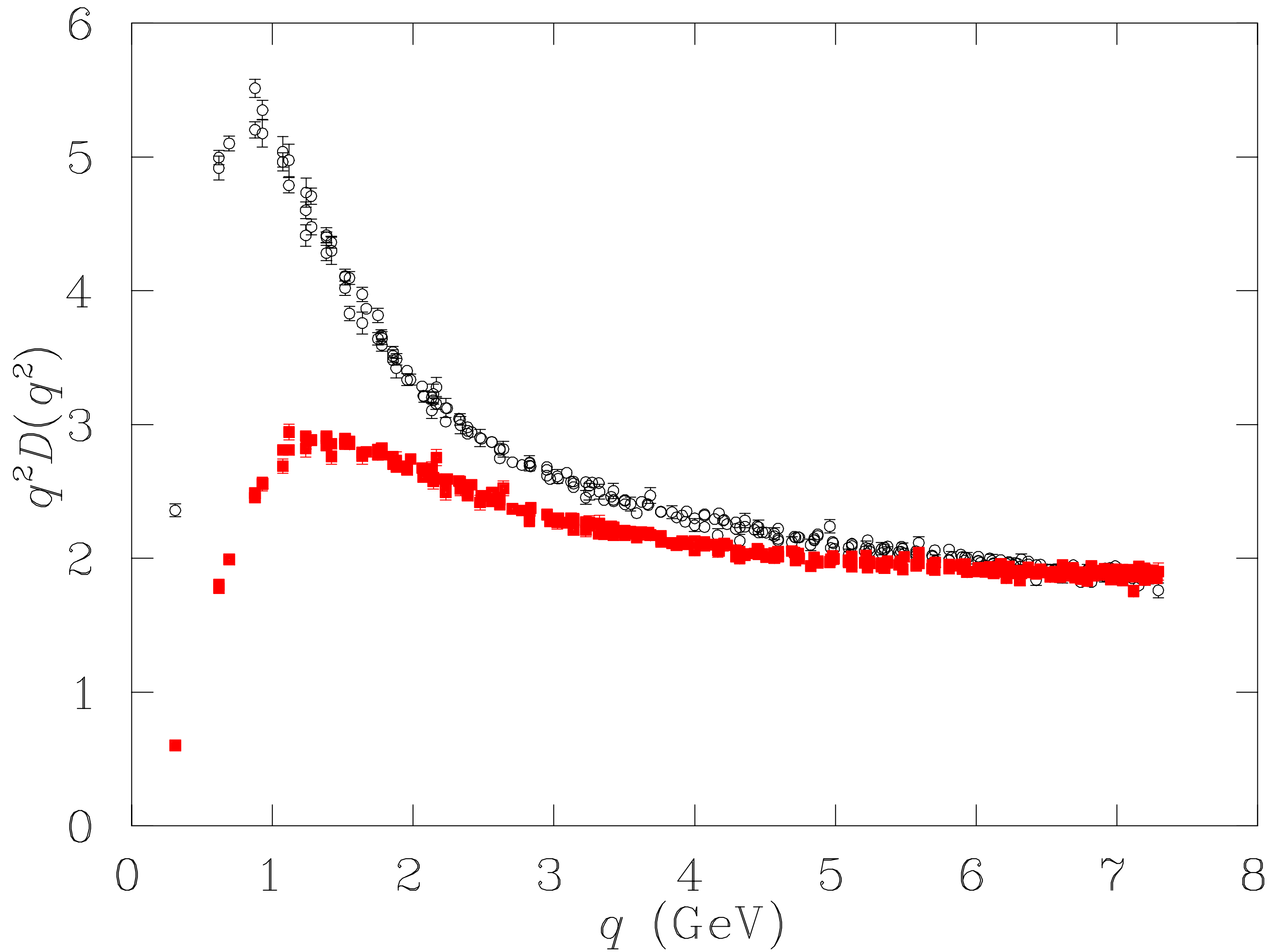
4. Vortices are removed by removing the centre phase

$$U_\mu(x) \to U'_\mu(x) = Z^*_\mu(x) \cdot U_\mu(x),$$

Static Quark Potential



Gluon Propagator



Centre Vortices and Mass Generation

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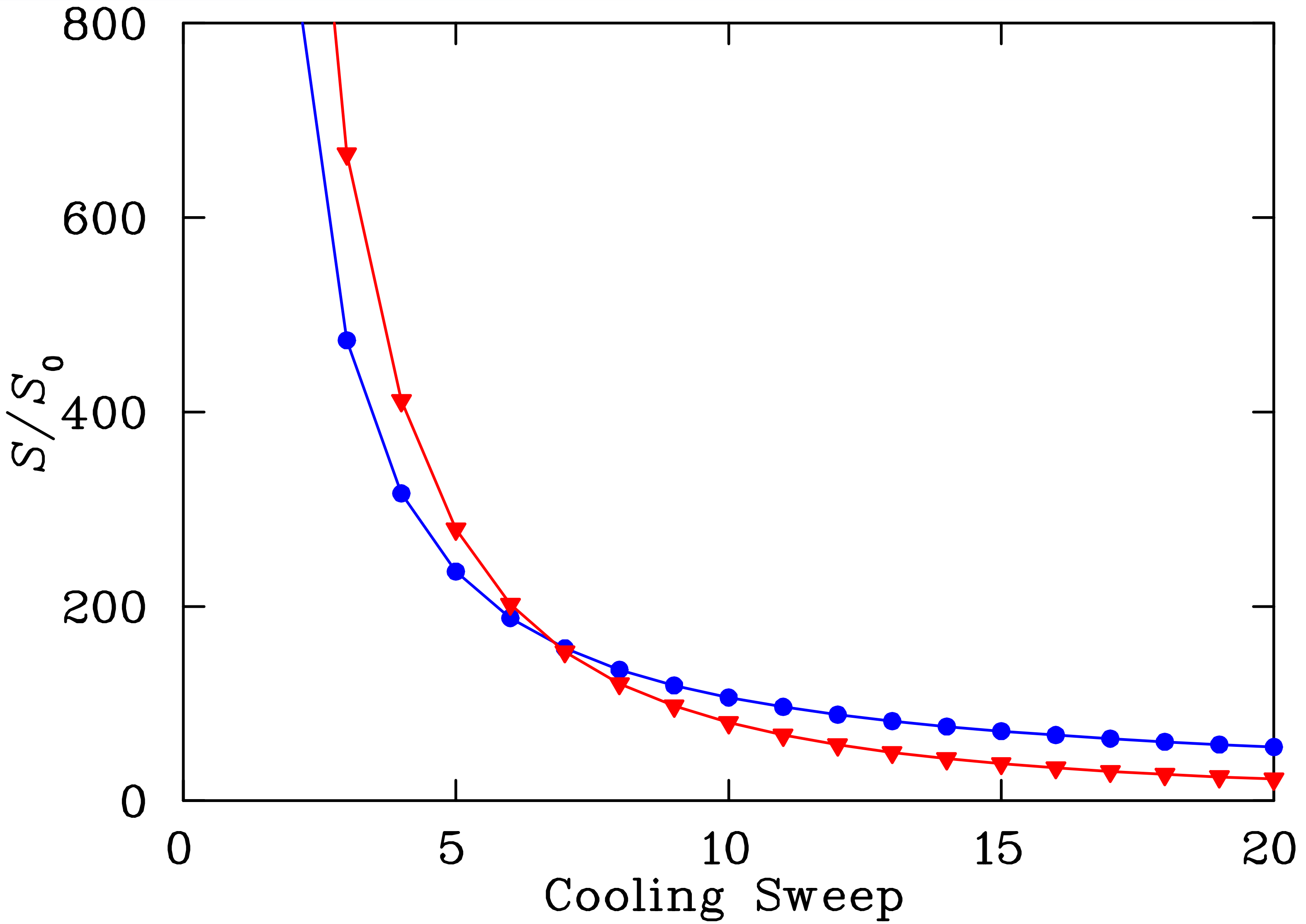
- Topologically non-trivial gauge fields (including instantons)
  - Give rise to zeromodes
- Hence, a link between centre vortices and topology implies a
  - Link between centre vortices and dynamical mass generation.

Gluon Action Evolution



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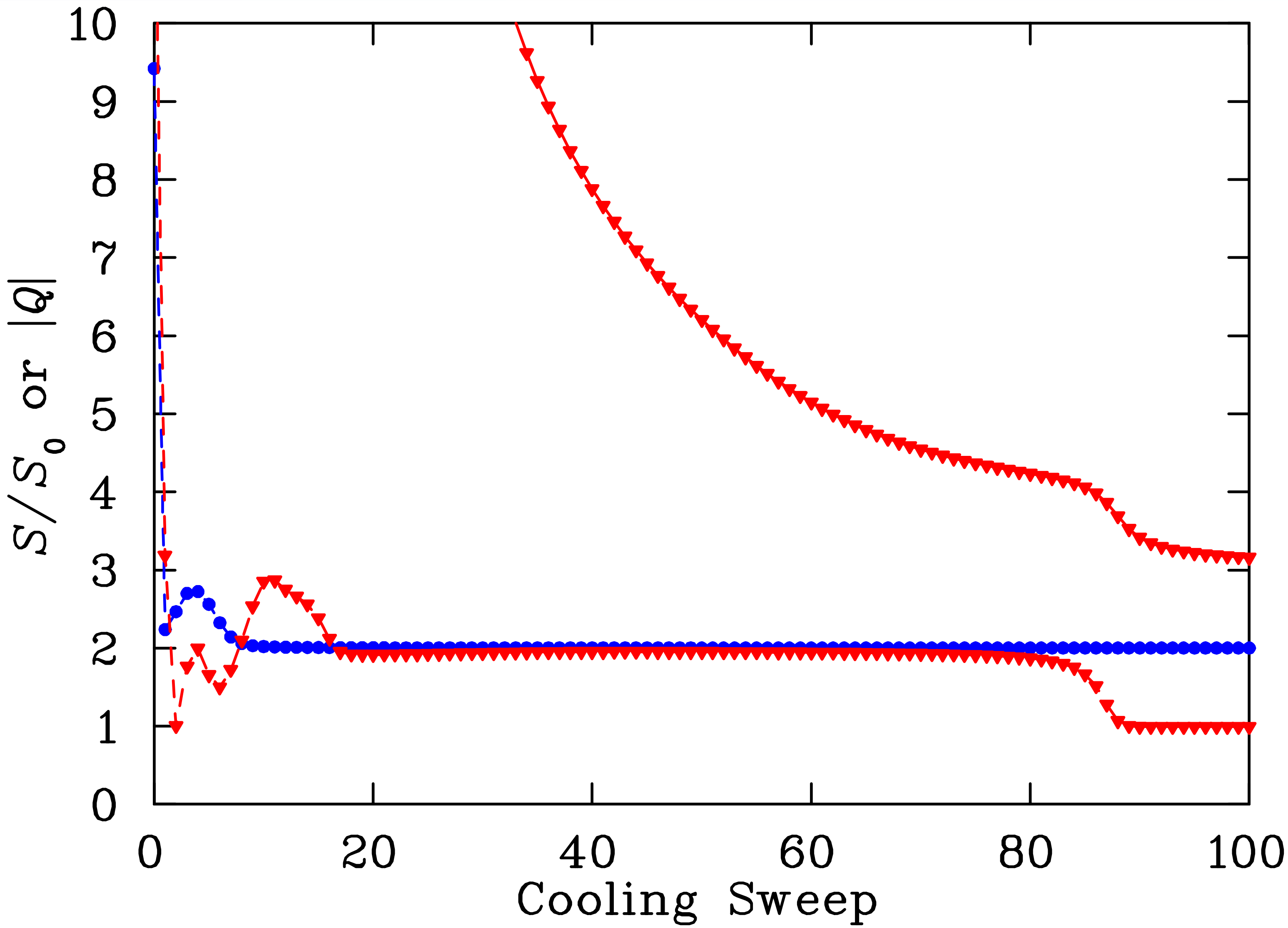

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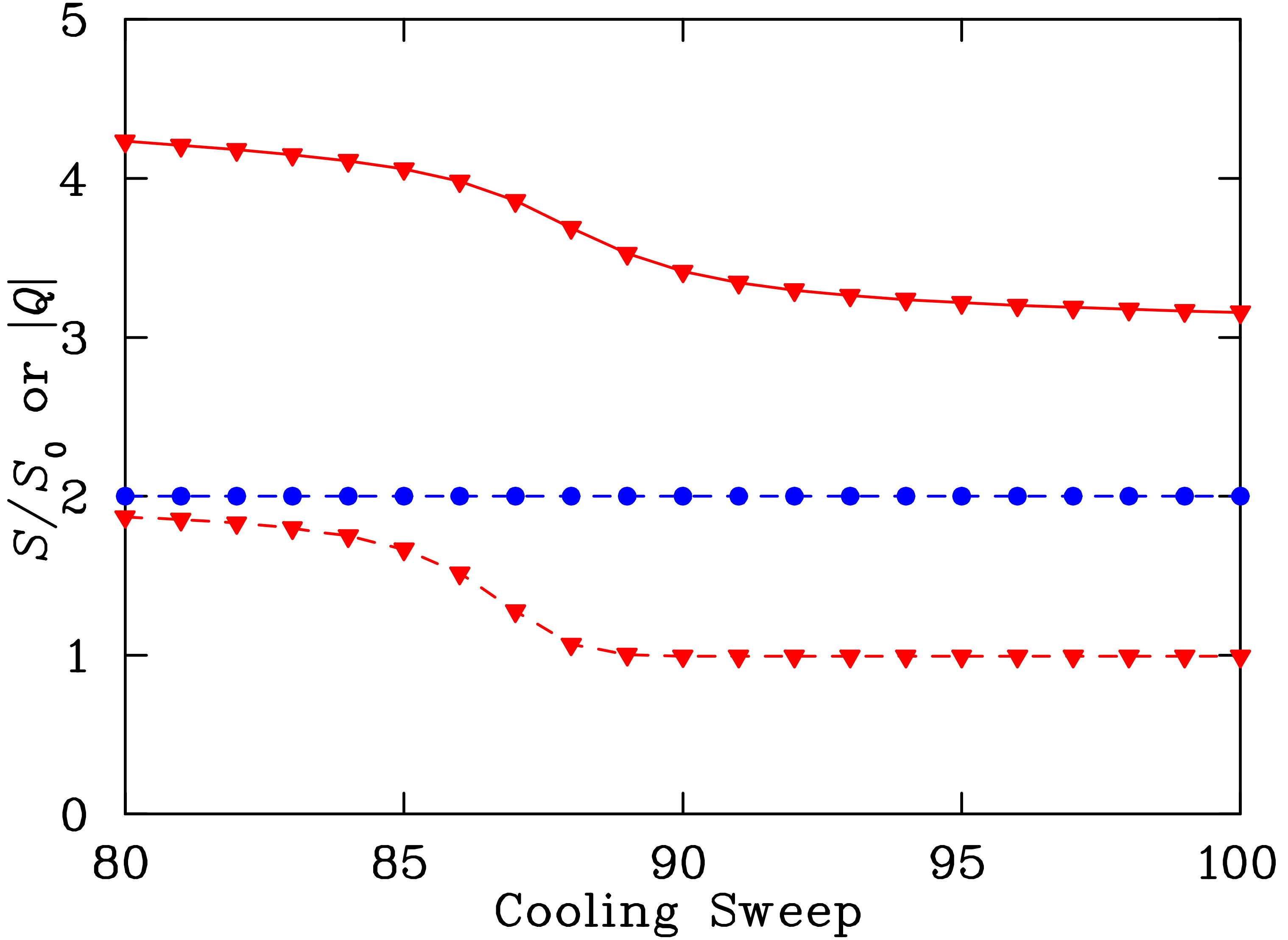


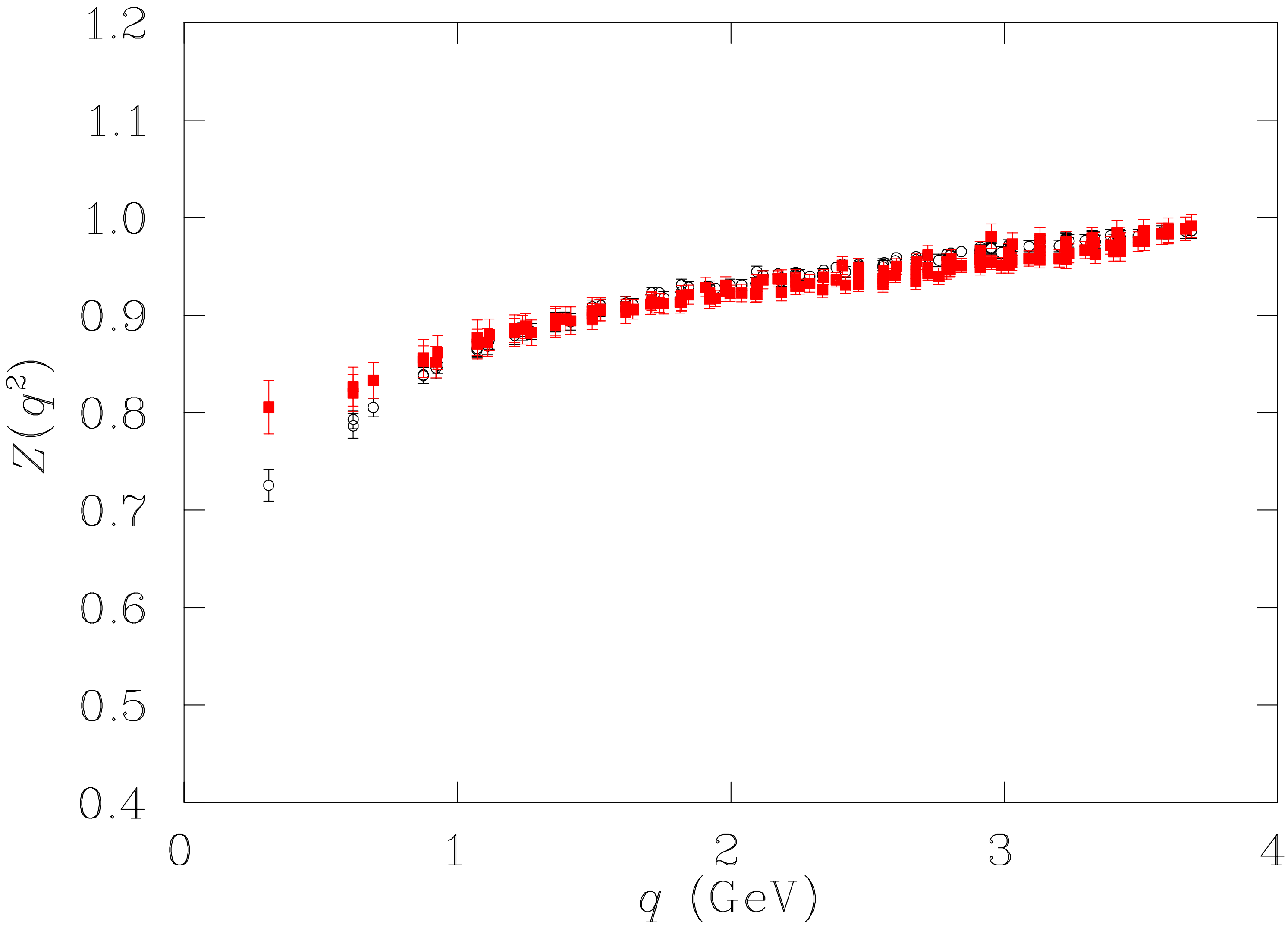
Quark Propagator Decomposition

- In a covariant gauge, Lorentz invariance allows

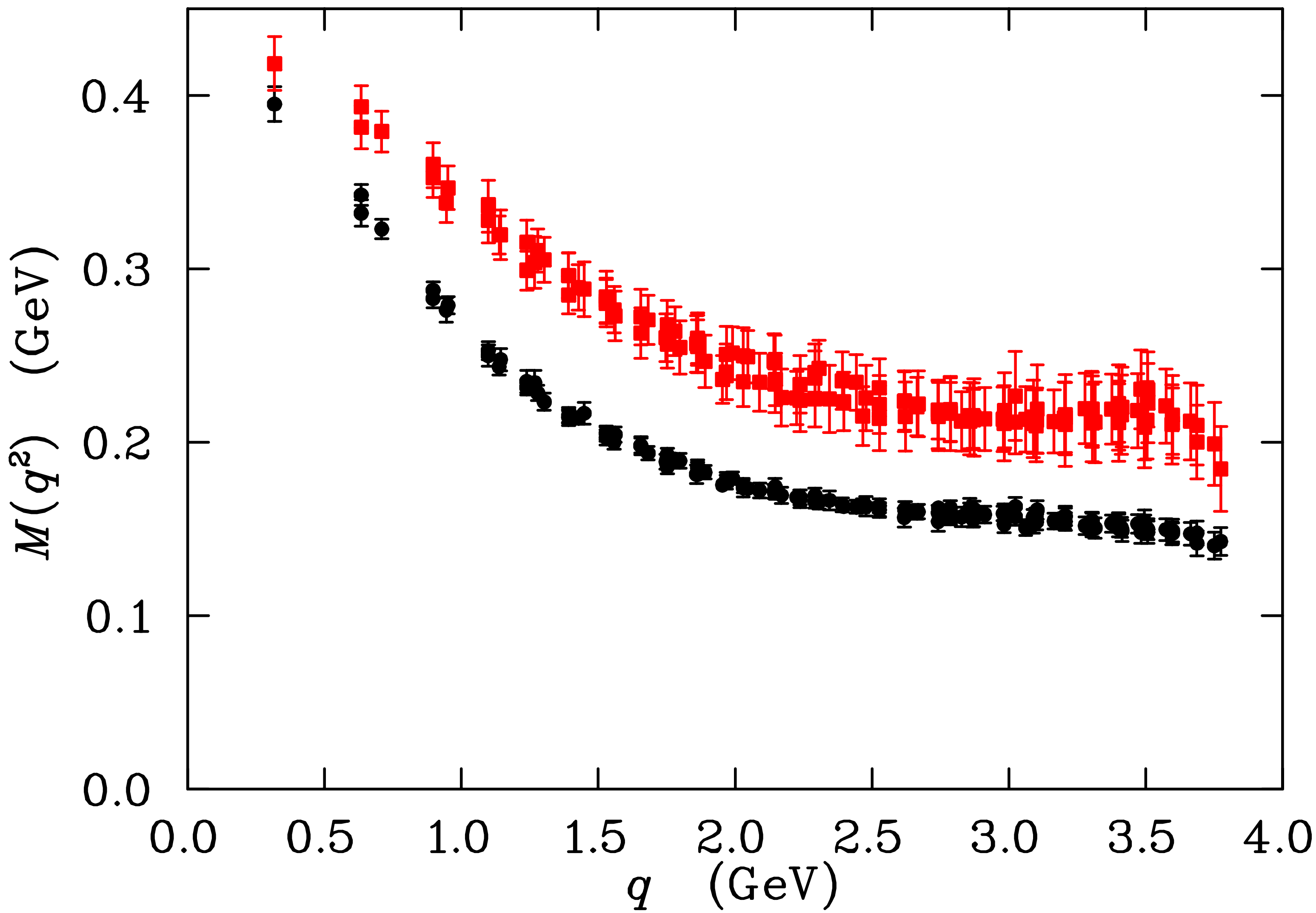
$$S^{aa}(\zeta;q) \equiv S(\zeta;q) = \frac{Z(\zeta;q^2)}{i\gamma\cdot q + M(q^2)}\,,$$

- $M(q^2)$ is the Mass function
- $Z(\zeta;q^2)$ is the Renormalization function
- ζ is the renormalization point (3 GeV) with conditions
  - $Z(\zeta;\zeta^2) \equiv 1$
  - $M(\zeta^2) \equiv m(\zeta)$
- For sufficiently large ζ, $m(\zeta) \to m_\zeta$, the current quark mass.

Quark Renormalization Function at $m_q^0 = 78$ MeV



Quark Mass Function at $m_q^0 = 116$ MeV



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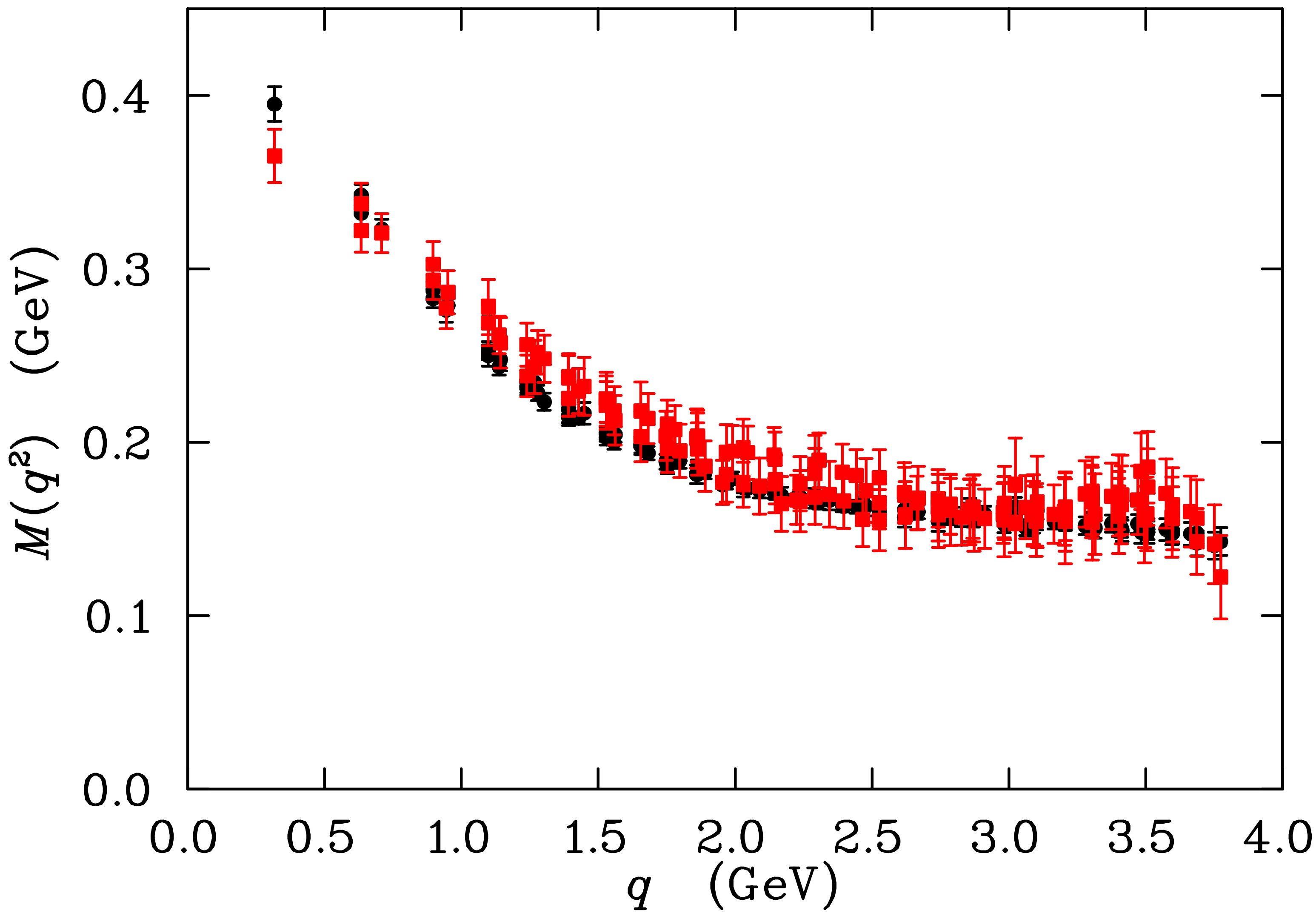

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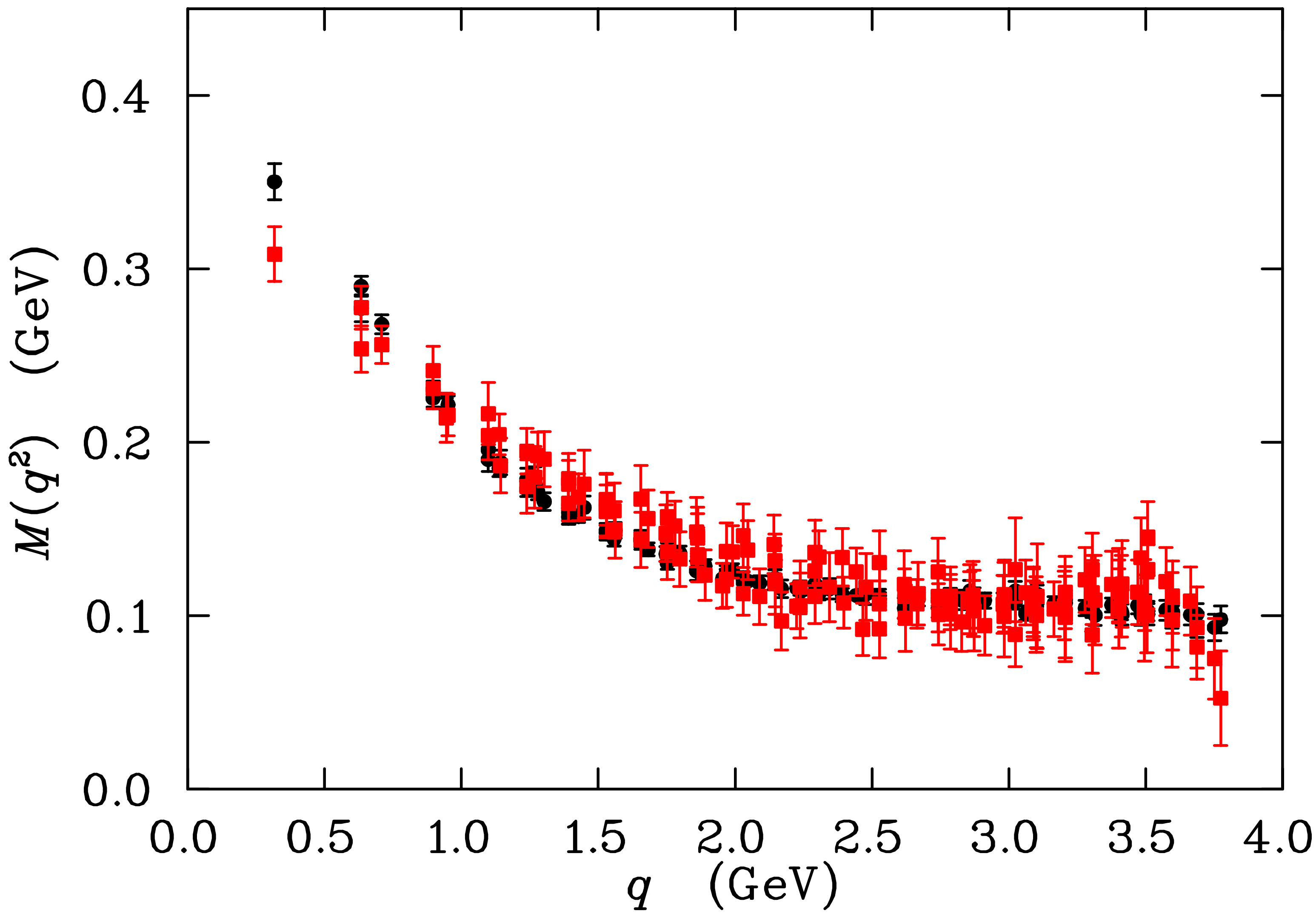
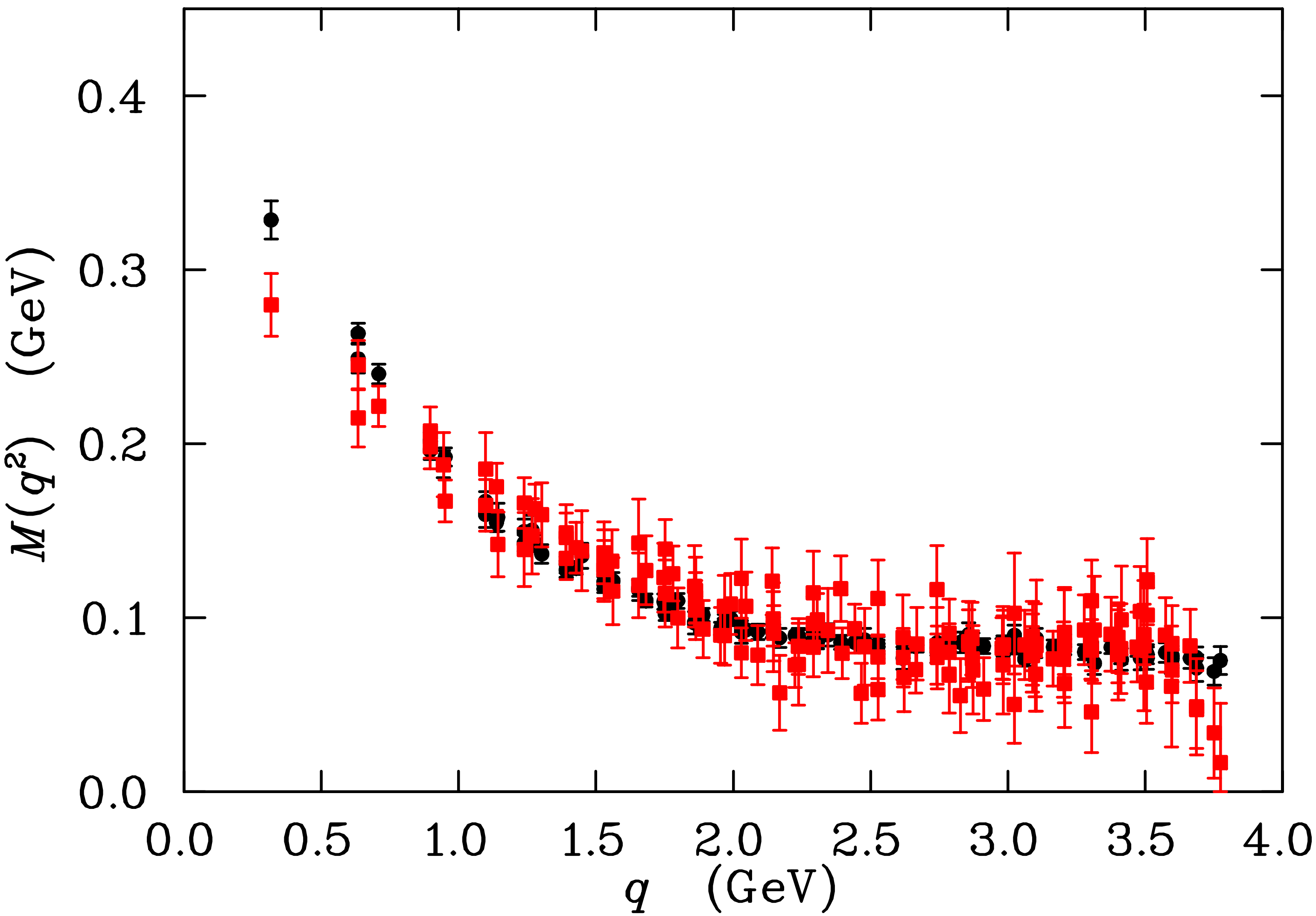
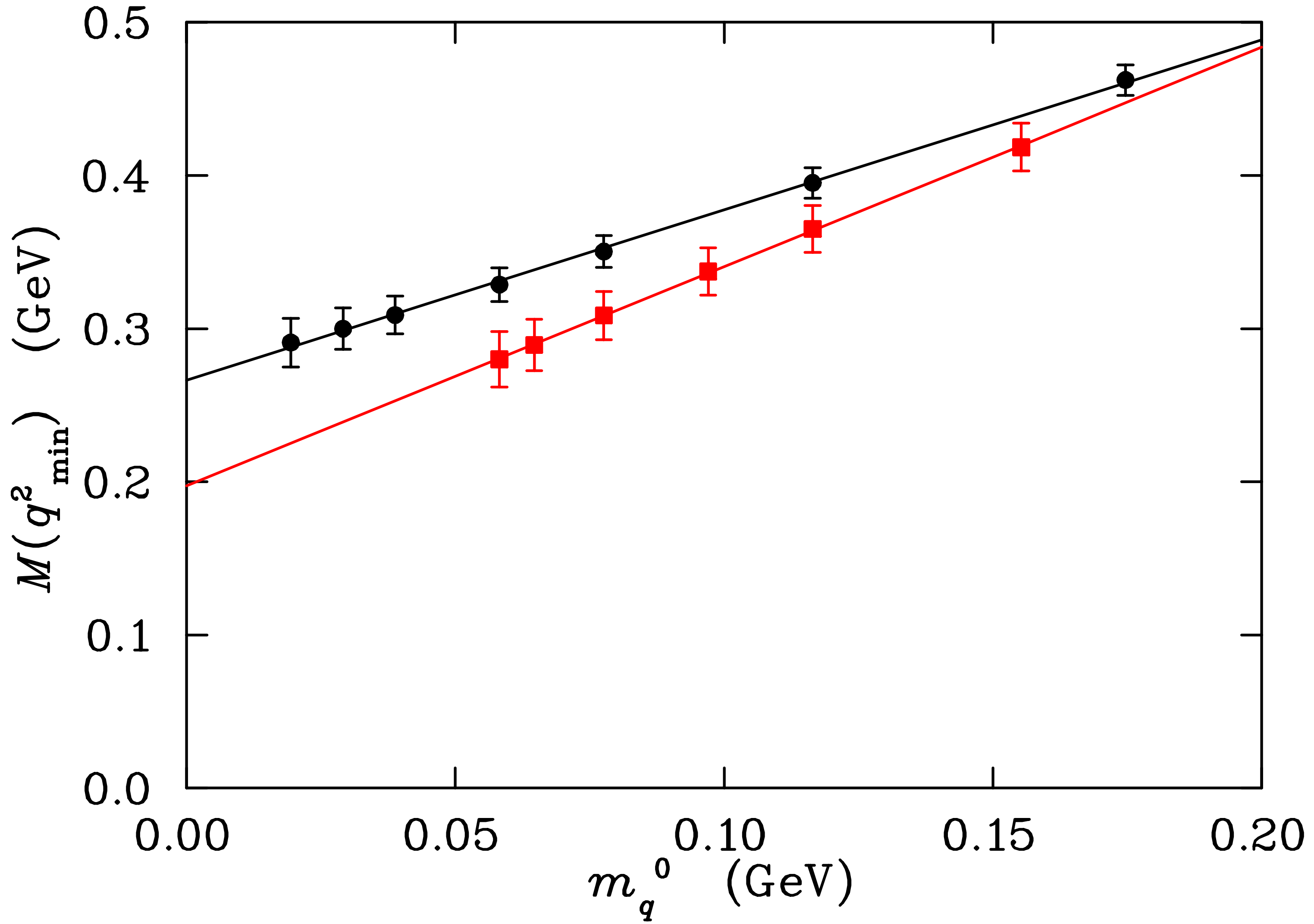


Quark Mass Function at $m_q^0 = 58$ MeV



Infrared Mass Function



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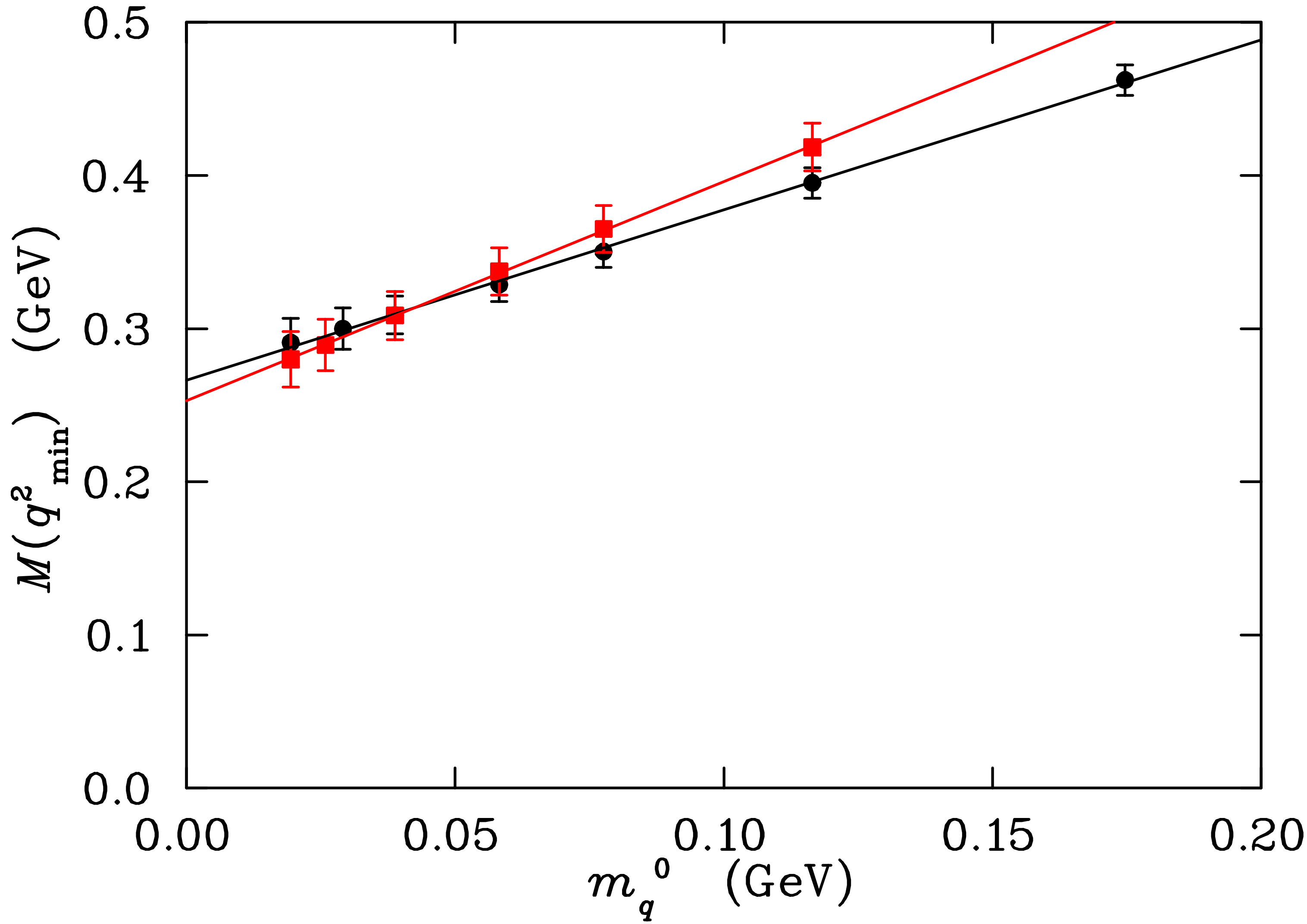
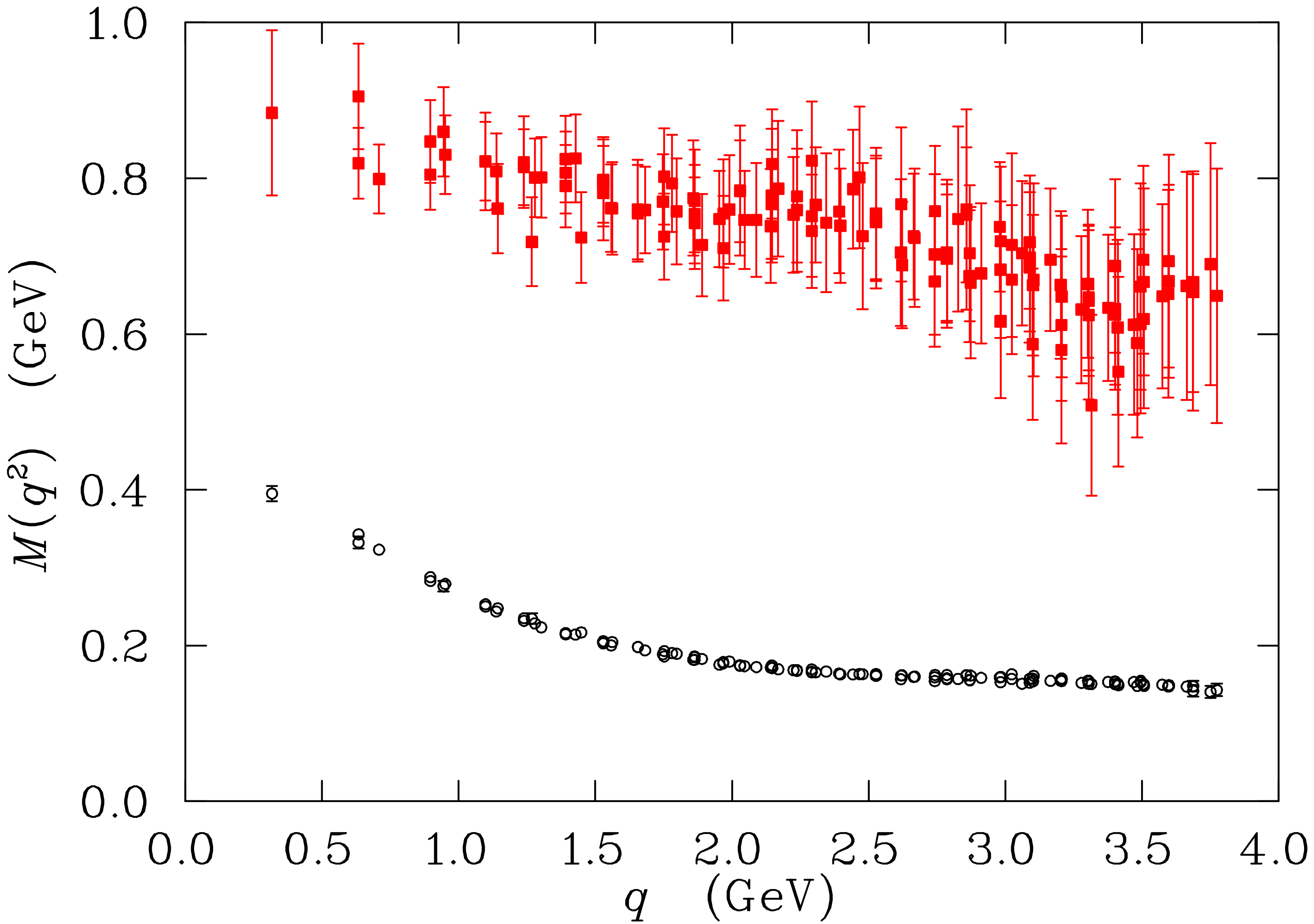
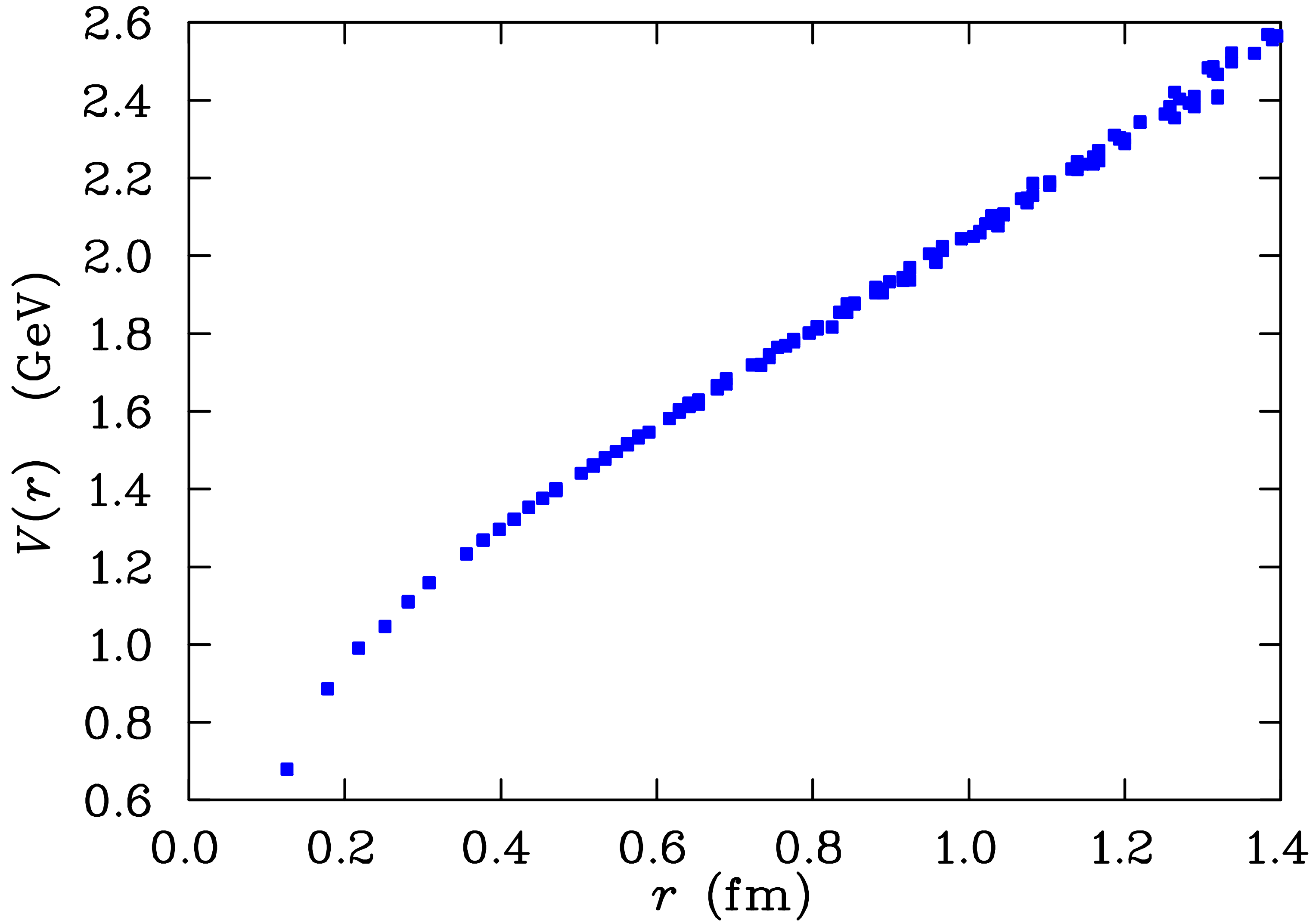


LCG Mass Function with $m_q^0 = 29$ MeV



Potential Energy between Heavy Quarks



Gluon Field Distribution in Mesons

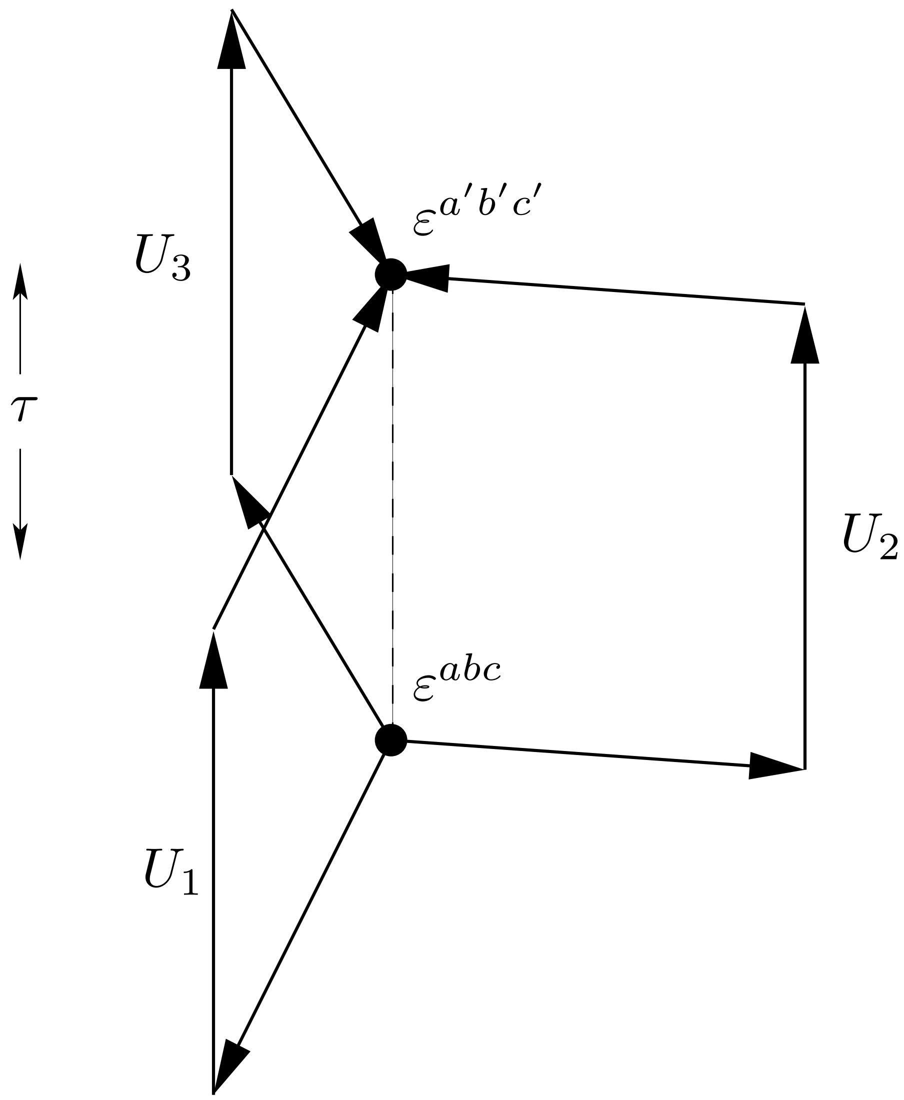
- How does the Vacuum respond to the presence of Quarks?

$$C(\vec{y},\vec{d}) = \frac{\langle Q(\vec{x})\ S(\vec{y}+\vec{x})\ Q^\dagger(\vec{x}+\vec{d})\rangle_{\vec{x}}}{\langle Q(\vec{x})\ Q^\dagger(\vec{x}+\vec{d})\rangle_{\vec{x}}\ \langle S(\vec{x})\rangle_{\vec{x}}}$$

- $Q(\vec{x})$ denotes a quark at position $\vec{x}$.
- $Q^\dagger(\vec{x}+\vec{d})$ denotes an antiquark at position $\vec{x}+\vec{d}$.
- $S(\vec{y}+\vec{x})$ denotes the action density at position $\vec{y}$ from the quark at $\vec{x}$.
- $\langle \ldots \rangle_{\vec{x}}$ denotes average over $\vec{x}$ and gluon field configurations.
- If there is no correlation between the action density and the locations of the quark and antiquark,

$$C(\vec{y}, d) = 1\,.$$

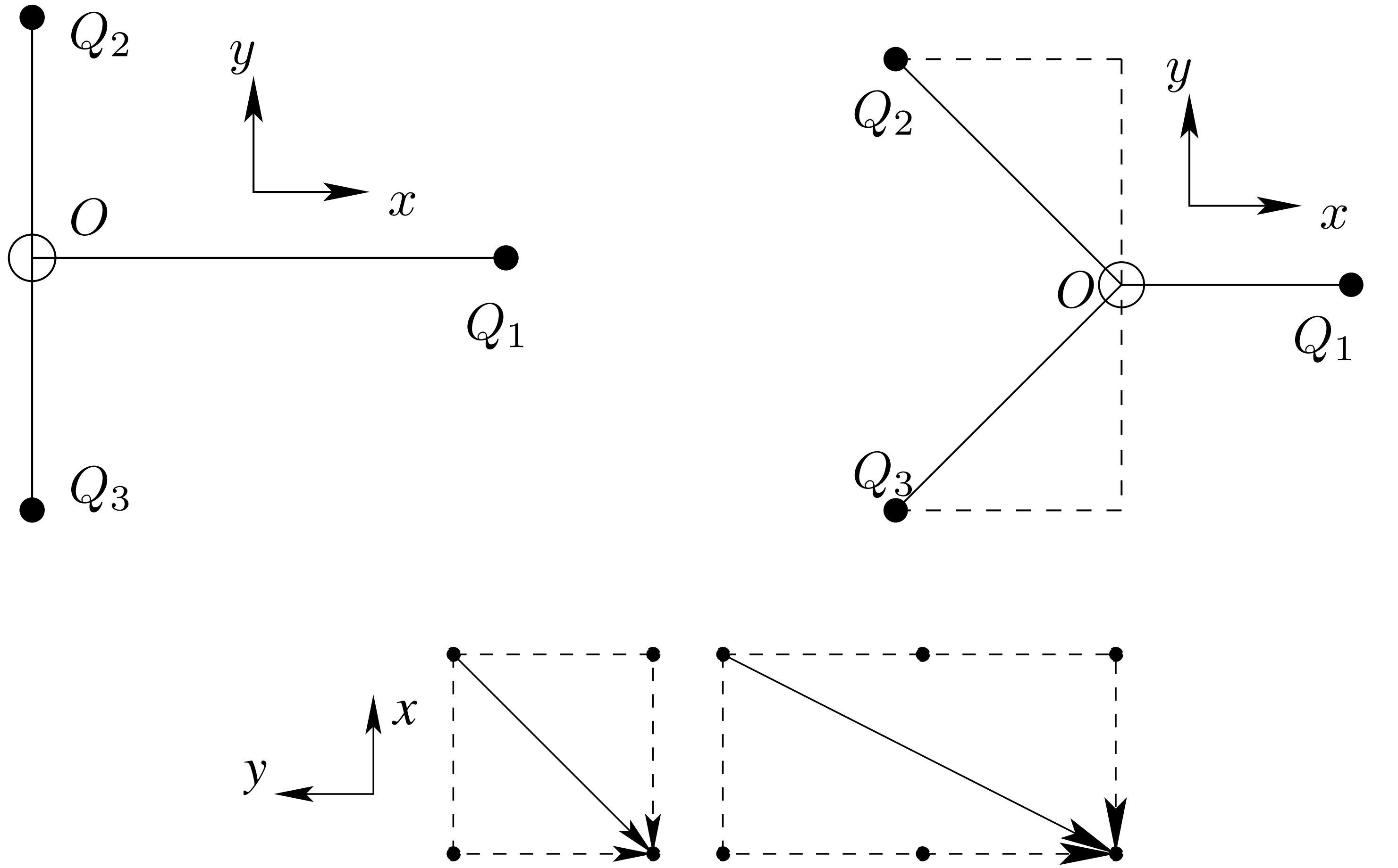
Baryonic Wilson Loop



Quark Coordinates

	(x, y) Coordinates (lattice units)				Distance (fm)	
#	Q_1	Q_2	Q_3	F	$\langle r_s \rangle$	$\langle d_{qq} \rangle$
1	$(1, 0)$	$(-1, 1)$	$(-1, -1)$	$(-0.42, 0)$	0.15	0.35
2	$(2, 0)$	$(-1, 2)$	$(-1, -2)$	$(0.15, 0)$	0.27	0.54
3	$(3, 0)$	$(-1, 2)$	$(-1, -2)$	$(0.15, 0)$	0.31	0.69
4	$(3, 0)$	$(-2, 3)$	$(-2, -3)$	$(-0.27, 0)$	0.42	0.89
5	$(4, 0)$	$(-3, 4)$	$(-3, -4)$	$(-0.69, 0)$	0.57	1.24
6	$(5, 0)$	$(-4, 5)$	$(-4, -5)$	$(-1.11, 0)$	0.72	1.58
7	$(7, 0)$	$(-4, 6)$	$(-4, -6)$	$(-0.54, 0)$	0.88	1.93
8	$(8, 0)$	$(-4, 7)$	$(-4, -7)$	$(0.04, 0)$	0.99	2.12

T- and Y-Shape Source Paths



Gluon Field Distribution in Baryons

- How does the Vacuum respond to the presence of Quarks?

$$C(\vec{y};\vec{r}_1,\vec{r}_2,\vec{r}_3;\tau) = \frac{\langle W_{3Q}(\vec{r}_1,\vec{r}_2,\vec{r}_3;\tau)\, S(\vec{y},\tau/2)\rangle}{\langle W_{3Q}(\vec{r}_1,\vec{r}_2,\vec{r}_3;\tau)\rangle\, \langle S(\vec{y},\tau/2)\rangle}$$

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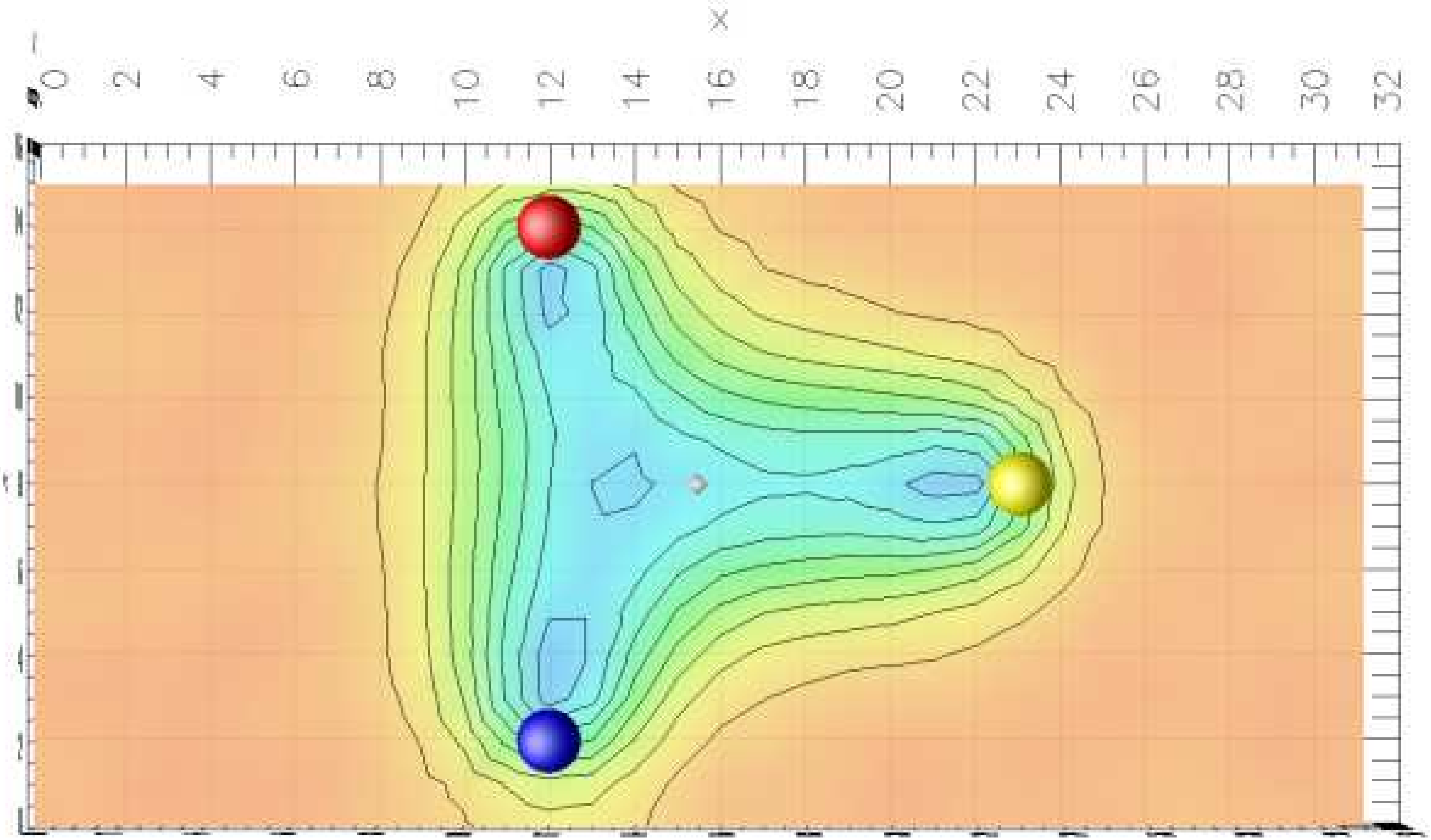
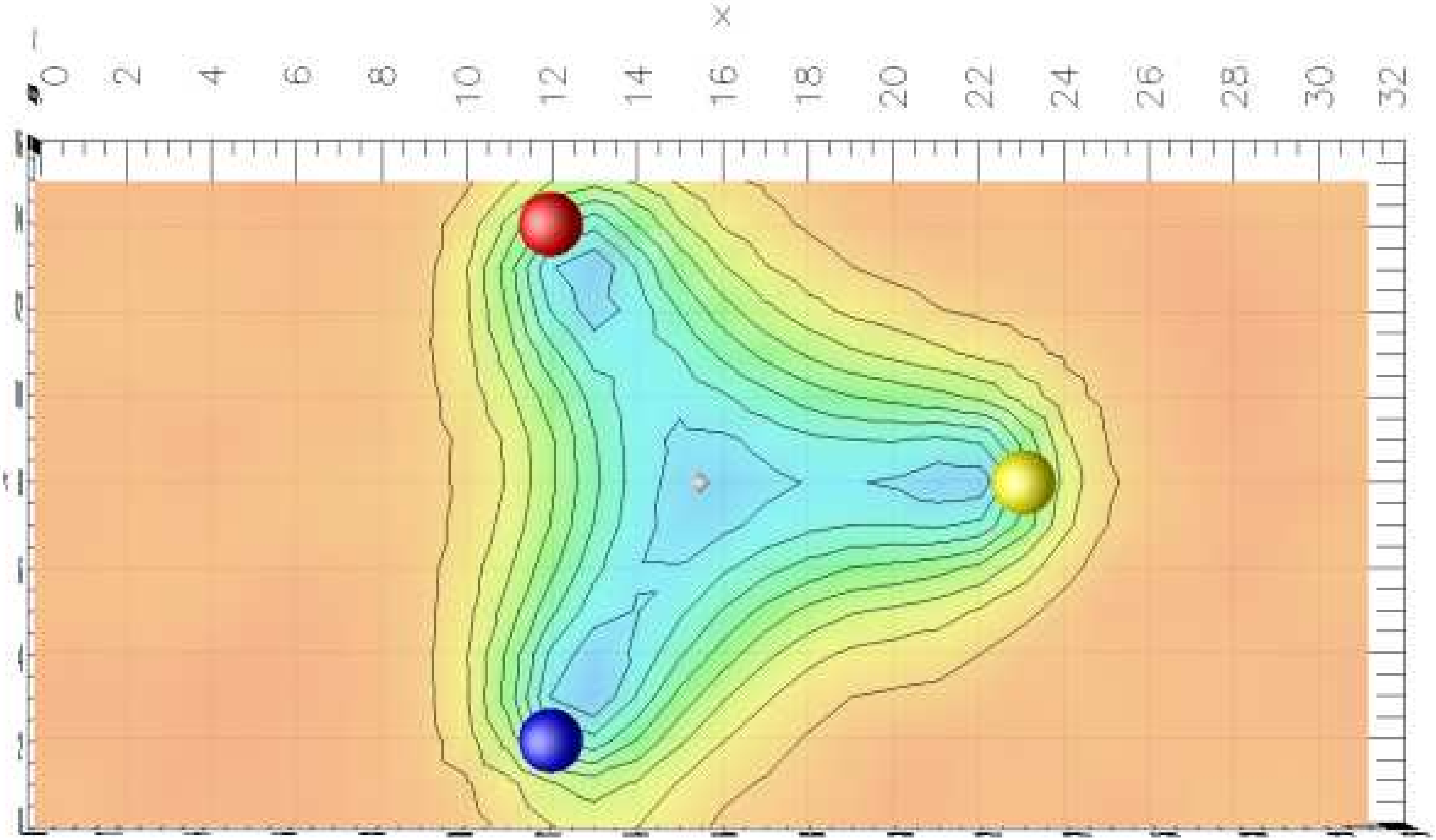
- Similar results are observed for $\vec{E}^2$ and $\vec{B}^2$ separately.

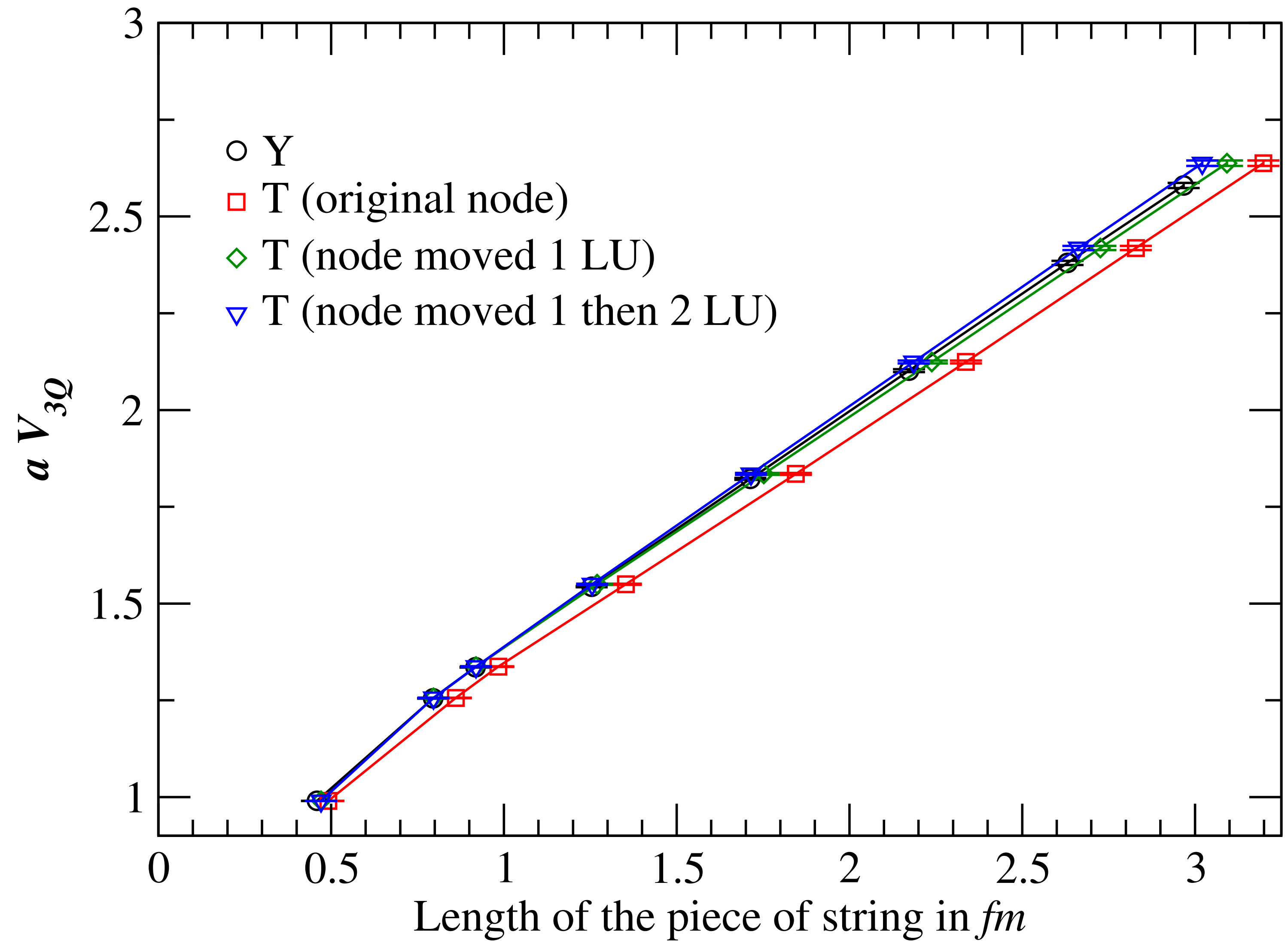
30-sweep T-shape Source



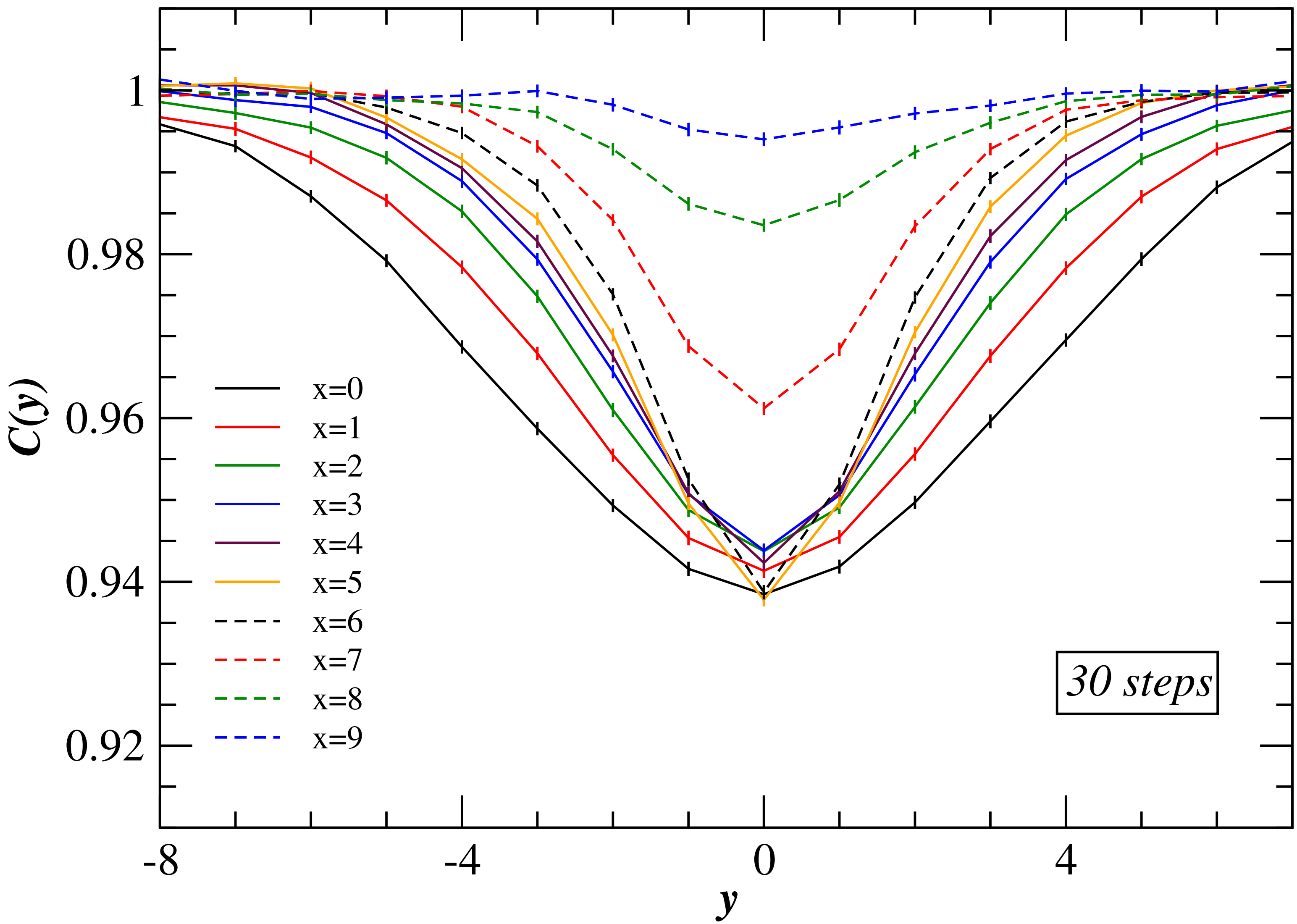
30-sweep Y-shape Source



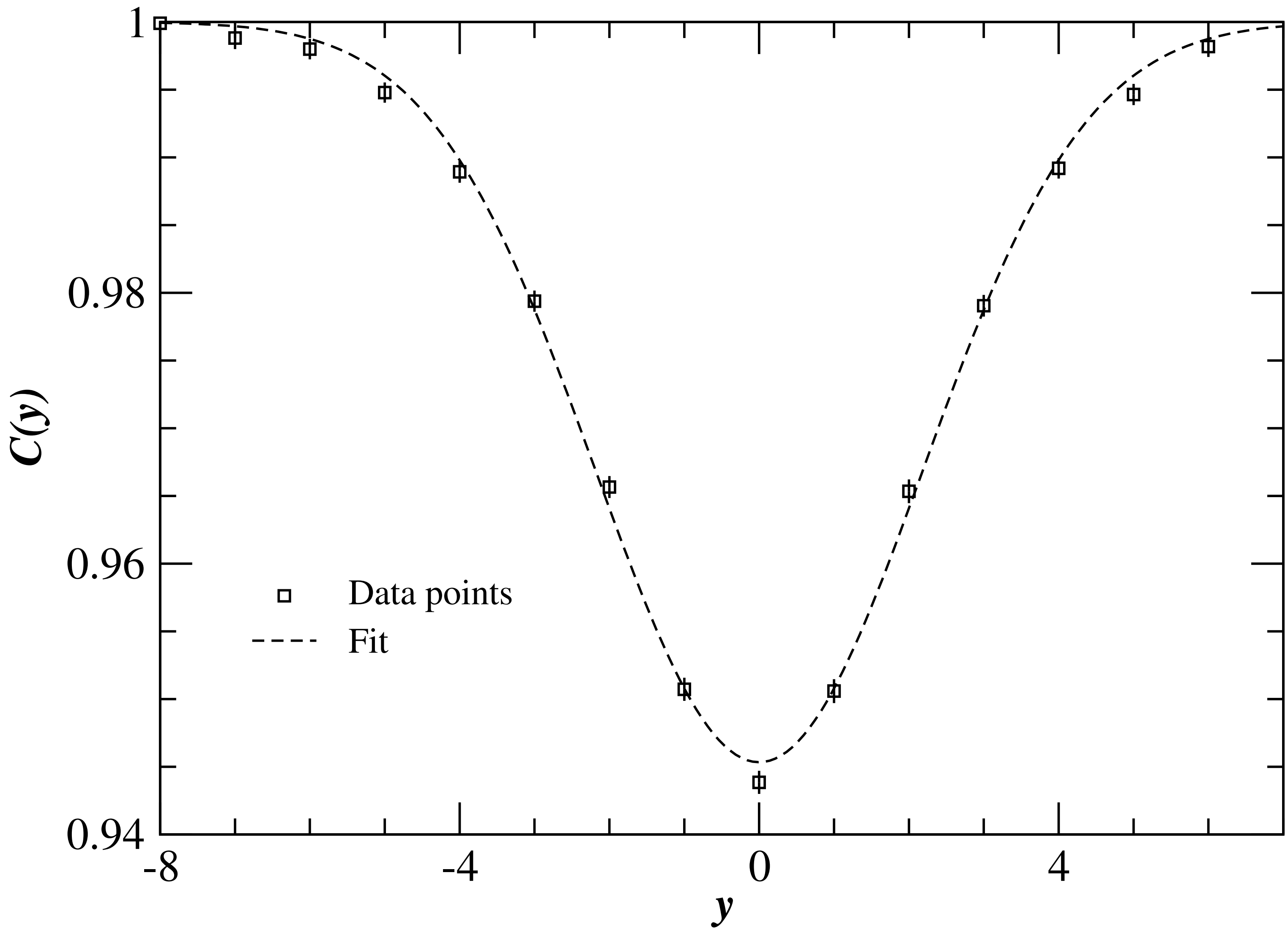
Effective Potential at $\tau = 1 \rightarrow 2$



Flux Tube Cross Section



Cross Section Fit



Baryonic Ground State Properties

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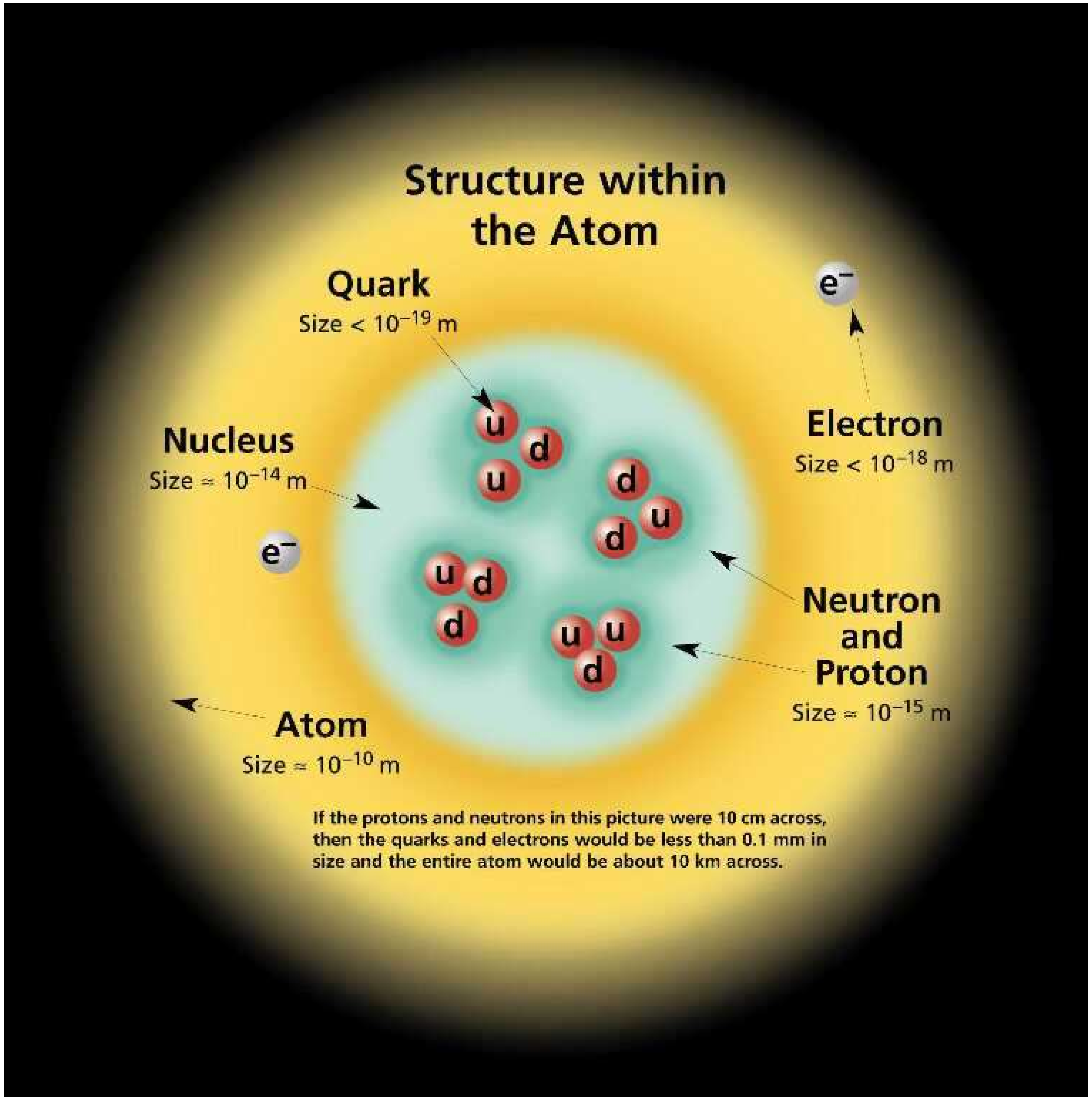
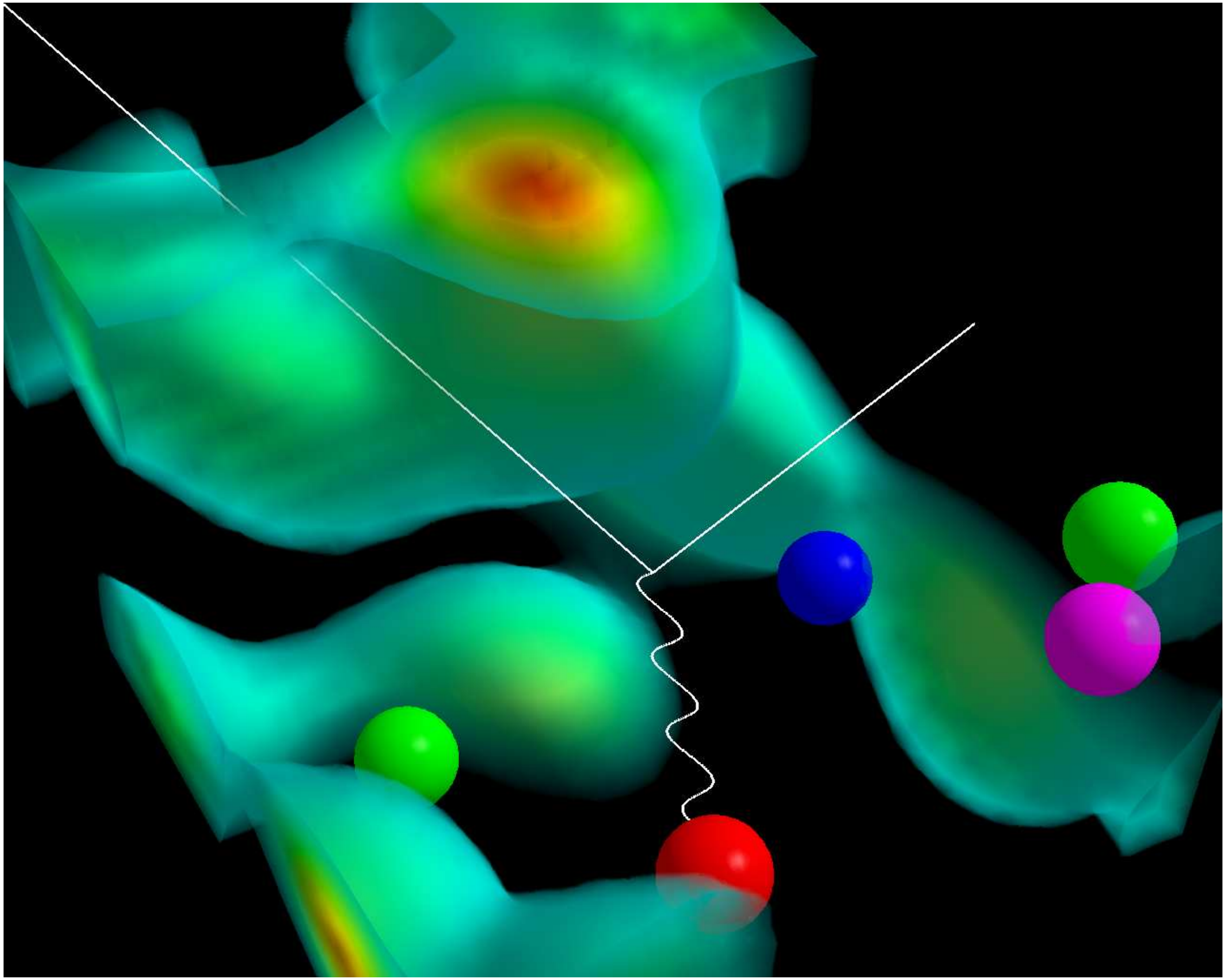
- Vacuum-field action suppressed by 7.2(6)%.
- Flux-tube node is 25% larger at 0.47(2) fm.
- Vacuum-field action suppression is 15(3)% larger at 8.1(7)%.

The Heart of the Atom



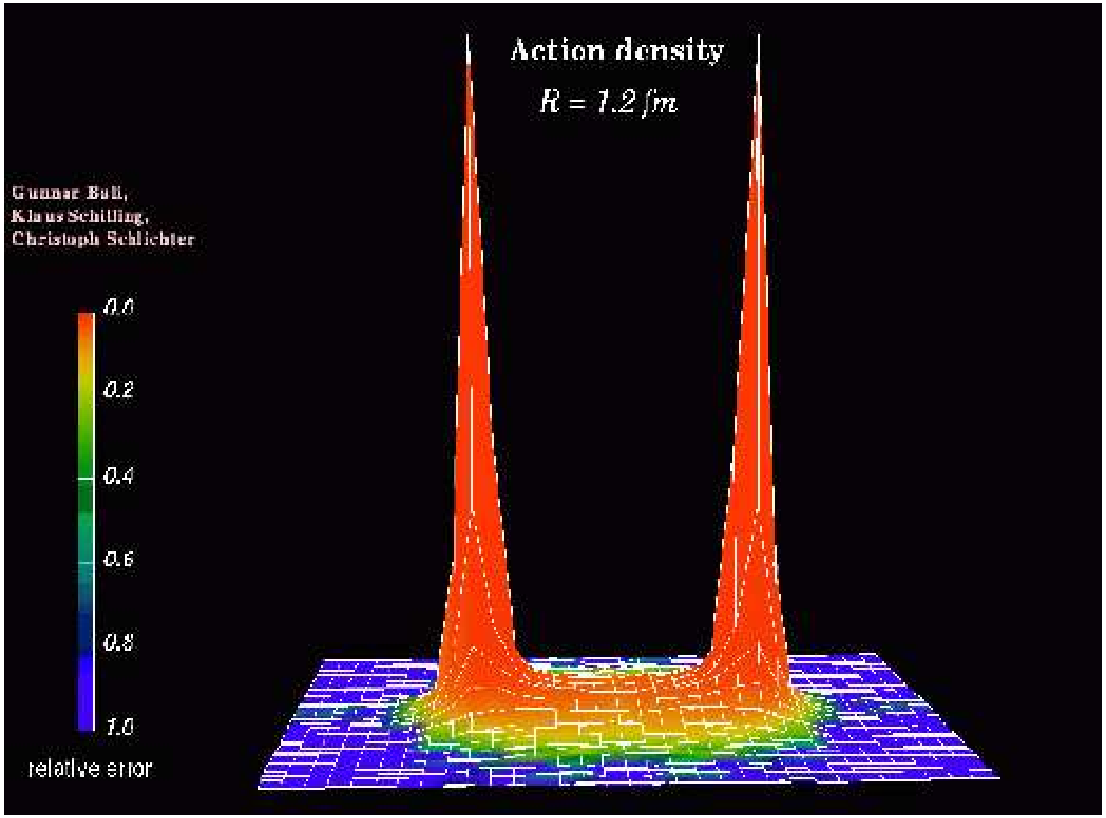
The Structure of the Nucleon



Information on the Web

- The software used to create the animations is
  - Advanced Visual System's AVS/Express
  - http://www.avs.com/
- Many of these animations are available on the web.
- http://www.physics.adelaide.edu.au/theory/staff/leinweber

Flux Tubes in SU(2) Gauge Theory



- G.S. Bali, K. Schilling and C. Schlichter (Wuppertal U.)
  - Phys. Rev. **D51** (1995) 5165

Enhancement or Expulsion?

- It is common to express the correlation as

$$C_S(\vec{y},\vec{d}) = \frac{\langle Q(\vec{x})\ S(\vec{y}+\vec{x})\ Q^\dagger(\vec{x}+\vec{d})\rangle_{\vec{x}}}{\langle Q(\vec{x})\ Q^\dagger(\vec{x}+\vec{d})\rangle_{\vec{x}}} - \langle S(\vec{x})\rangle_{\vec{x}}$$

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- In Euclidean space

$$S(\vec{x}) = \frac{1}{2} tr\left(\vec{B}^2_{\rm Eucl} + \vec{E}^2_{\rm Eucl}\right) = \frac{1}{2} tr\left(\vec{B}^2 - \vec{E}^2\right) > 0$$

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- The sign of the correlation may be selected freely.

Gluon Field Distribution in Mesons

- How does the Vacuum respond to the presence of Quarks?

$$C(\vec{y},\vec{d}) = \frac{\langle Q(\vec{x})\ S(\vec{y}+\vec{x})\ Q^{\dagger}(\vec{x}+\vec{d})\rangle_{\vec{x}}}{\langle Q(\vec{x})\ Q^{\dagger}(\vec{x}+\vec{d})\rangle_{\vec{x}}\ \langle S(\vec{x})\rangle_{\vec{x}}}$$

- $Q(\vec{x})$ denotes a quark at position $\vec{x}$.
- $Q^{\dagger}(\vec{x}+\vec{d})$ denotes an antiquark at position $\vec{x}+\vec{d}$.
- $S(\vec{y}+\vec{x})$ denotes the action density at position $\vec{y}$ from the quark at $\vec{x}$.
- $\langle \ldots \rangle_{\vec{x}}$ denotes average over $\vec{x}$ and gluon field configurations.
- If there is no correlation between the action density and the locations of the quark and antiquark,

$$C(\vec{y},d) = 1\,.$$