Confinement of gluons

-

Operators, Green's functions and topological configurations

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Overview

- Confinement
  - What is it, how do we see it & why is it there?
  - Gribov-Zwanziger scenario & the Faddeev-Popov operator

Reviews: Alkofer et al. PR 2000, Greensite PNPP 2003, Fischer JPG 2005

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- The role of topological configurations
- Summary & outlook

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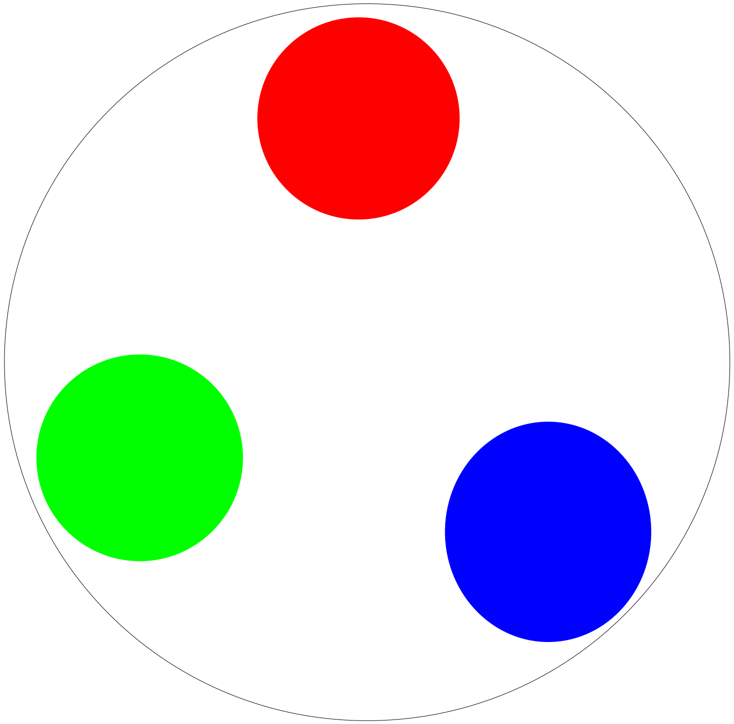
- Substructure cannot be isolated: Confinement

Substructure: Quarks and gluons

- Baryon: 3 (valence-)quarks



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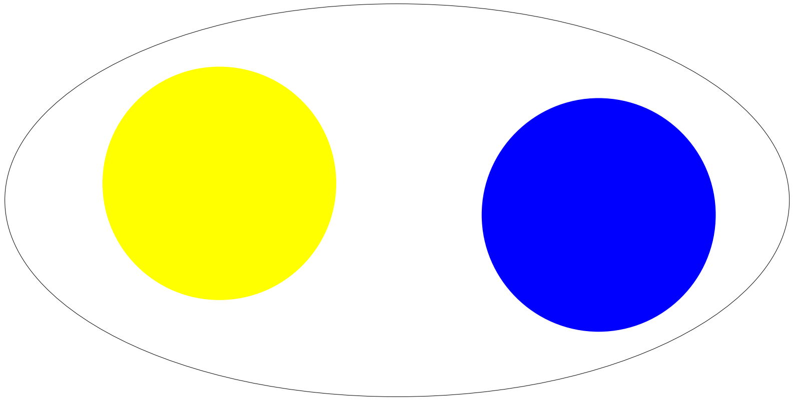

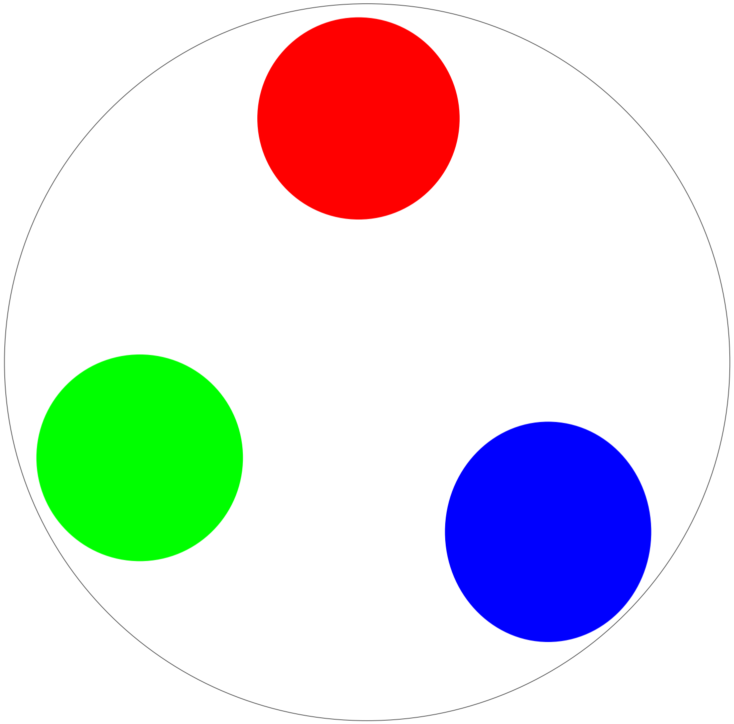

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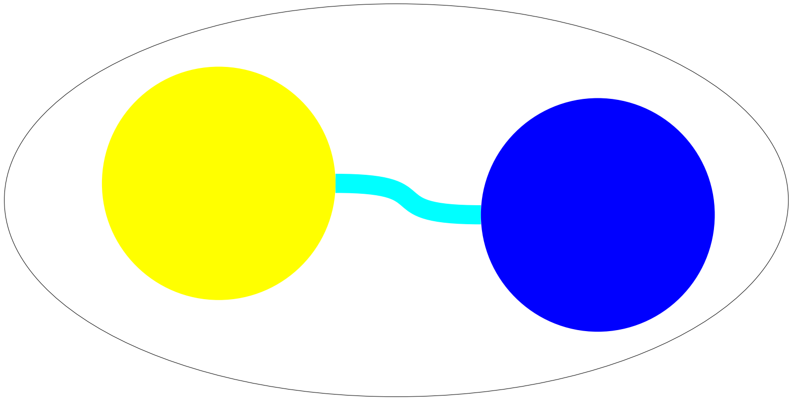

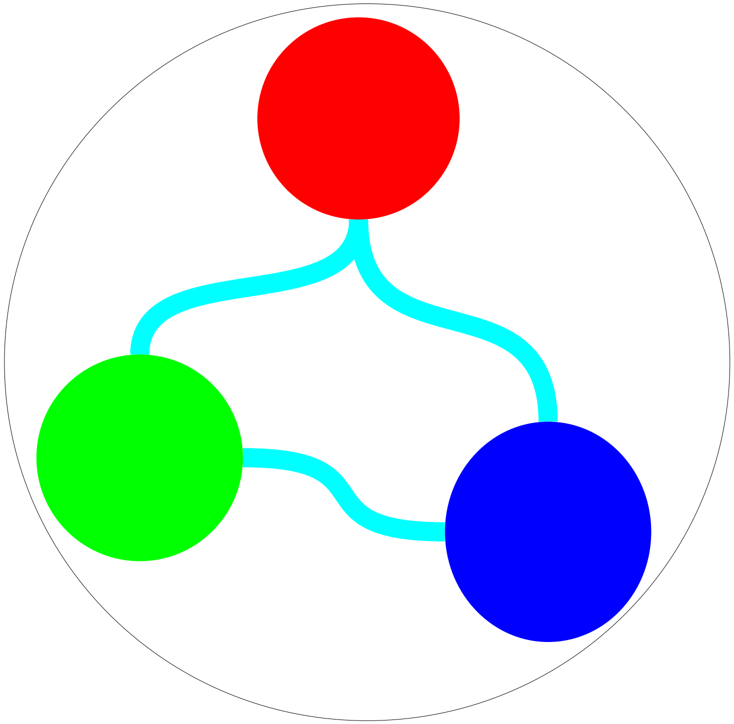

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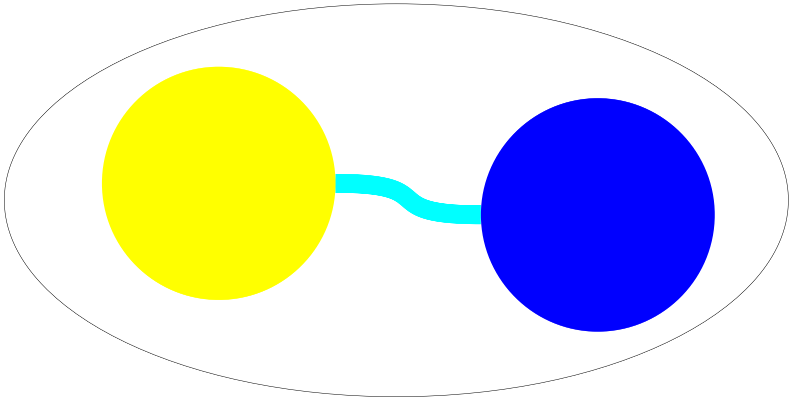

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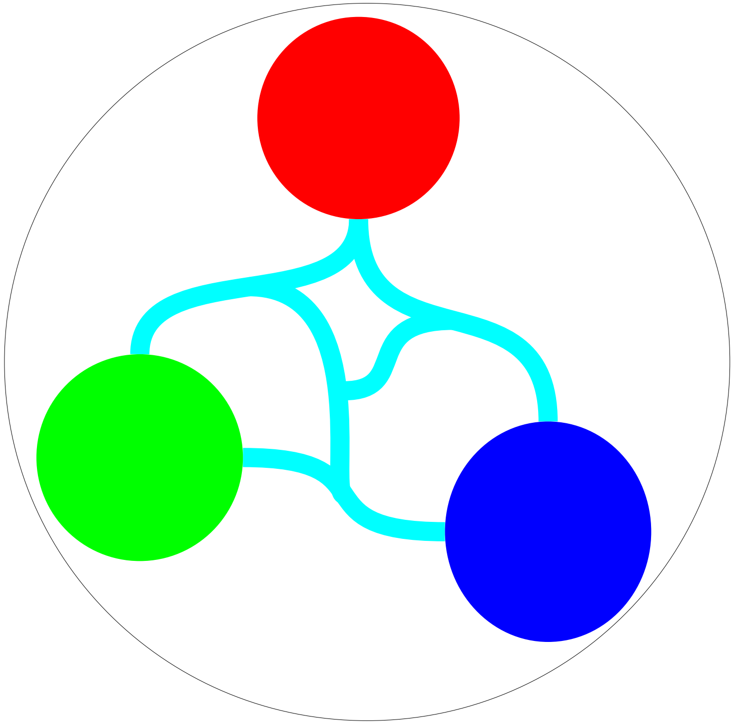

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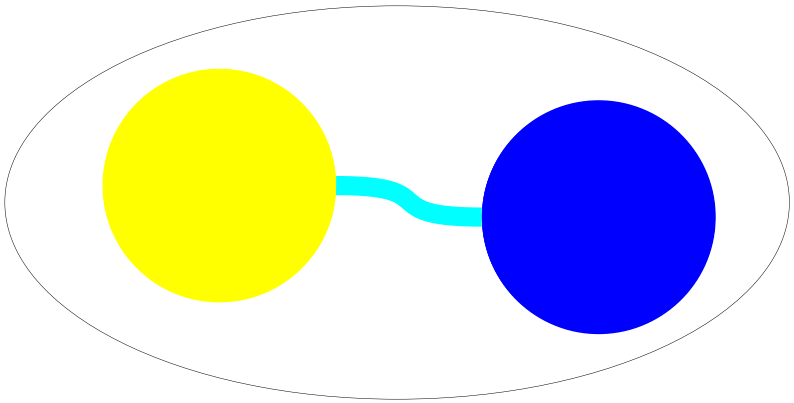

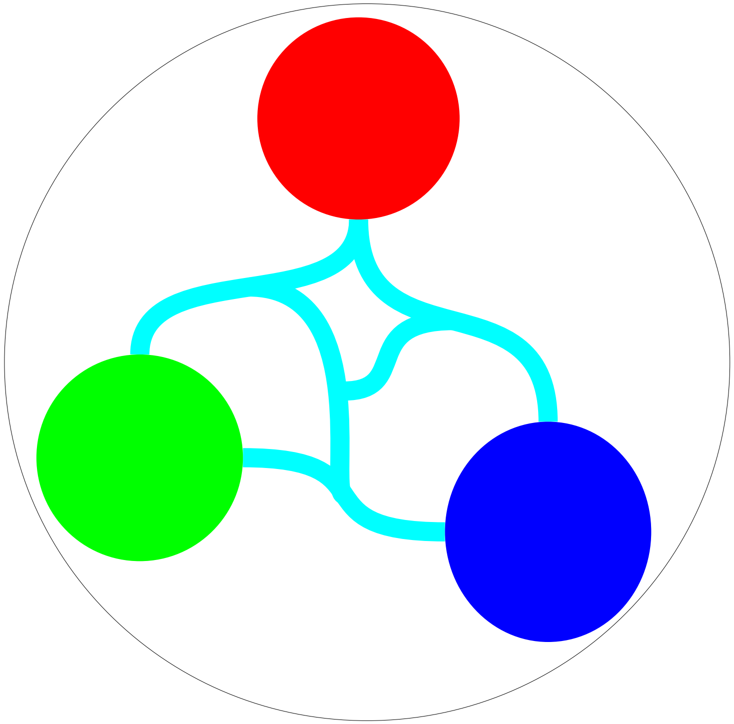

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- Gluons are also charged
- No free quarks and gluons: Confinement
  - Measured to very high precision for quarks

QCD - The theory of quarks and gluons

- QuantumChromoDynamics is a gauge theory

$$L = -\frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \bar{\Psi}(\gamma_\mu D_\mu + m)\Psi$$

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- Quarks (likely) subject to, but not source of confinement - Gluons alone: Yang-Mills theory

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  - How to establish confinement?

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  - Sum rule for gluons

$$Overlap\ with\ one\ particle + \int dq^2\, spectral\ function(q^2) = \frac{1}{Z_3} = 0$$

    - Z_3 (divergent) renormalization constant
    - Likely also valid at finite temperature

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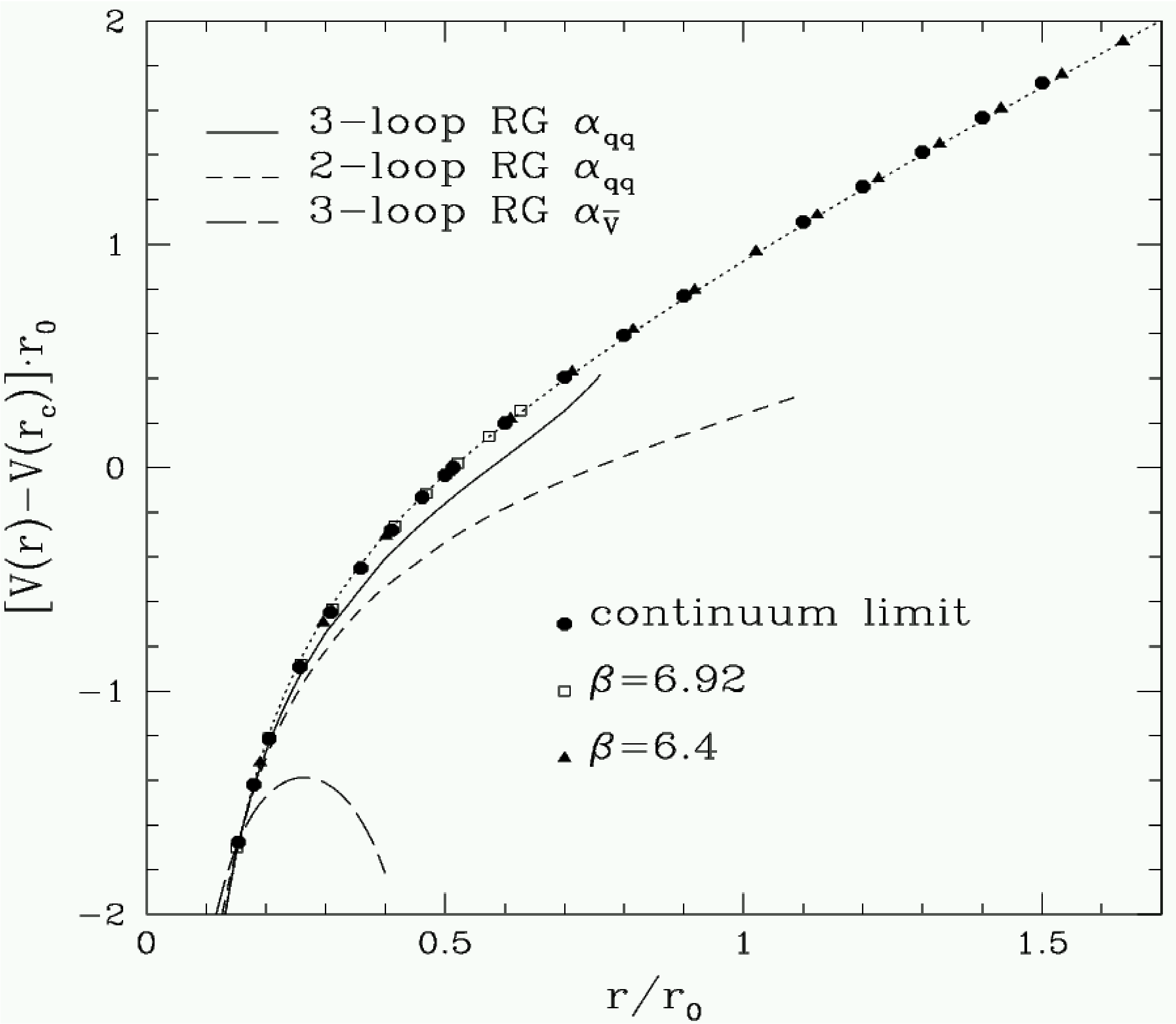
Confinement of quarks

- Inter-quark potential confining



[Figures from Sommer et al., 2001)]

Confinement of quarks

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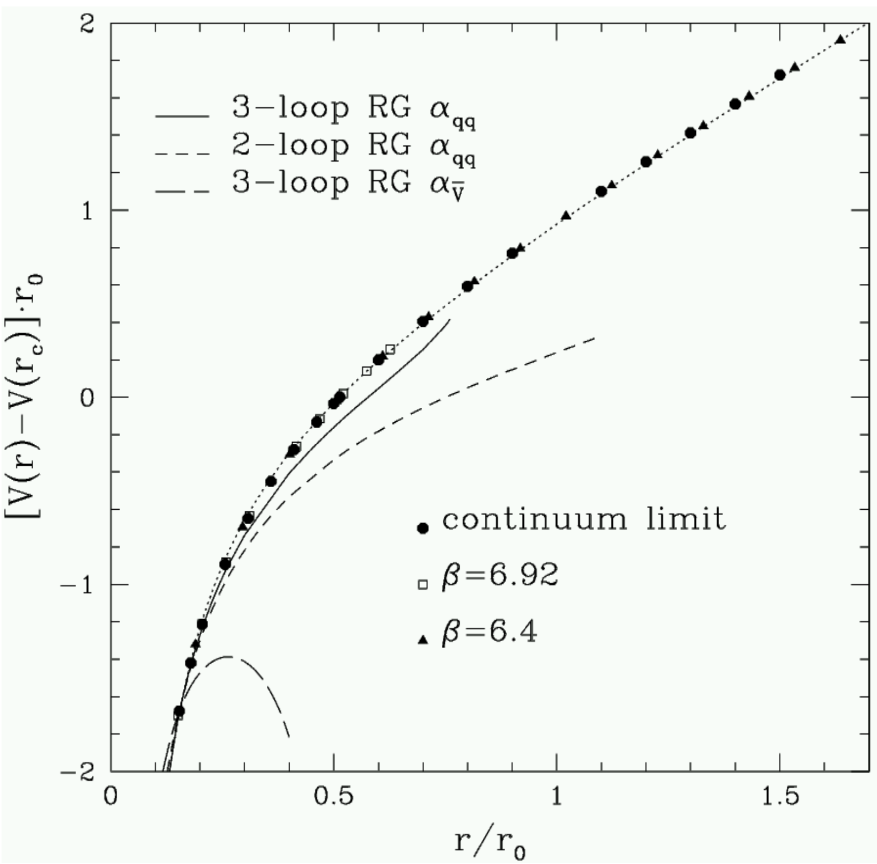
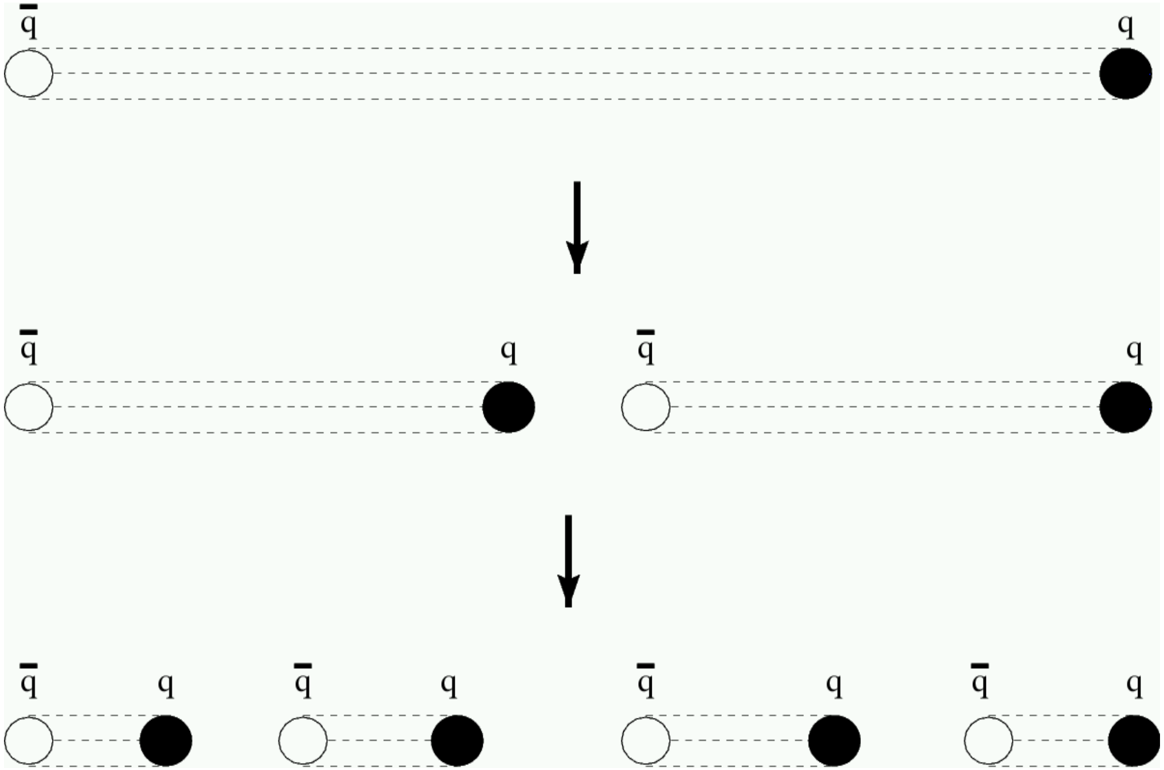
  - Flattened by string breaking





[Figures from Sommer et al., 2001 (left) and from Greensite, 2003 (right)]

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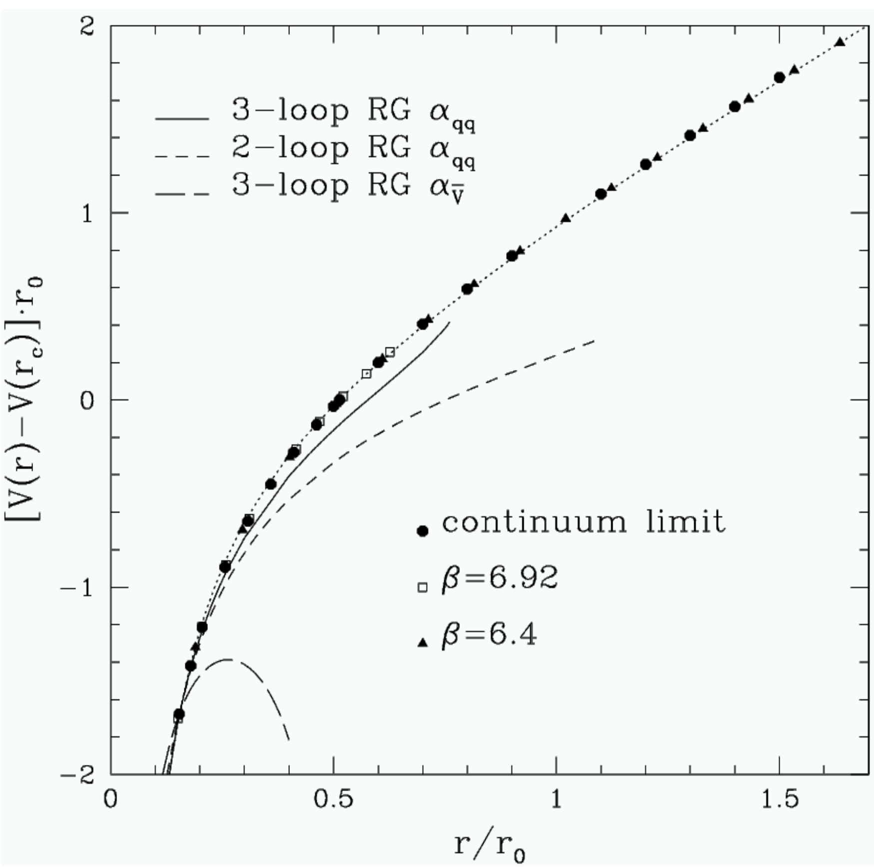
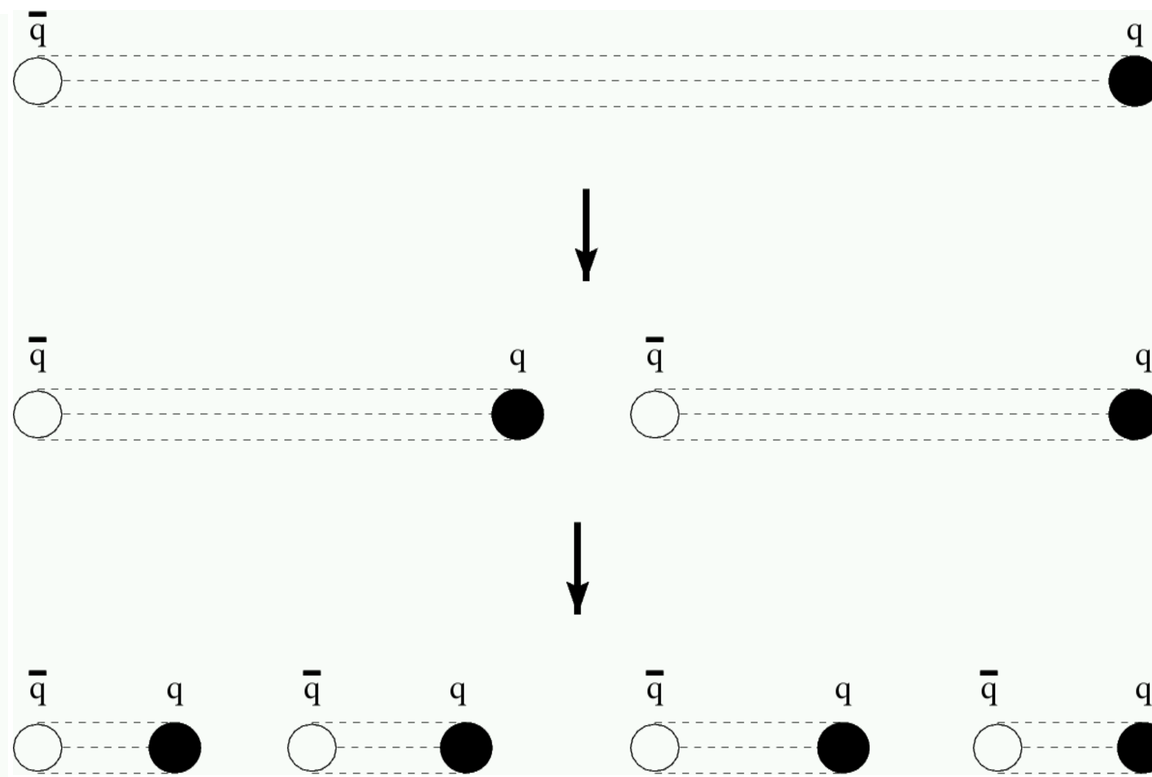
- Origin of linear potential?





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  - Works only for non-dynamic objects

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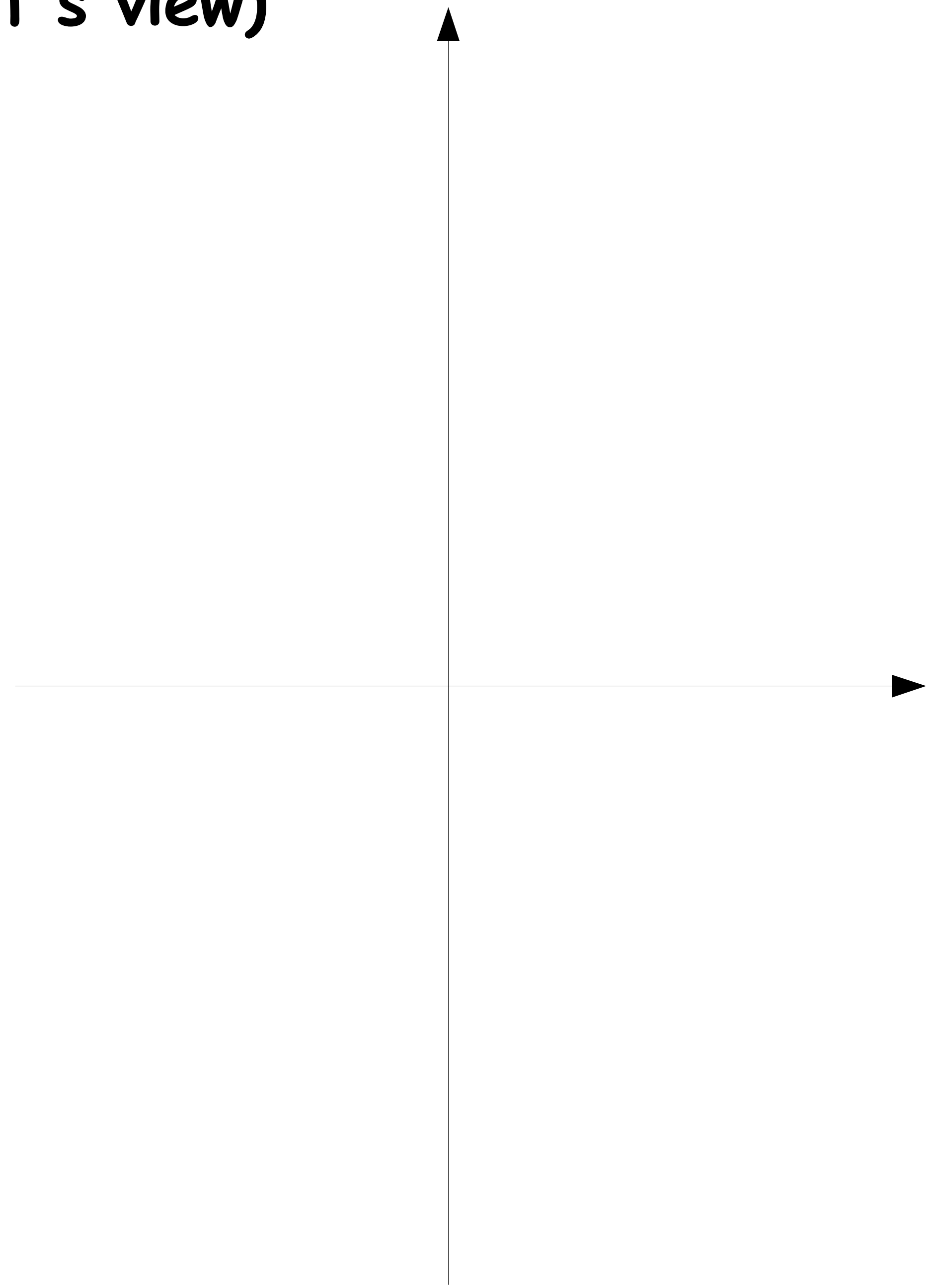

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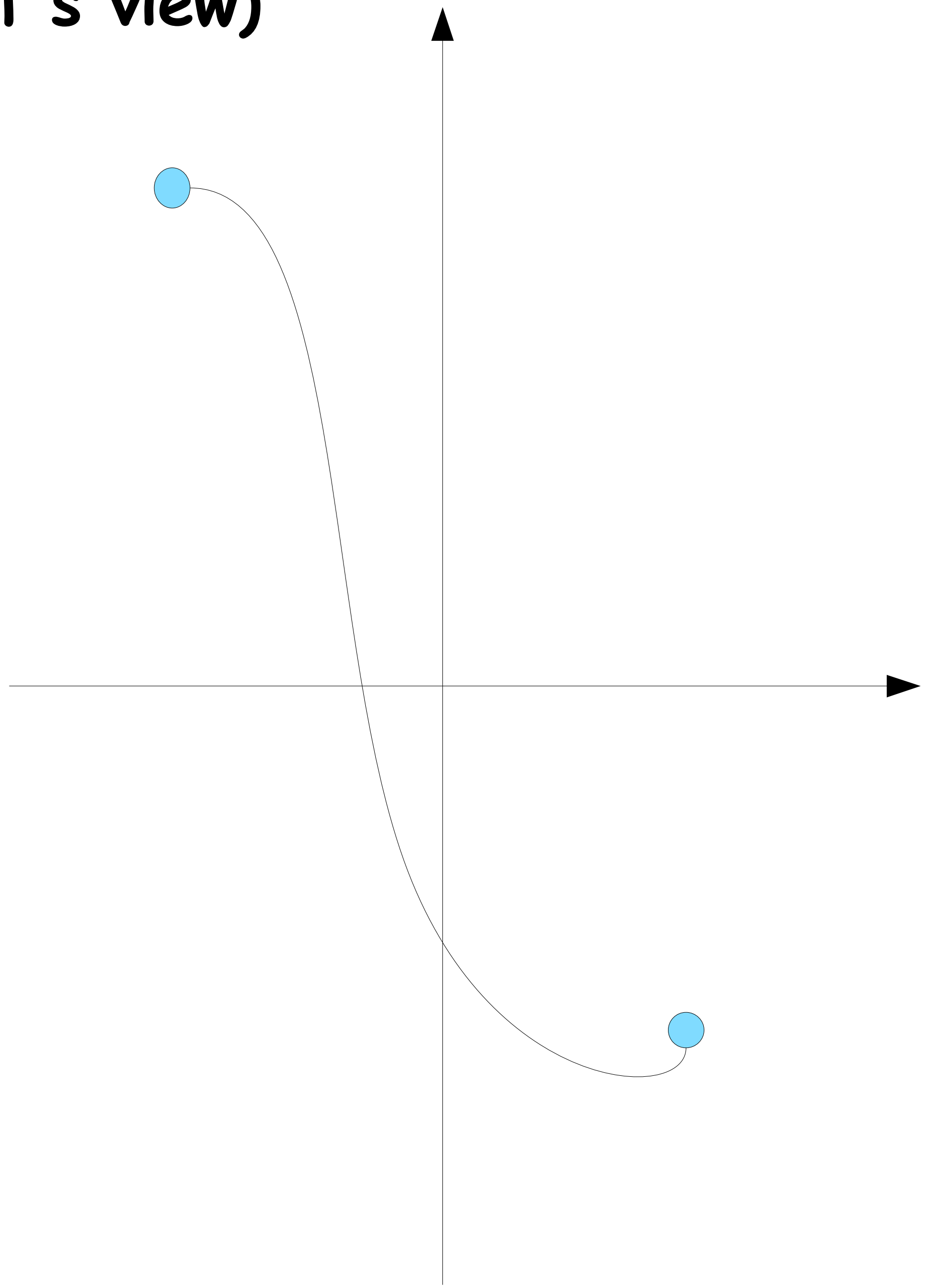

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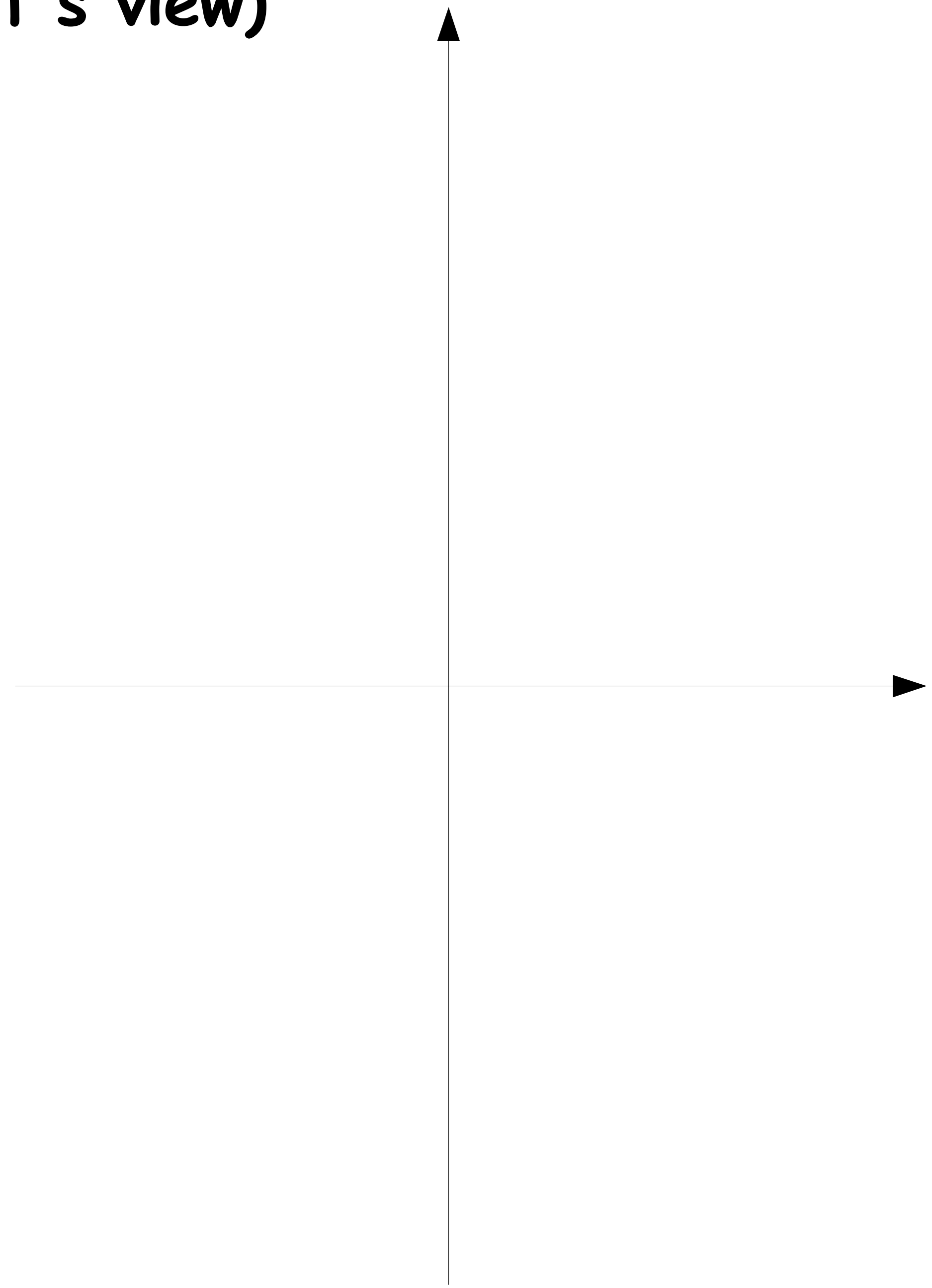

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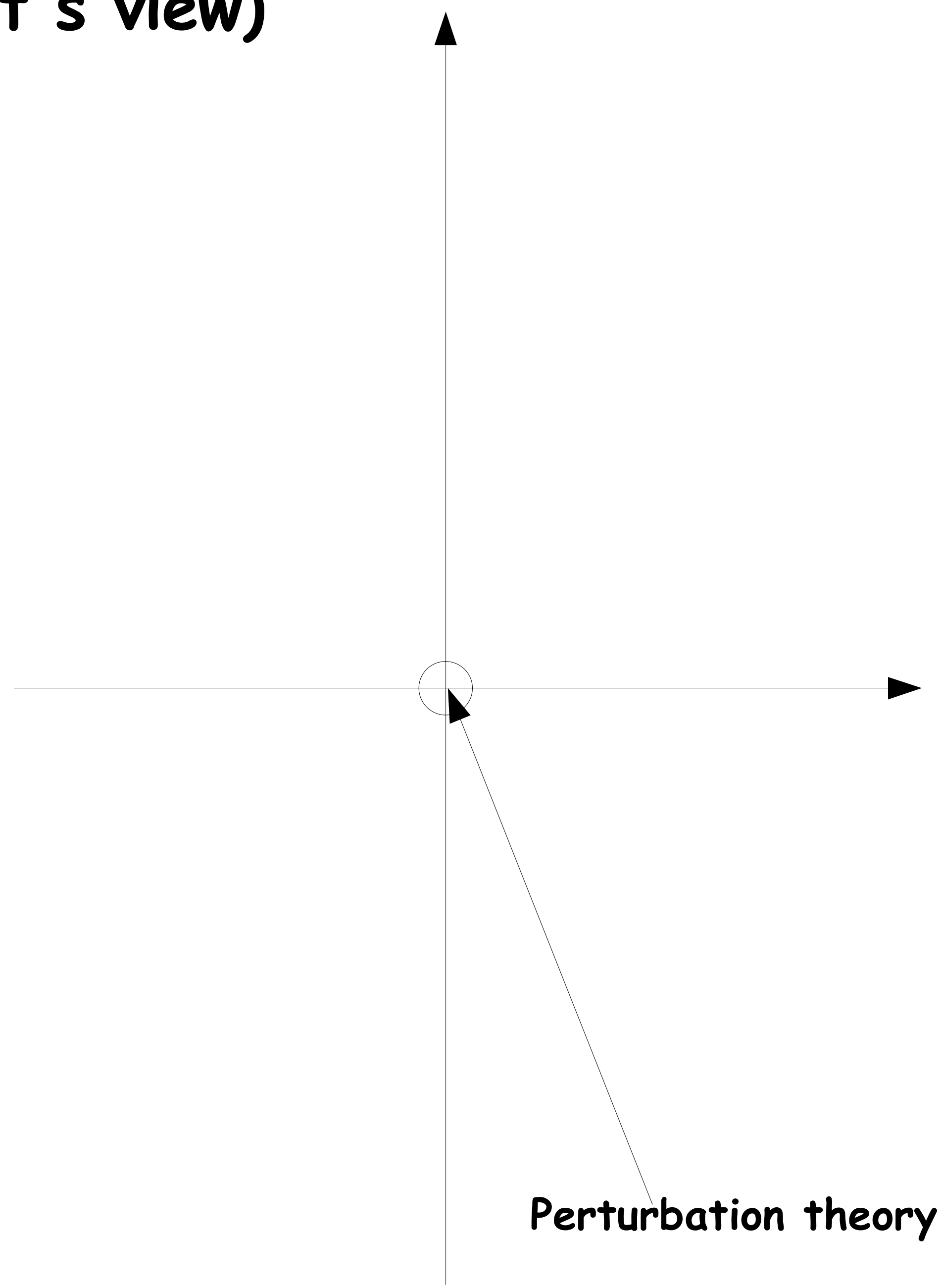

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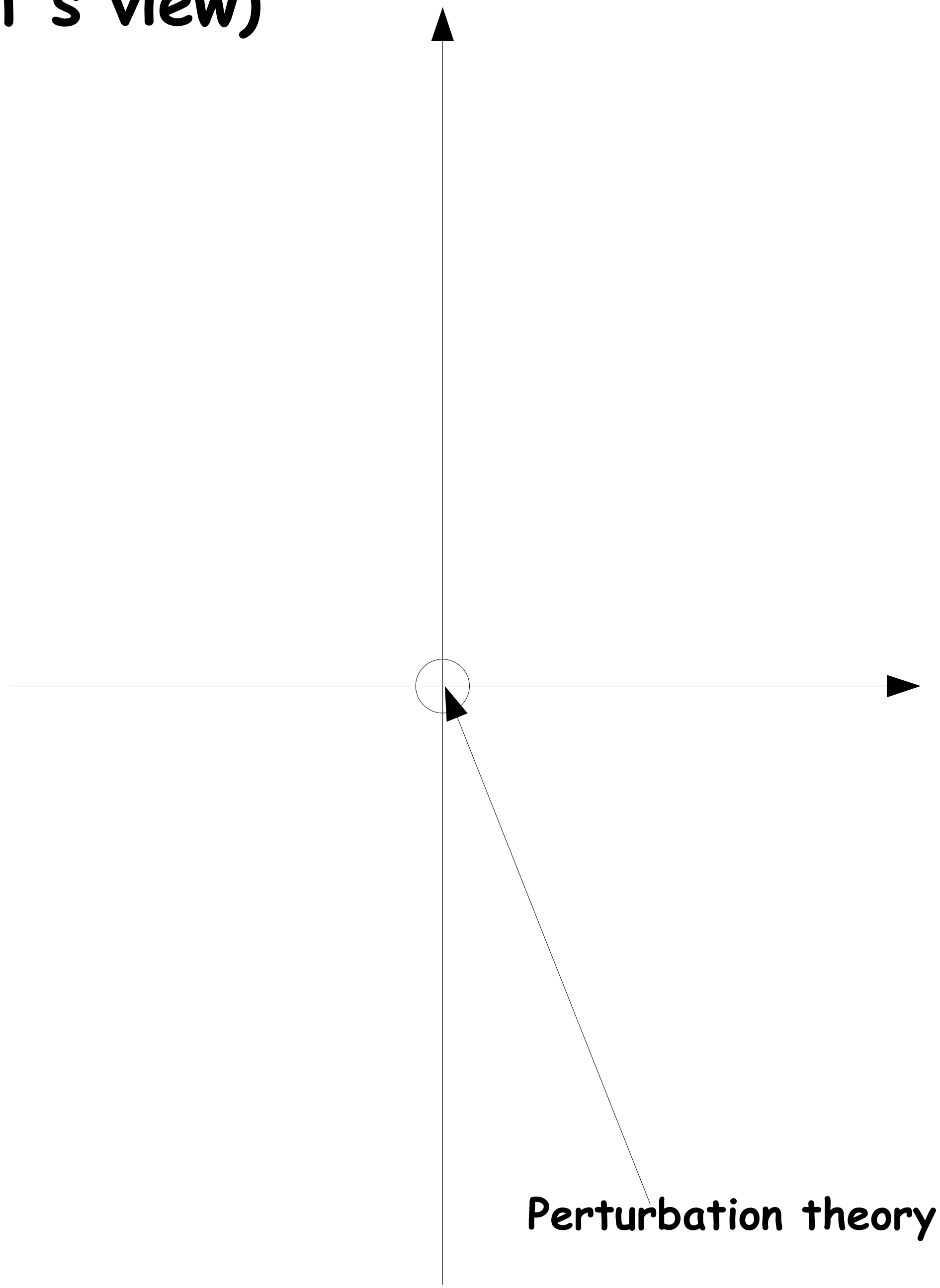

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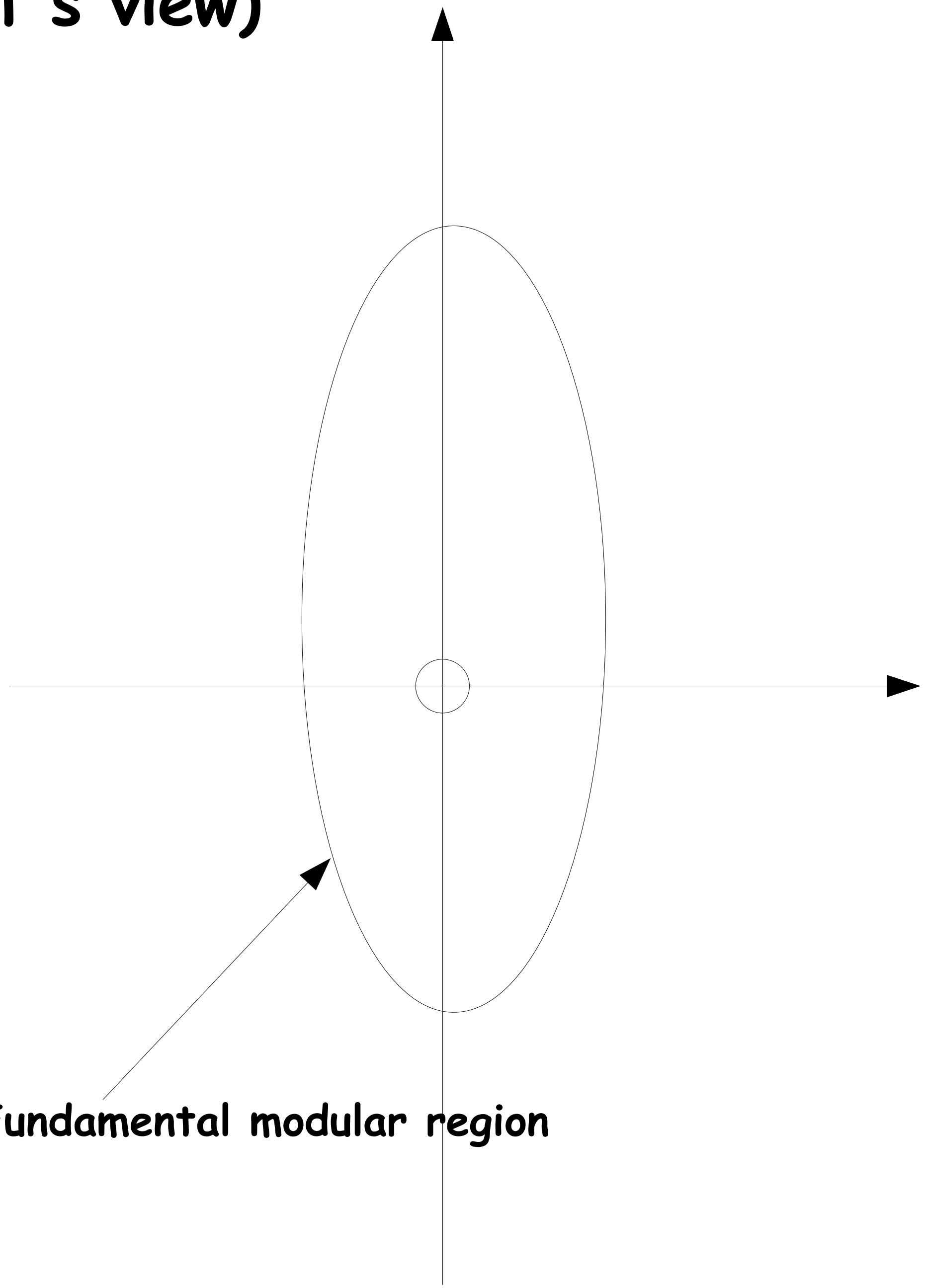

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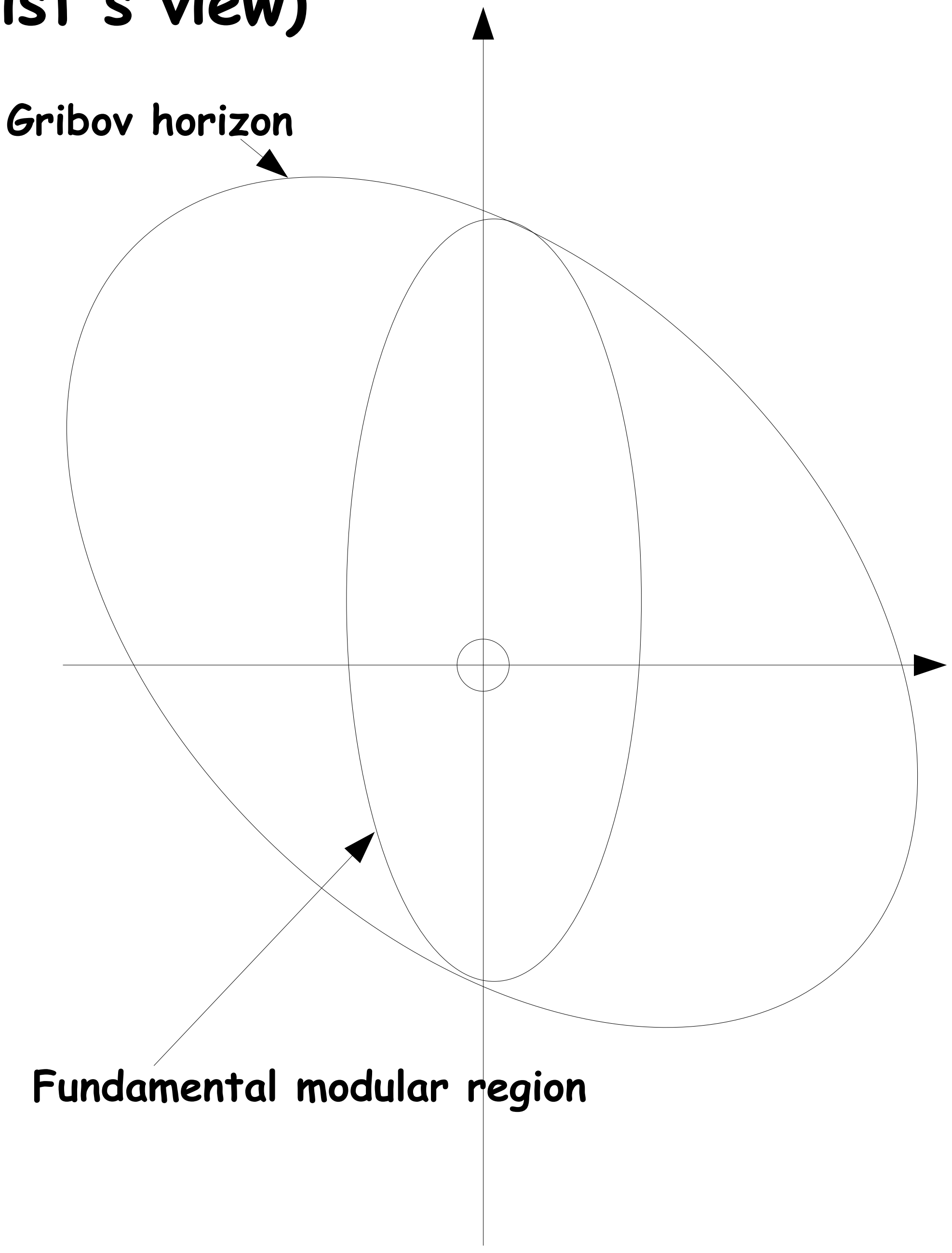

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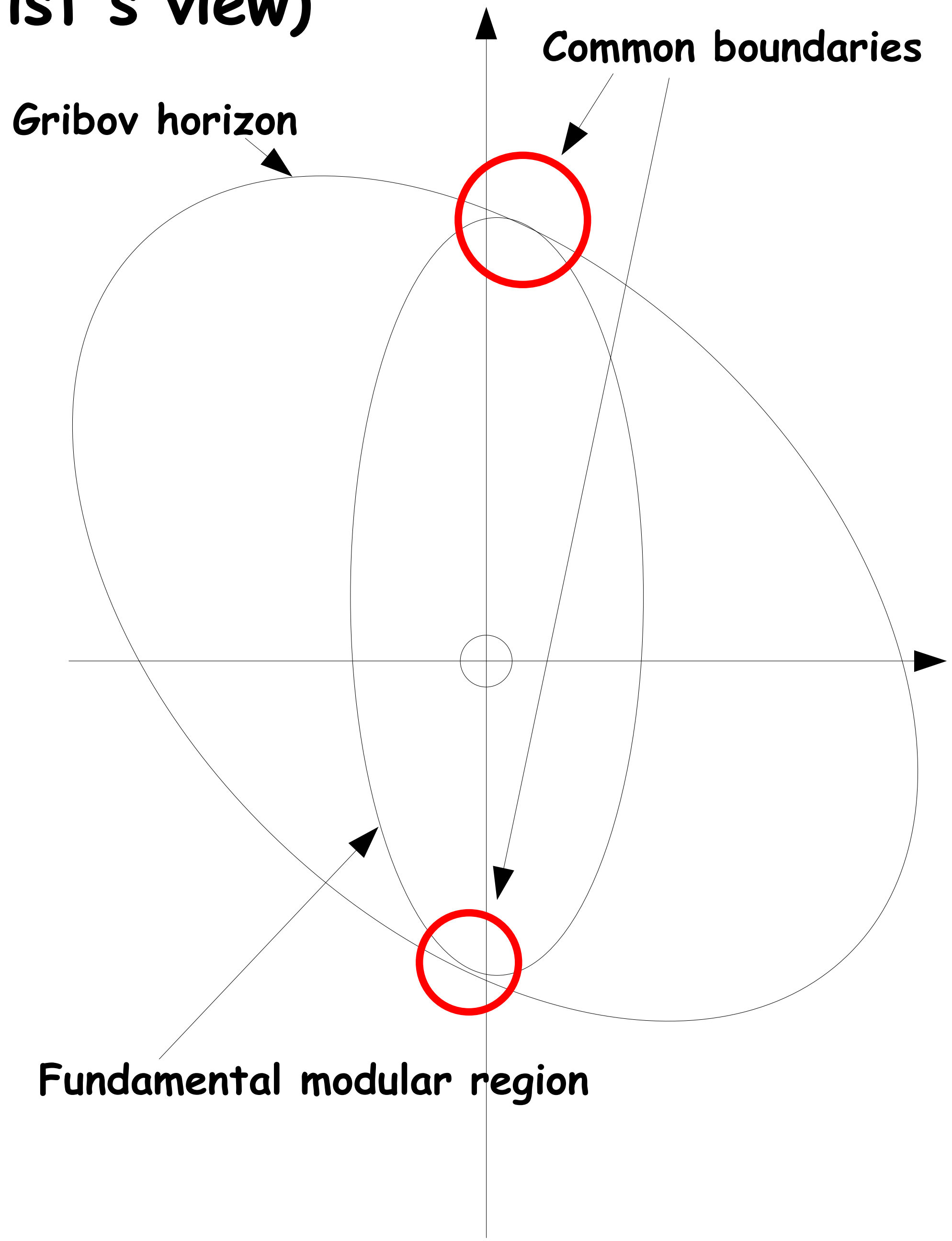

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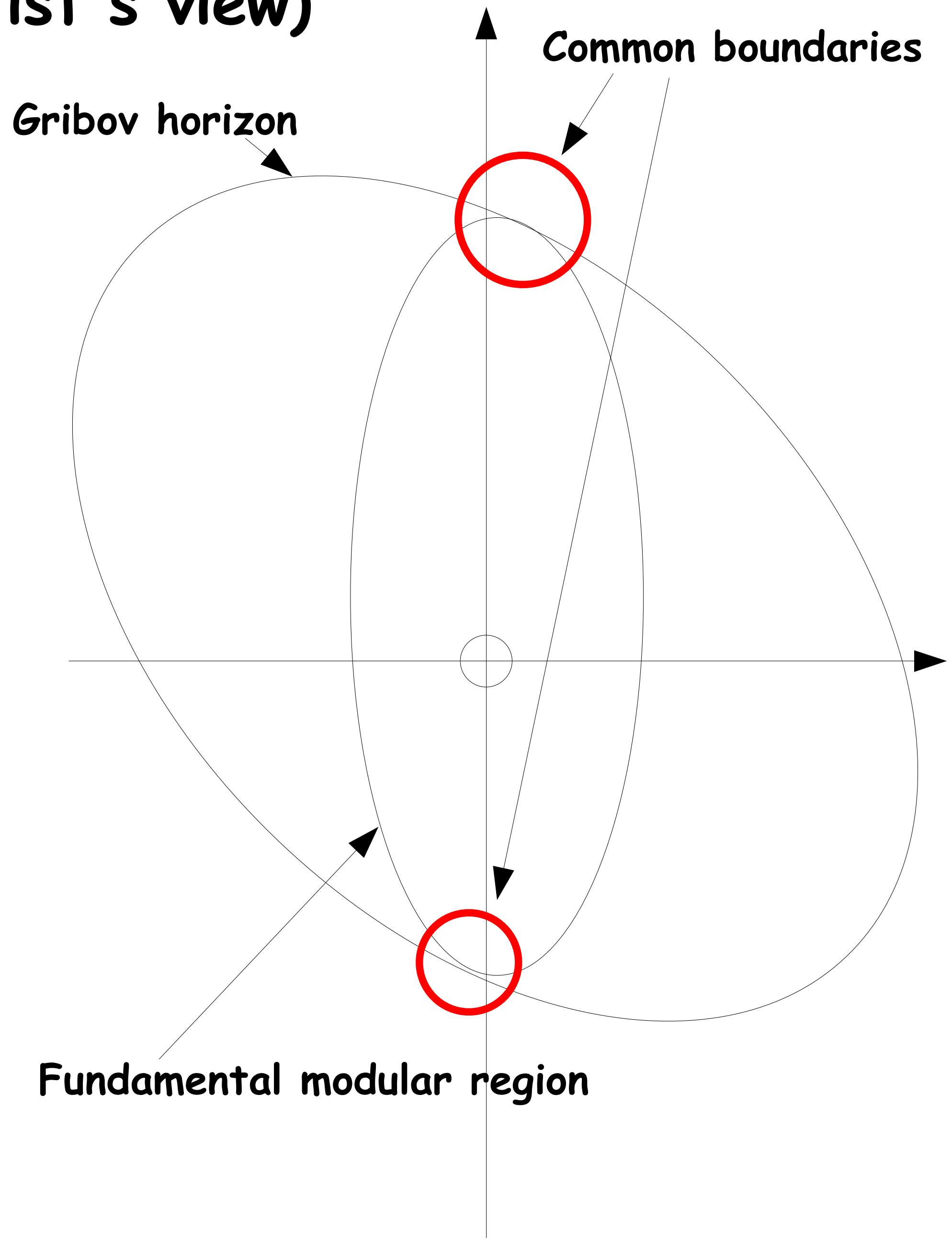

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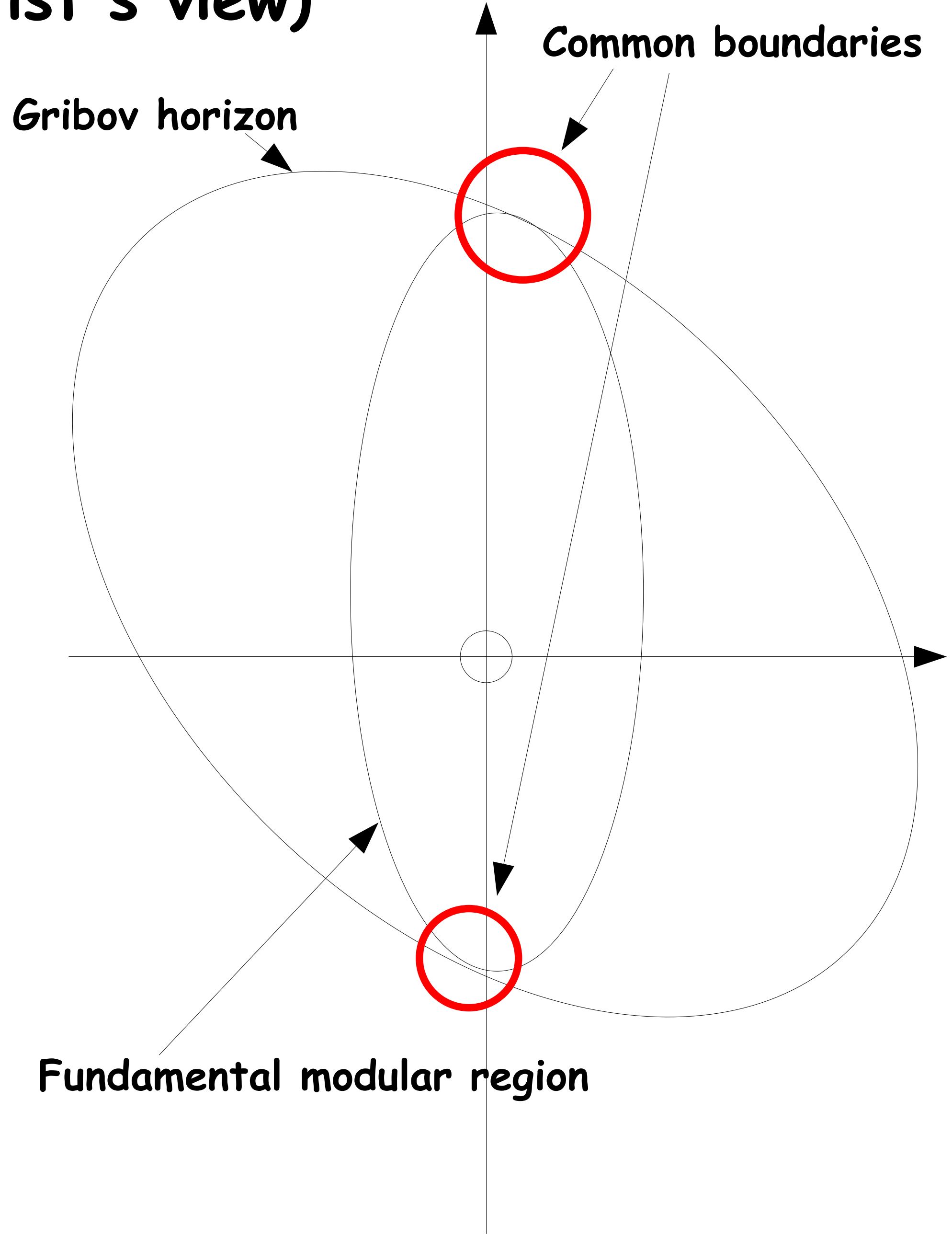

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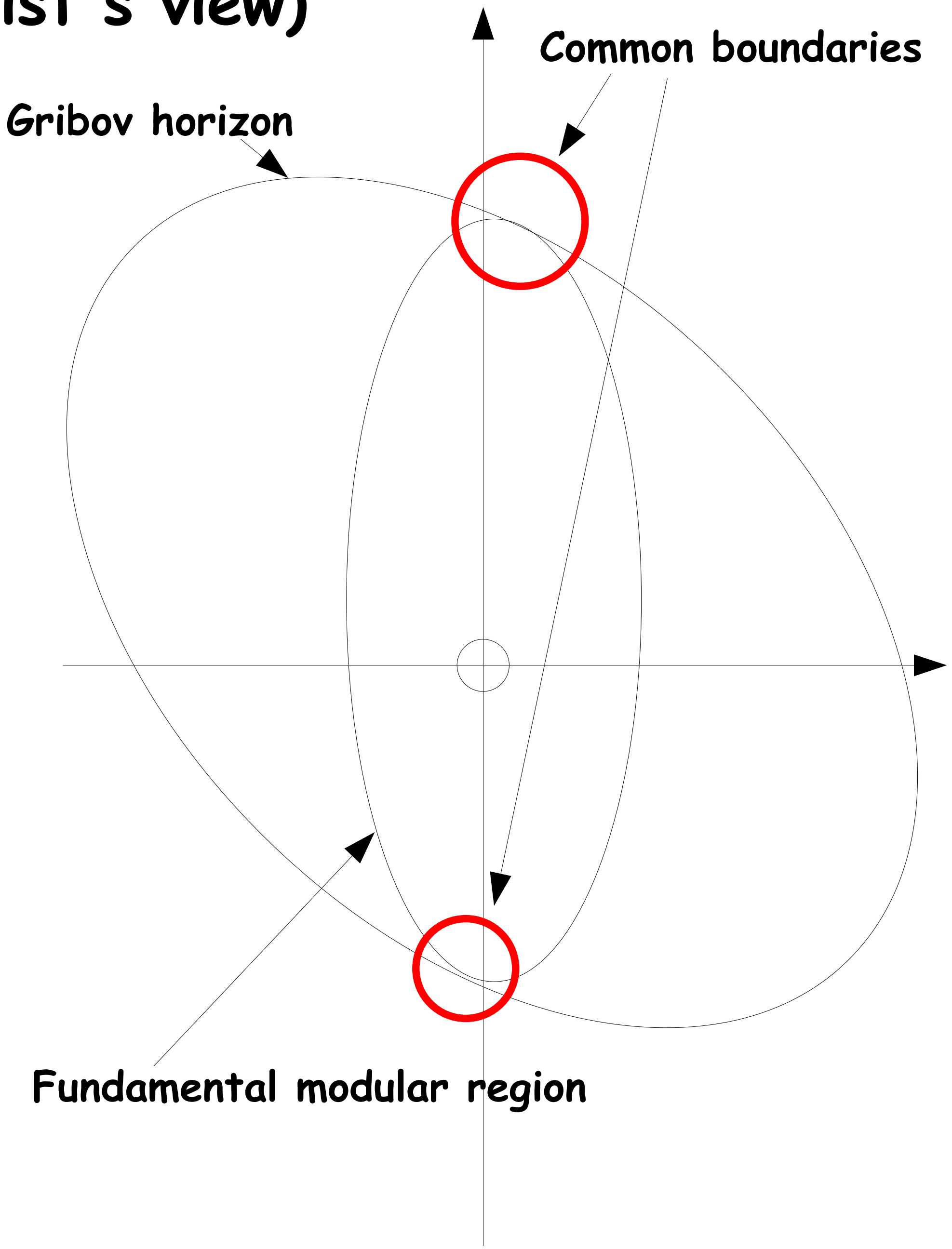

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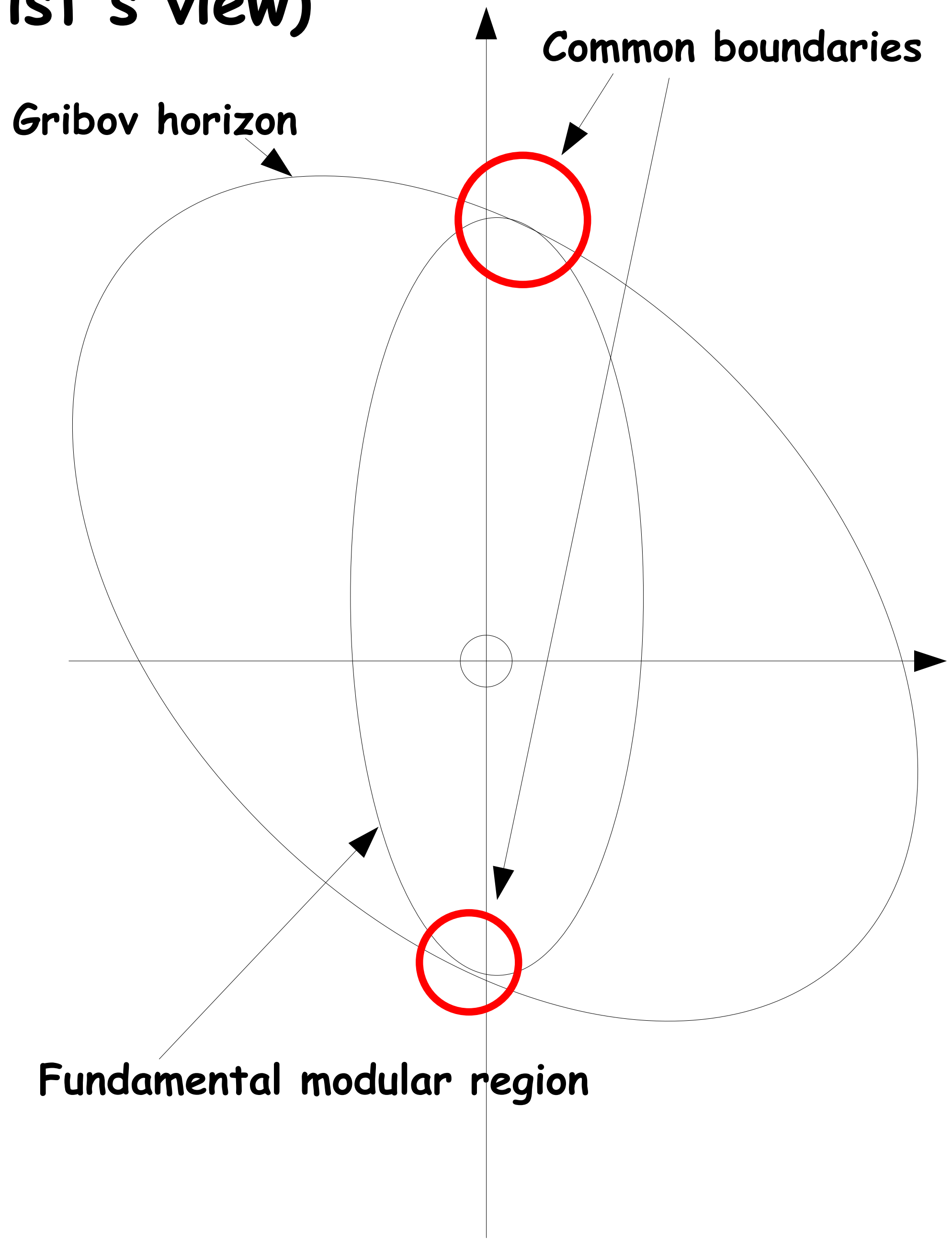
- Leads to positivity violating spectral functions



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Lambda gauges

- (Symbolic) Lagrangian for Gaussian average:

$$L=-\frac{1}{4}F_{\mu\nu}^{a}F_{\mu\nu}^{a}-\bar{c}^{a}\partial'_{\mu}D_{\mu}^{ab}c^{b}$$

$$F_{\mu\nu}^{a}=\partial_{\mu}A_{\nu}^{a}-\partial_{\nu}A_{\mu}^{a}-gf^{abc}A_{\mu}^{b}A_{\nu}^{c}$$

$$D_{\mu}^{ab}=\delta^{ab}\partial_{\mu}-gf^{abc}A_{\mu}^{c}$$

- Degrees of freedom:

Gluons: A_{μ}^{a}

Ghosts: $\bar{c}^{a}, c^{a}$

(Intermediate states - not observable)

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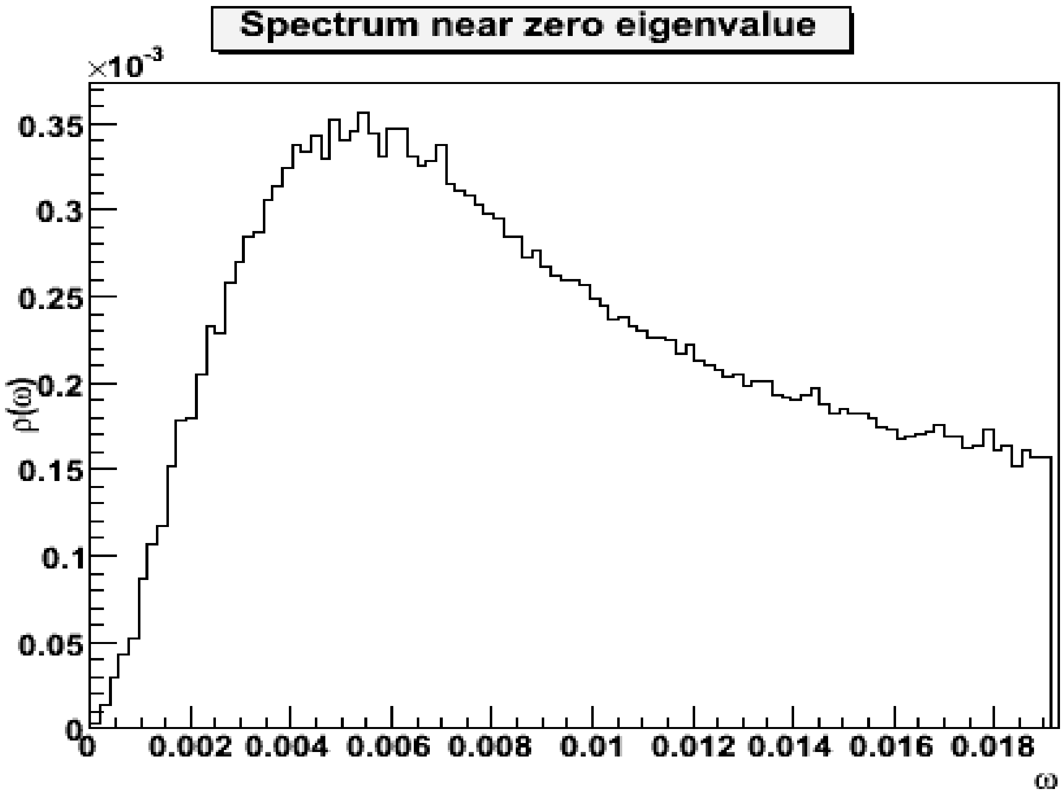
- Second-order differential operator ("Hamilton-like")
- Simpler in Landau gauge

$$M^{ab}=-\delta^{ab}\partial_\mu\partial_\mu+gf^{abc}A_\mu^c\partial_\mu$$

  - No (non-trivial) zero-modes in the vacuum

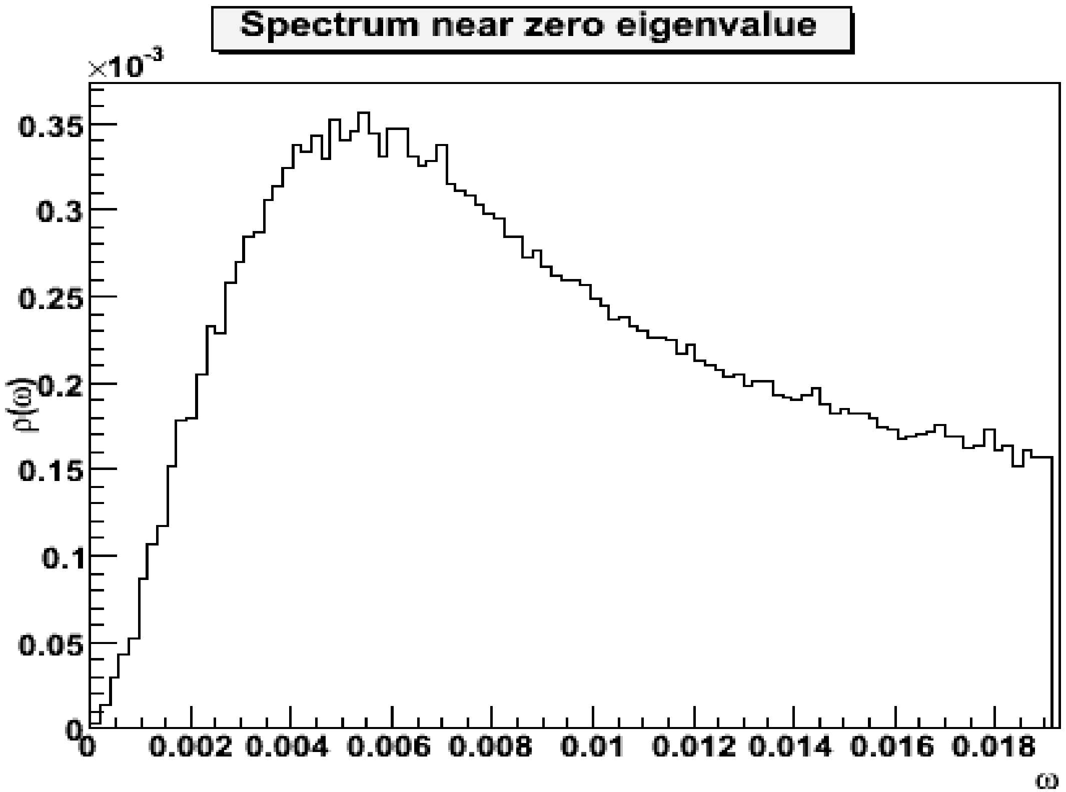
Landau-gauge Faddeev-Popov operator eigenspectrum

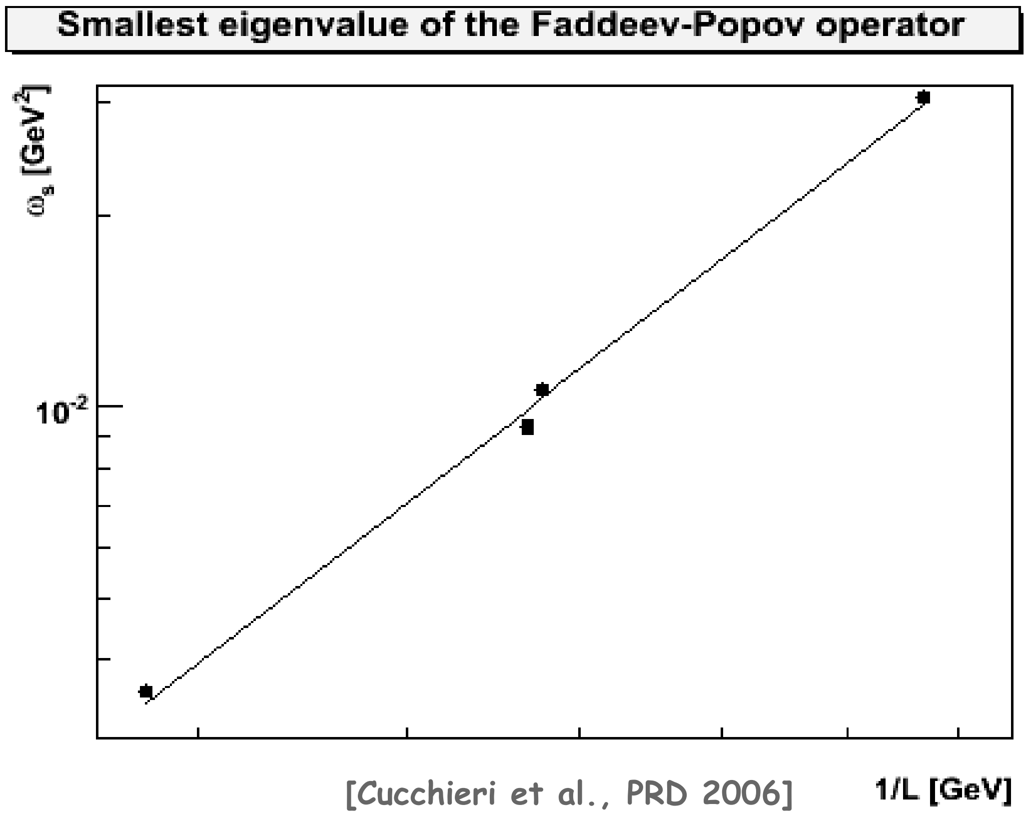


[Cucchieri et al., PRD 2006]

- Near zero **enhanced** compared to vacuum

Landau-gauge Faddeev-Popov operator eigenspectrum





[Cucchieri et al., PRD 2006]

- Near zero enhanced compared to vacuum
- Average configuration in the continuum limit on the Gribov horizon
- Agrees with Gribov-Zwanziger scenario

Propagators [Introduction: Alkofer et al., PR 2001]

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- Ghost linked to the Faddeev-Popov operator

$$D^{ab}_G(x-y) \sim <(\partial'_\mu D^{ab}_\mu)^{-1}> = <(\partial'_\mu(\delta^{ab}\partial_\mu-g f^{abc}A^c_\mu))^{-1}>$$

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      - Infrared enhancement - mediates long-range forces

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  - No further approximations
    - Assumption: Wick-rotation works
    - All non-perturbative effects taken correct

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Methods

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- Analytical methods – operators and topological objects
- Other methods
- Combination of methods necessary
  - Successful cooperation

Landau gauge

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- Most intensively studied gauge so far

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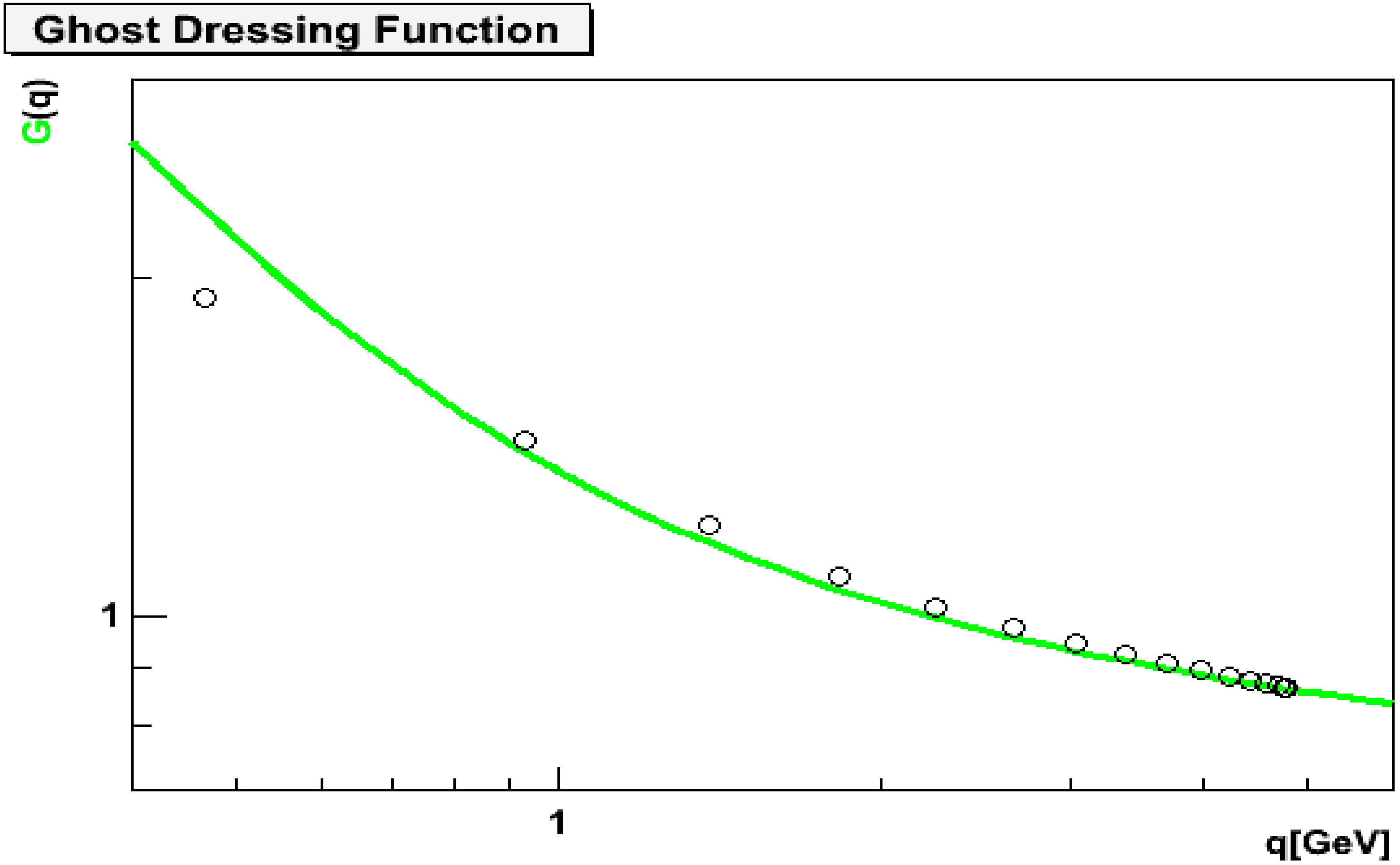
    - Numerical values of exponents under rather well-supported assumptions [Lerche et al., PRD 2002, Zwanziger PRD 2002]
      - Depend only on dimensionality

Ghost

[DSE: Fischer et al., PLB 2002,
Lattice 32^4: Cucchieri et al., unpublished]



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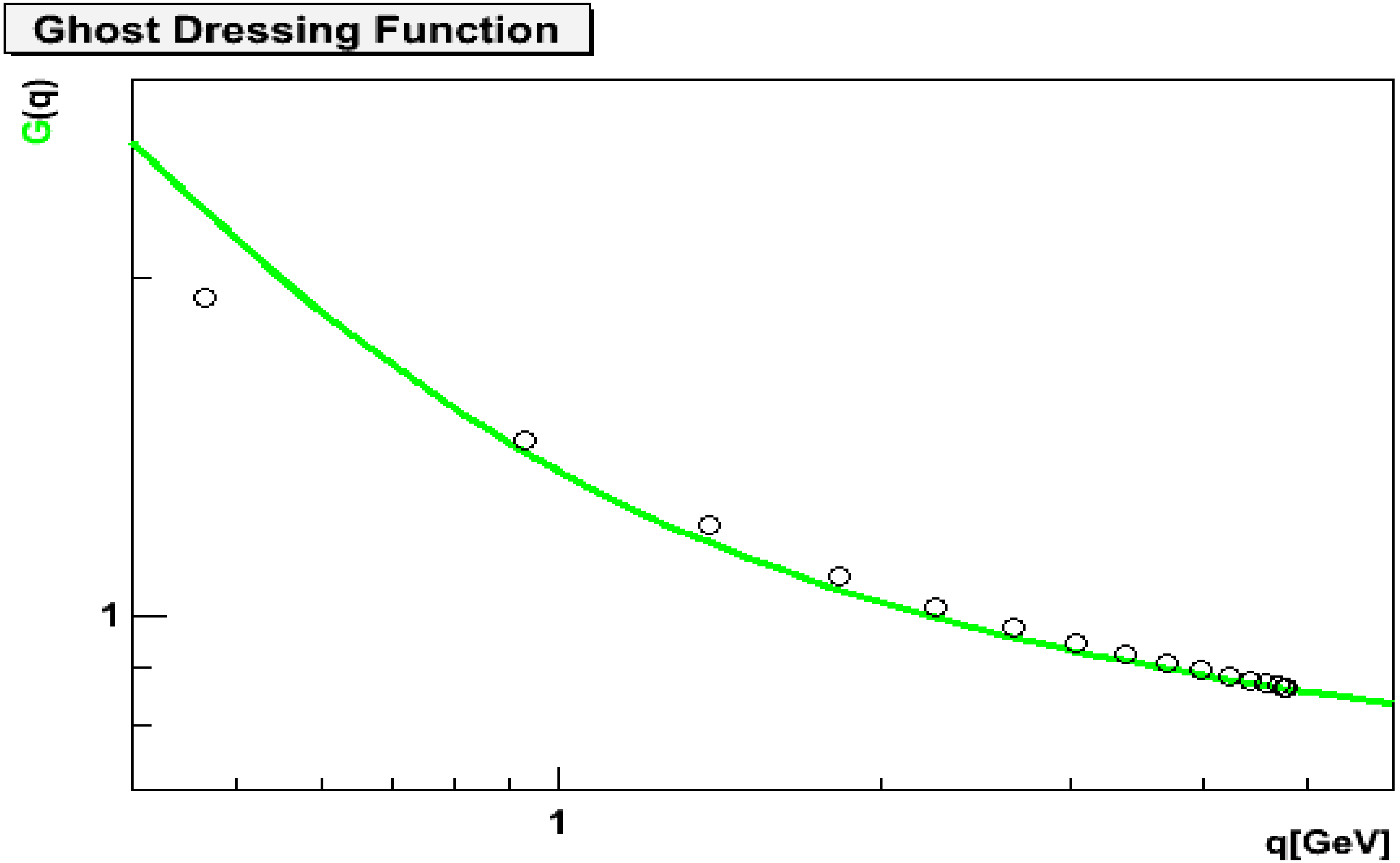

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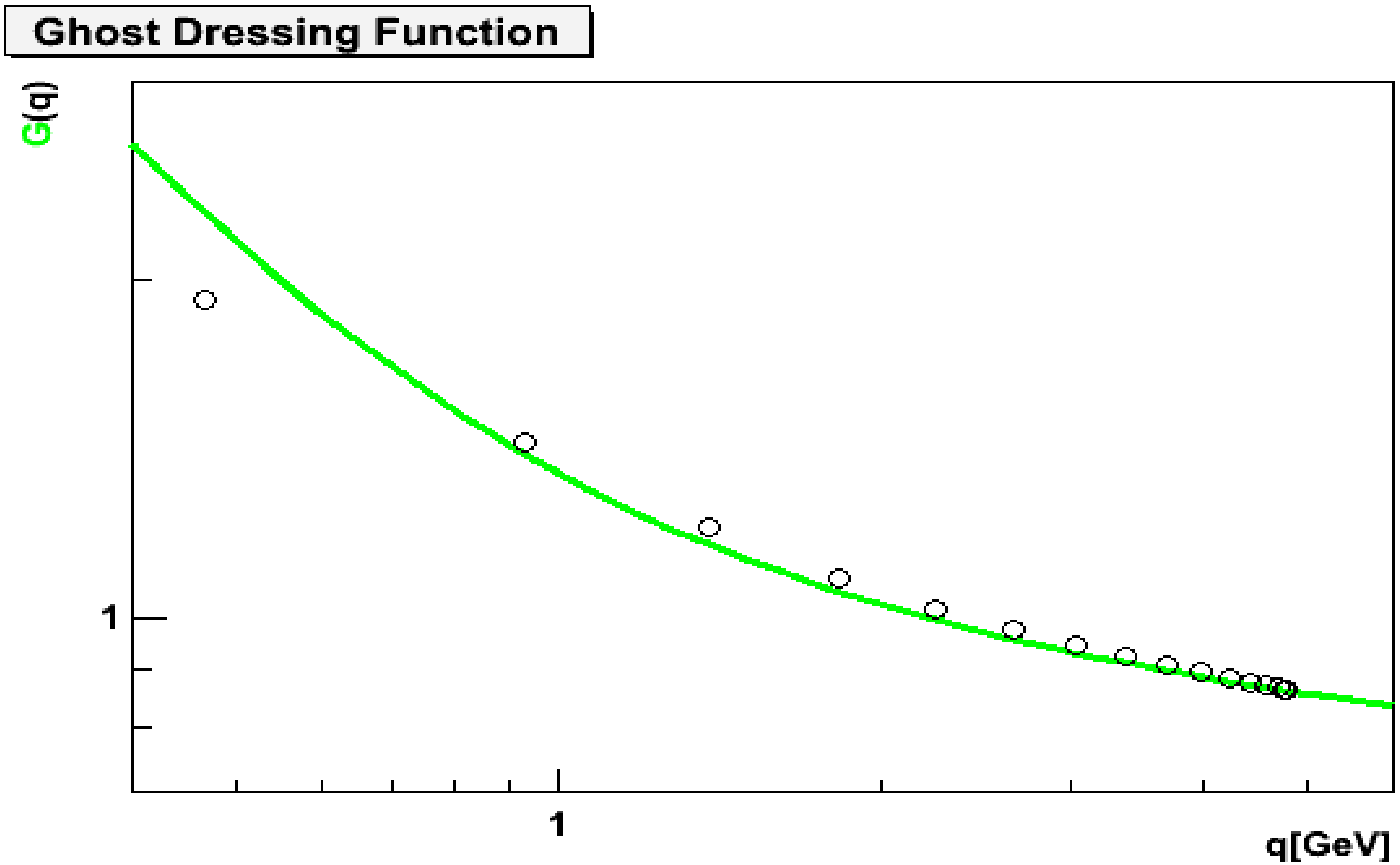

- IR divergent: Mediates long-range forces
- DSEs gives power-law: $G(p) \sim (p^2)^{-0.60}$ [Zwanziger PRD 2002, Lerche et al. PRD 2002]
- Confirmed by RG calculations [Pawlowski et al., PRL 2004]

Gluon

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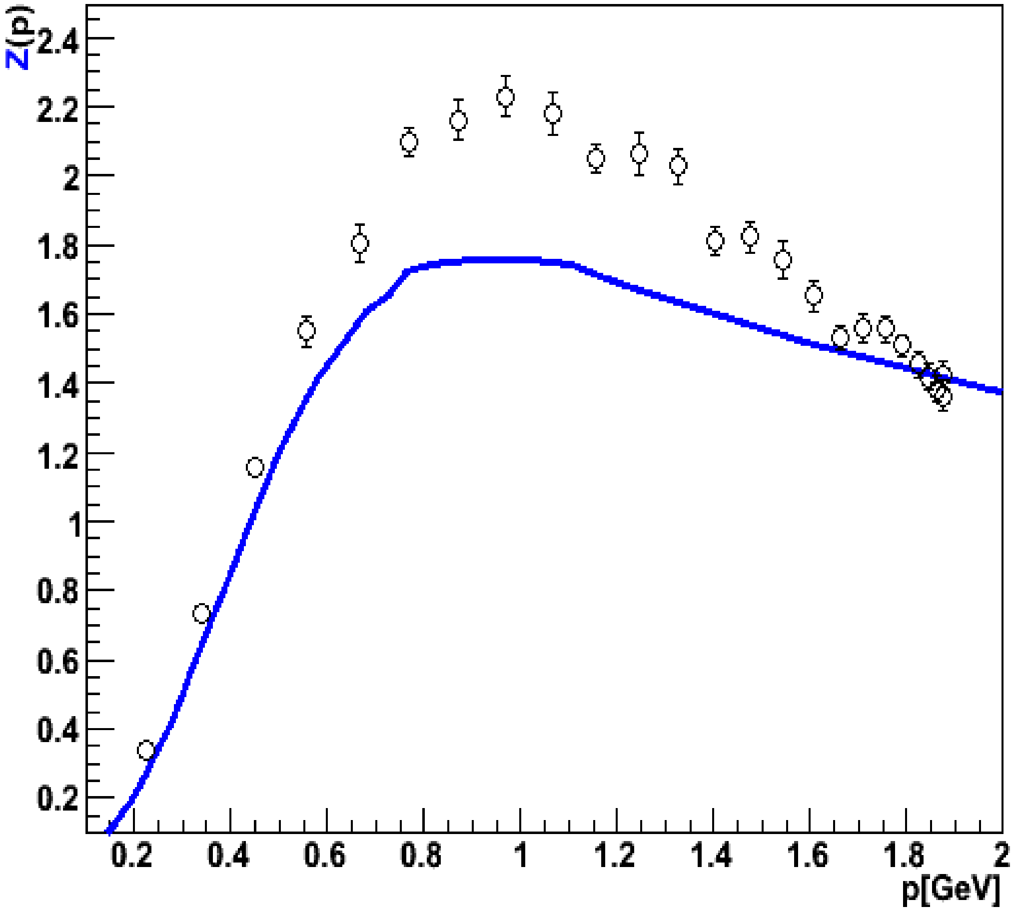

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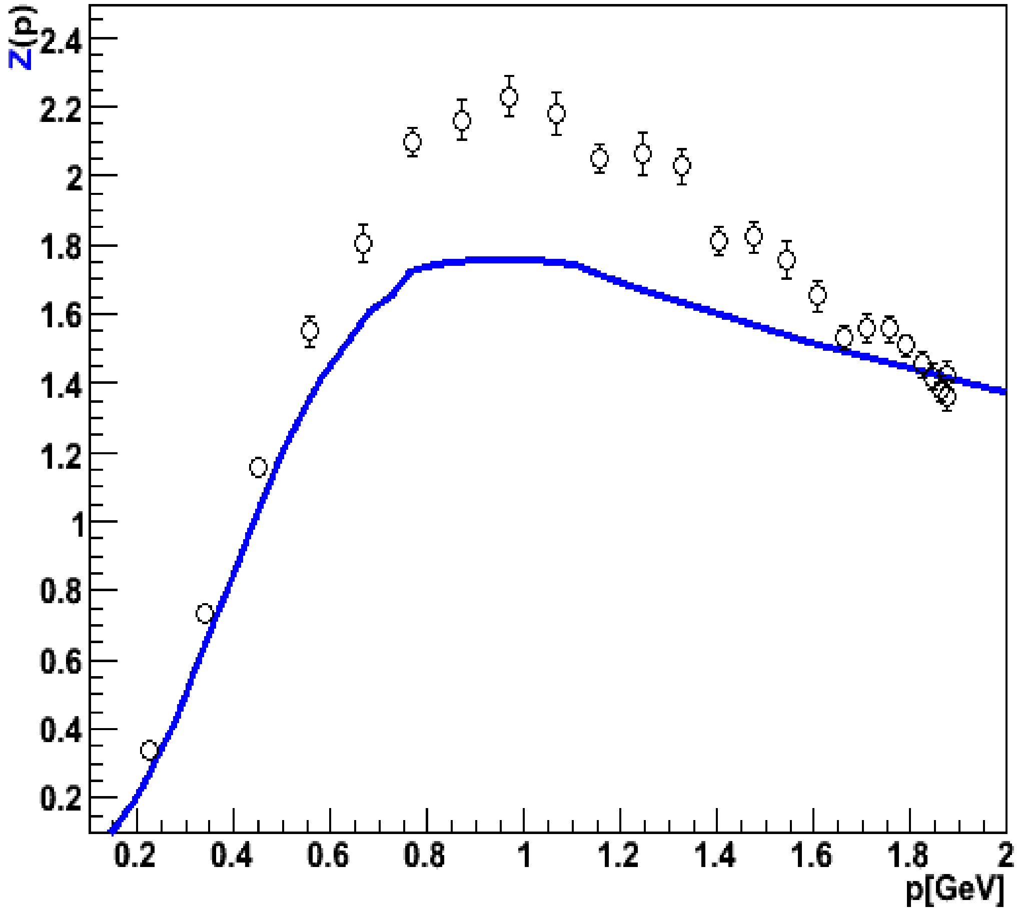

- Infrared vanishing - confined
- DSEs and RG gives $Z(p) \sim (p^2)^{1.19}$ [Zwanziger PRD 2002, Lerche et al. PRD 2002, Pawlowski et al., PRL 2004]

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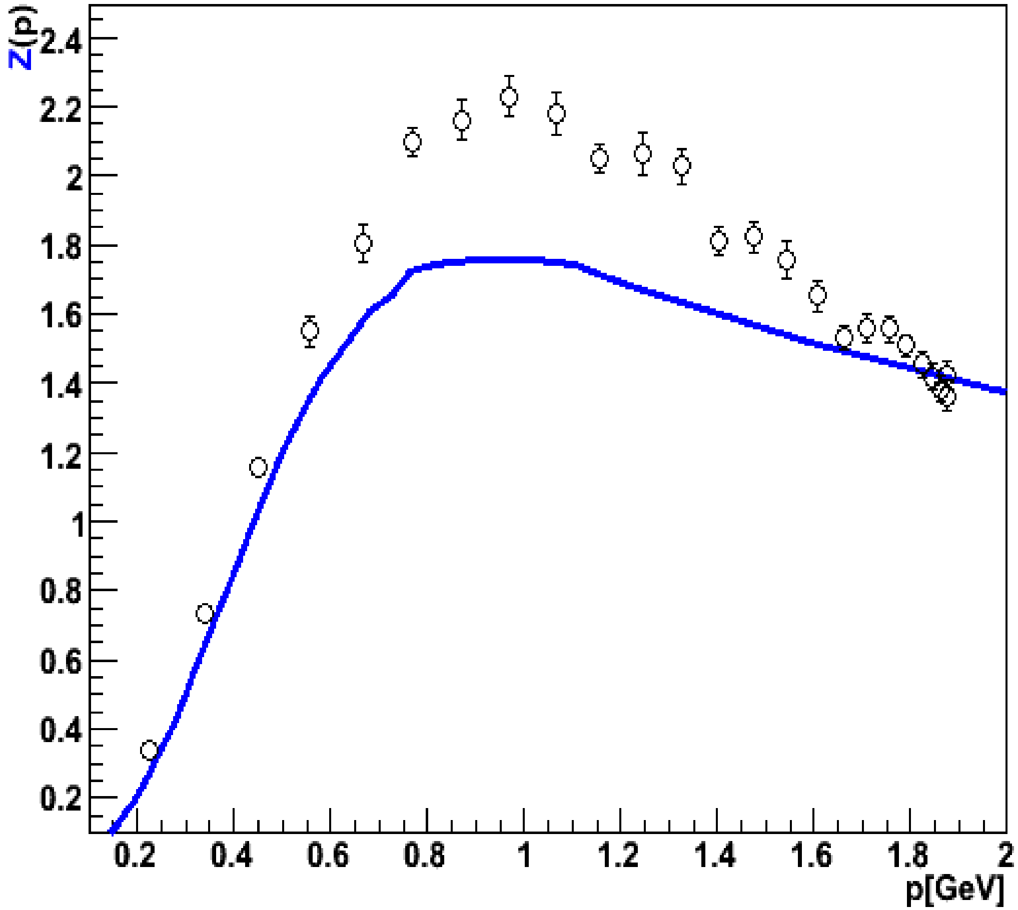

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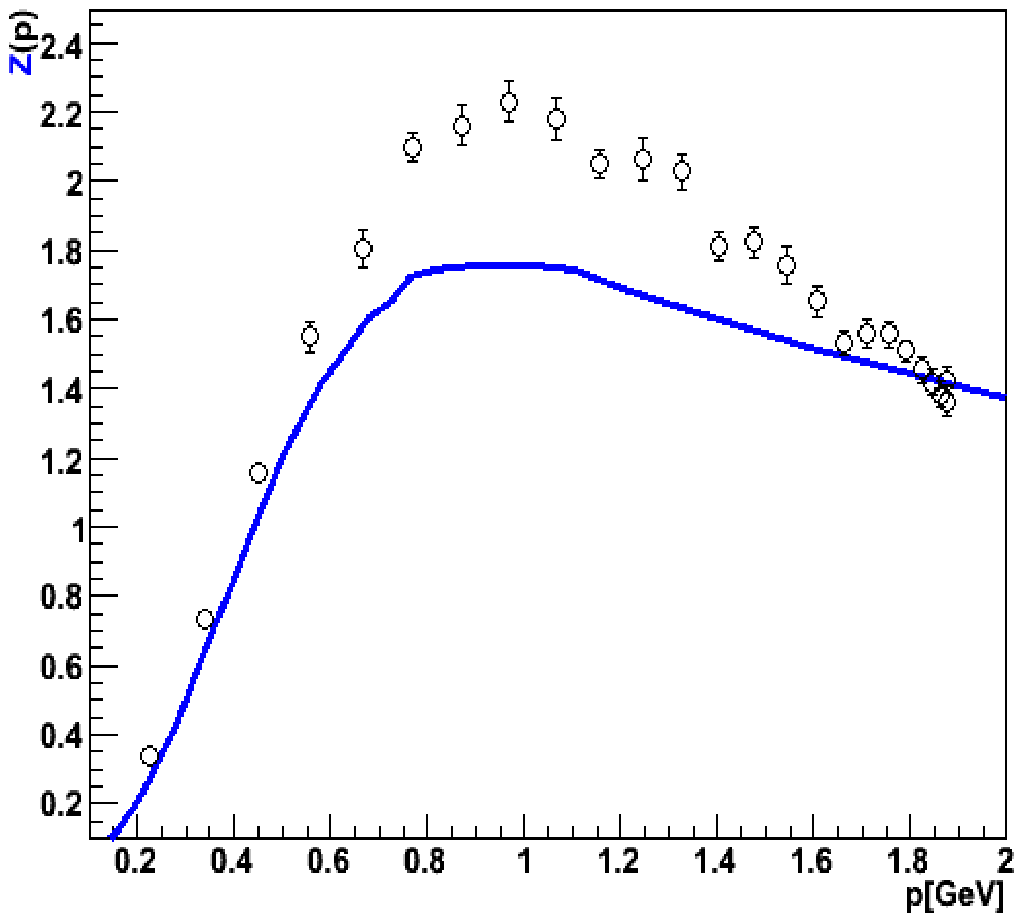

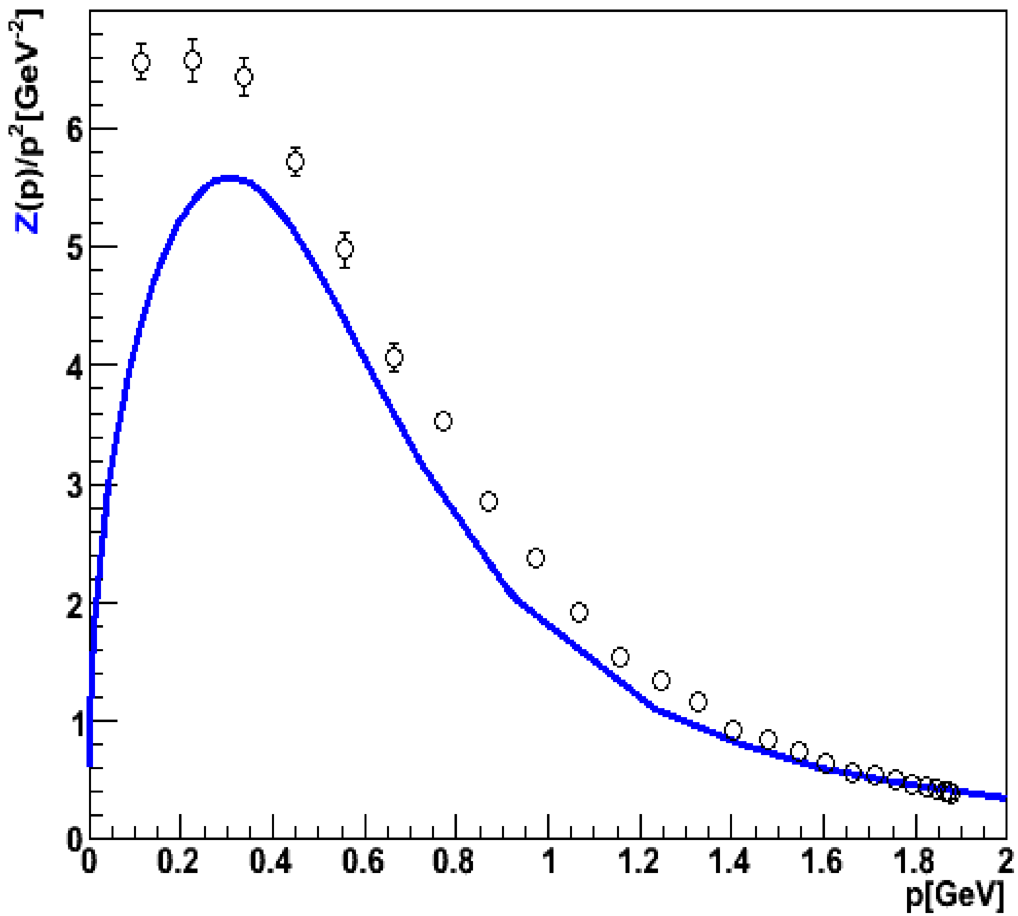

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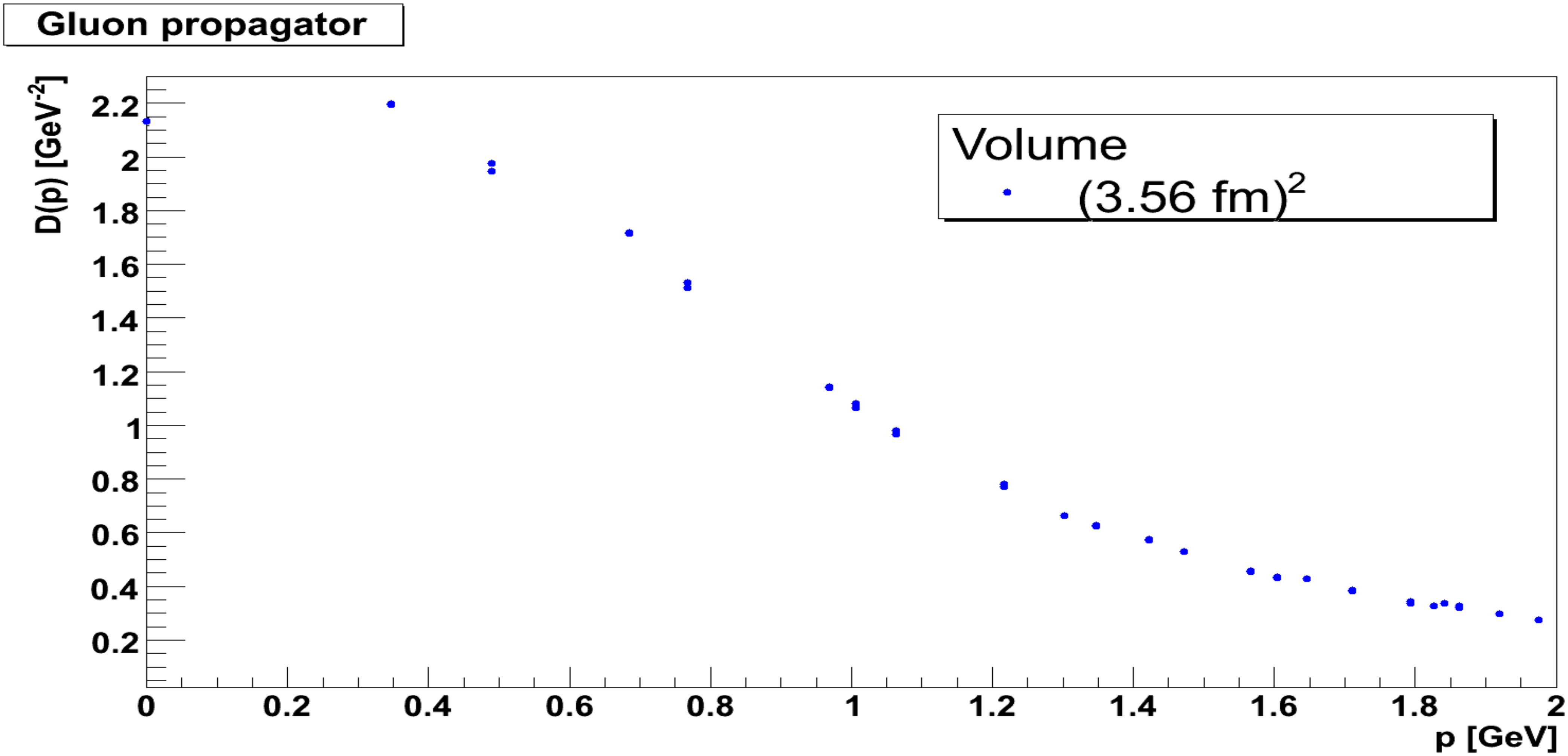
Very large lattices needed: 2d

[Maas, unpublished]



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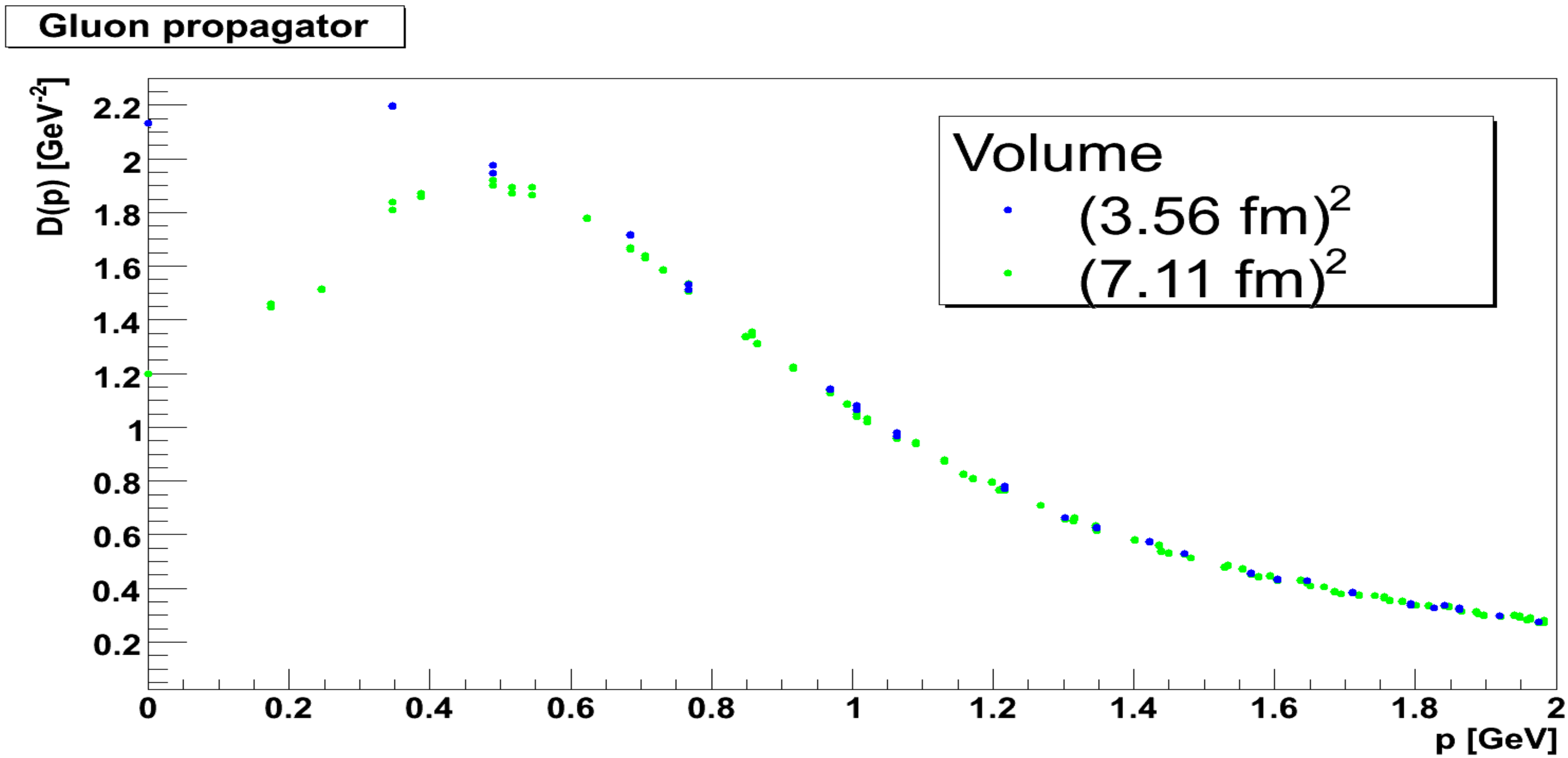

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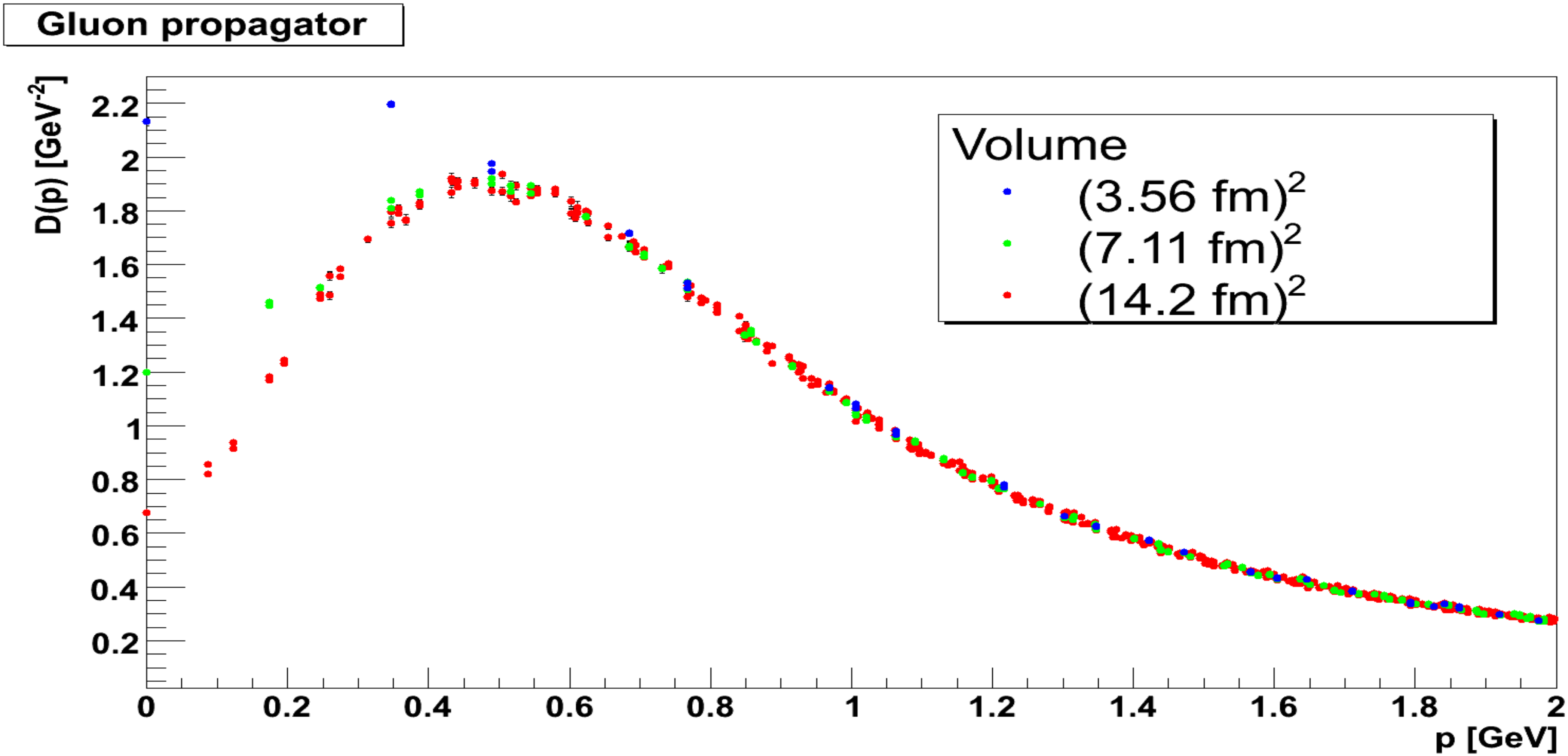

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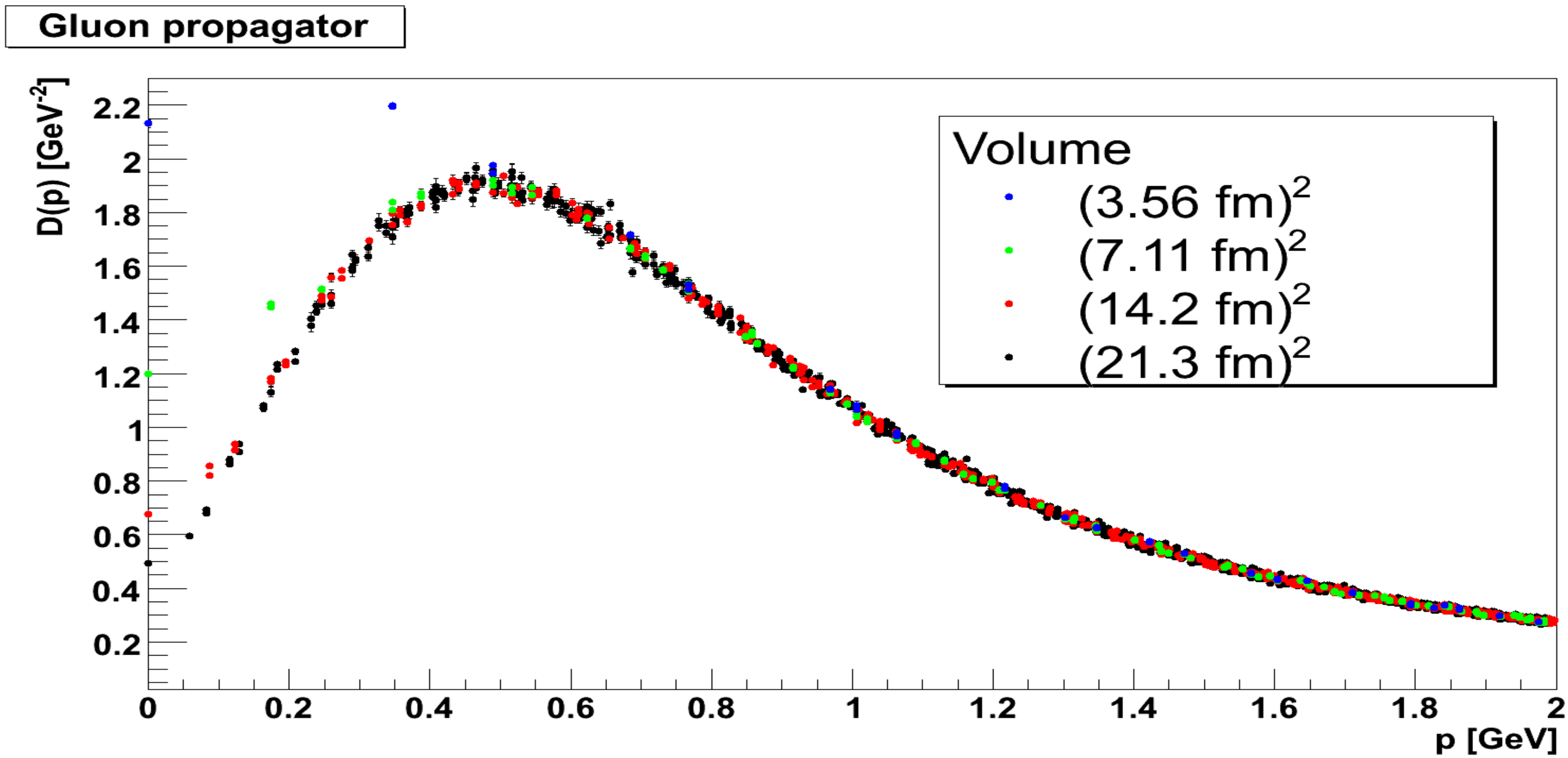

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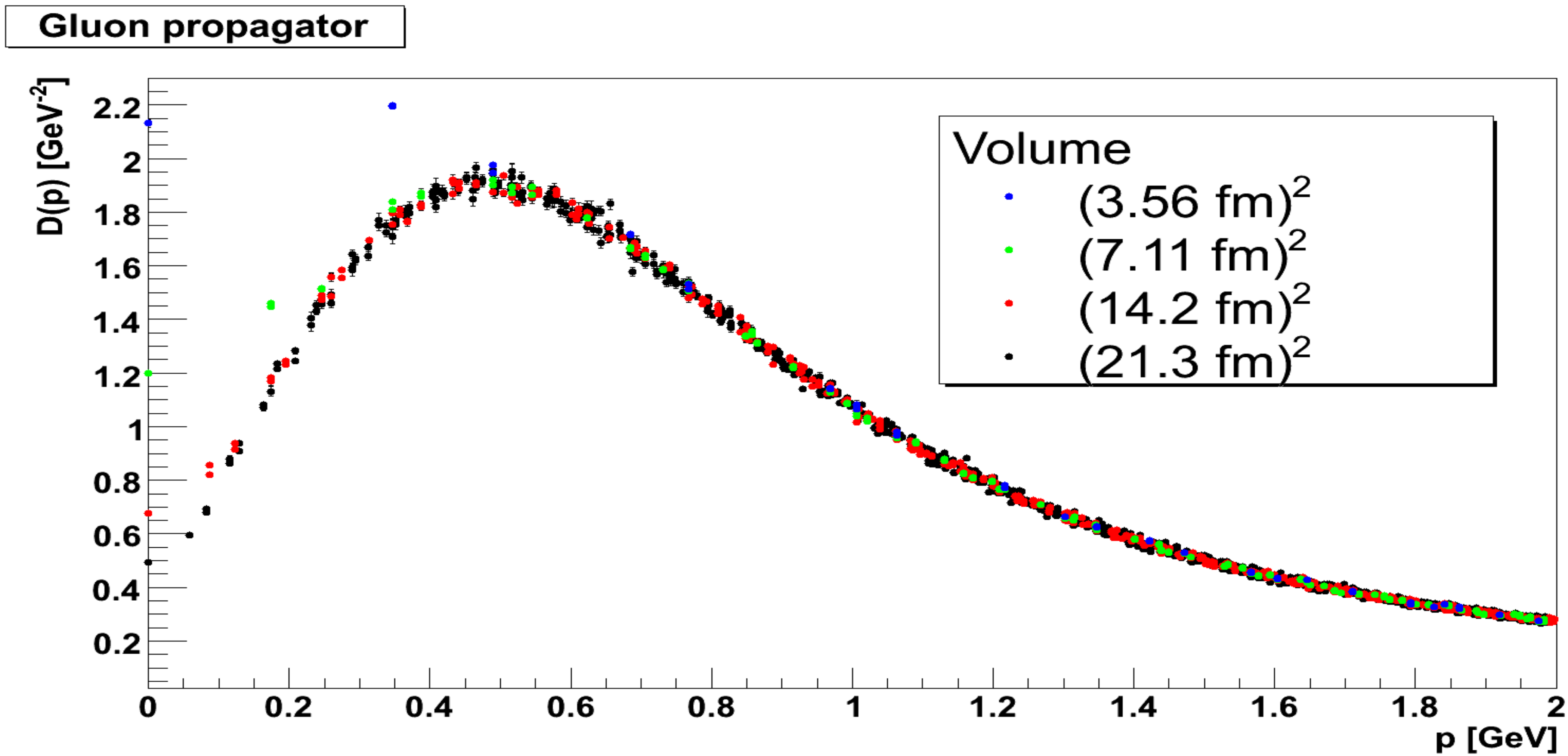

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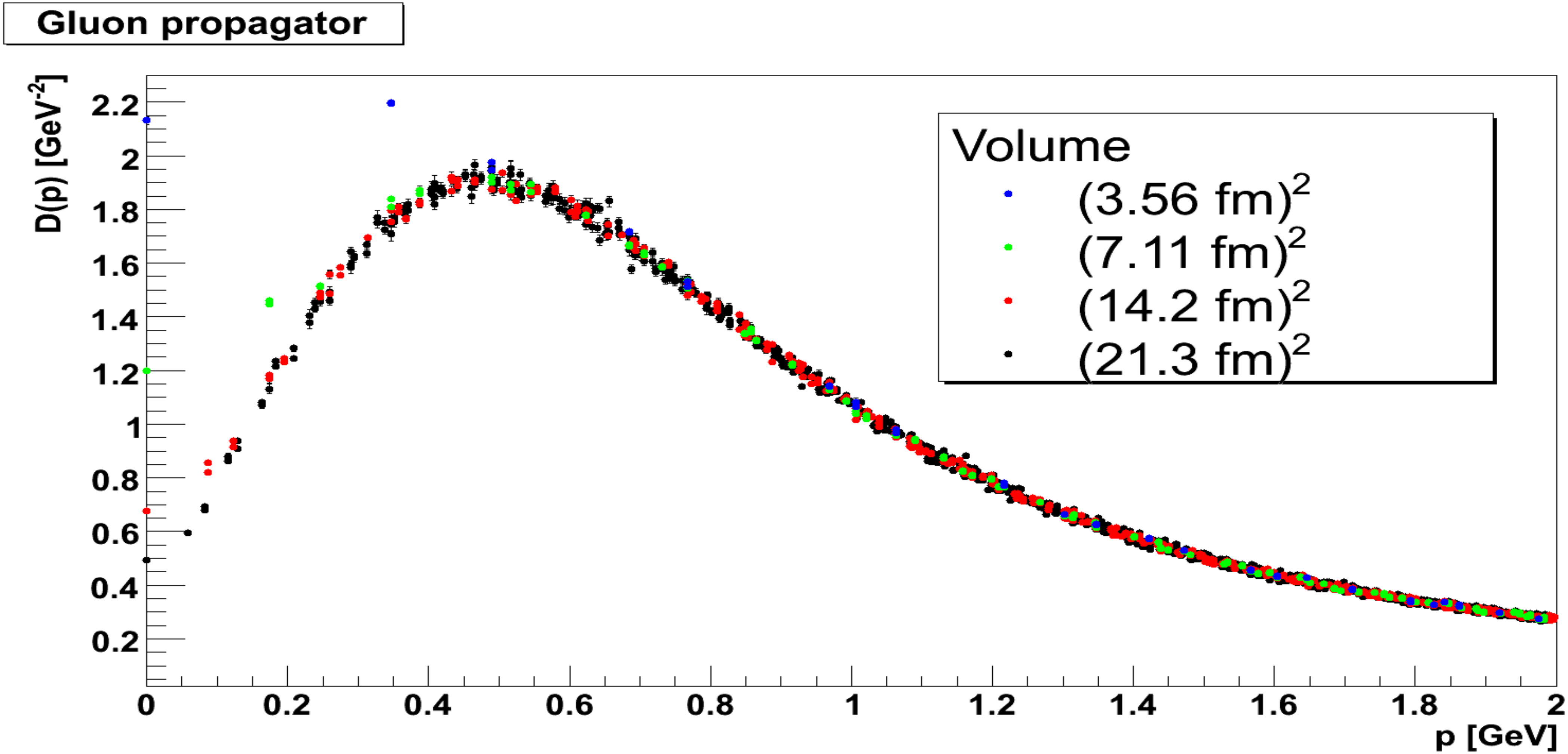

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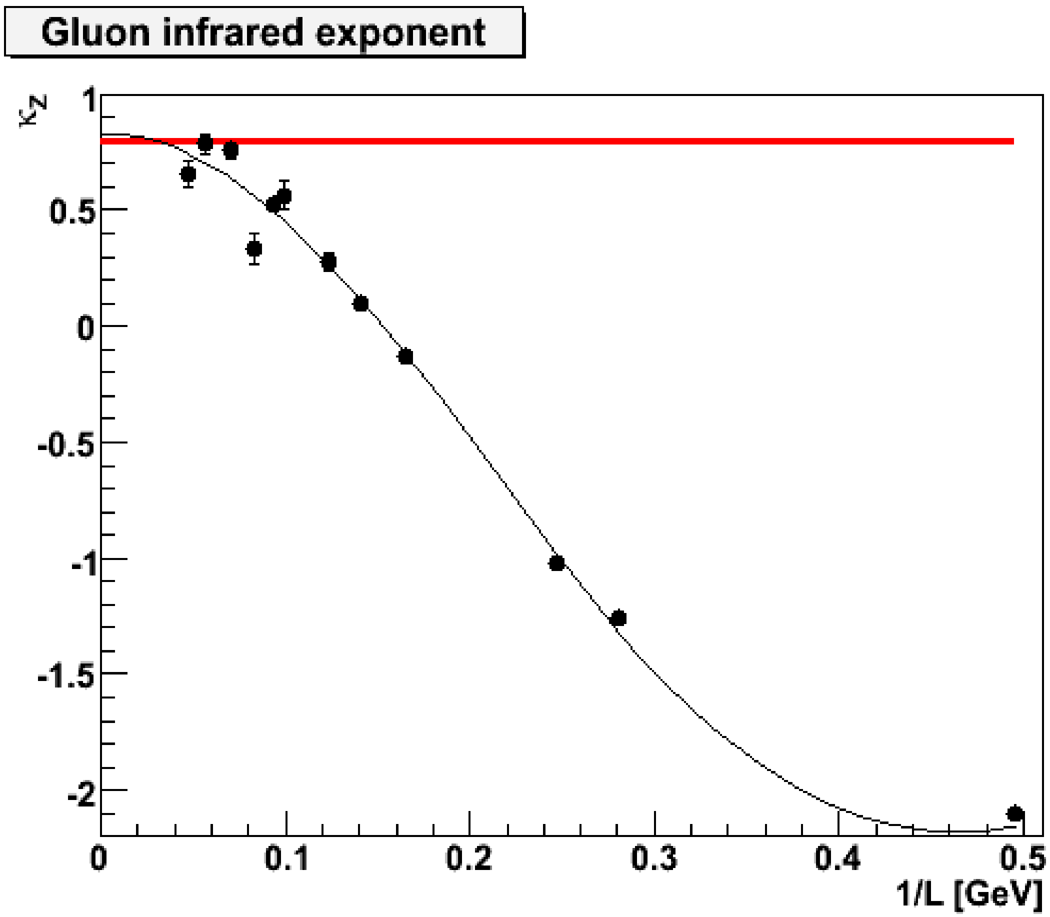
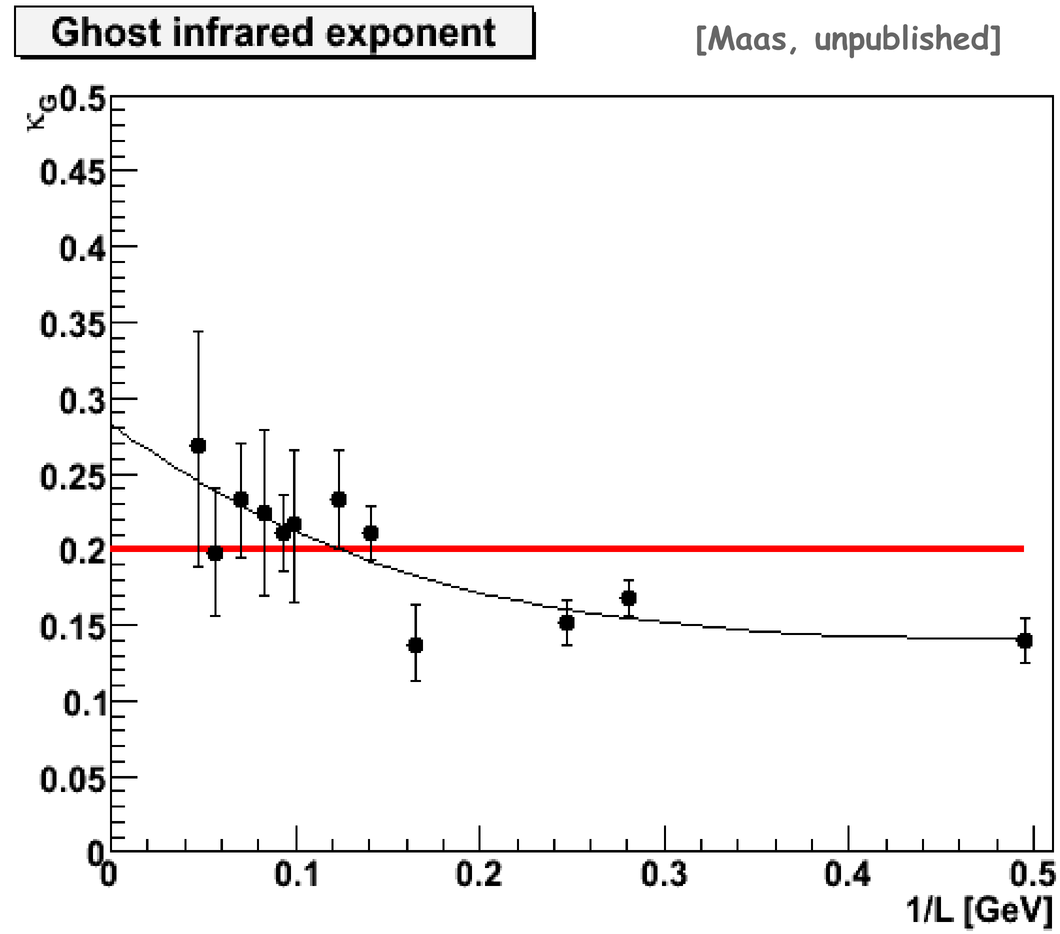
- Effects less pronounced for the ghost

Possibility to extract exponents quantitatively

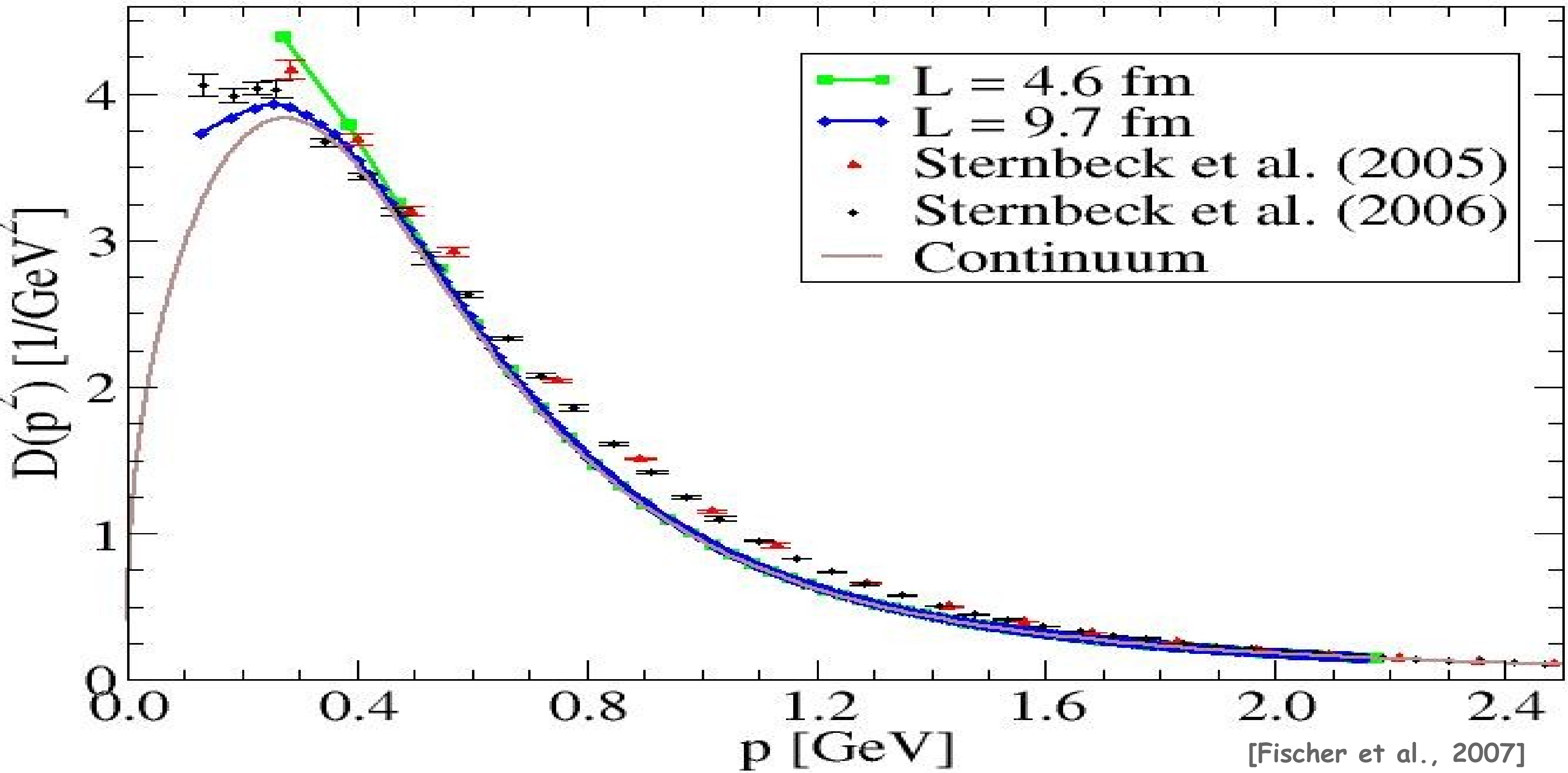




[Maas, unpublished]

- Results compatible with predictions (red)
- Requires better statistics and larger volumes

Lattice vs. DSE in a finite volume



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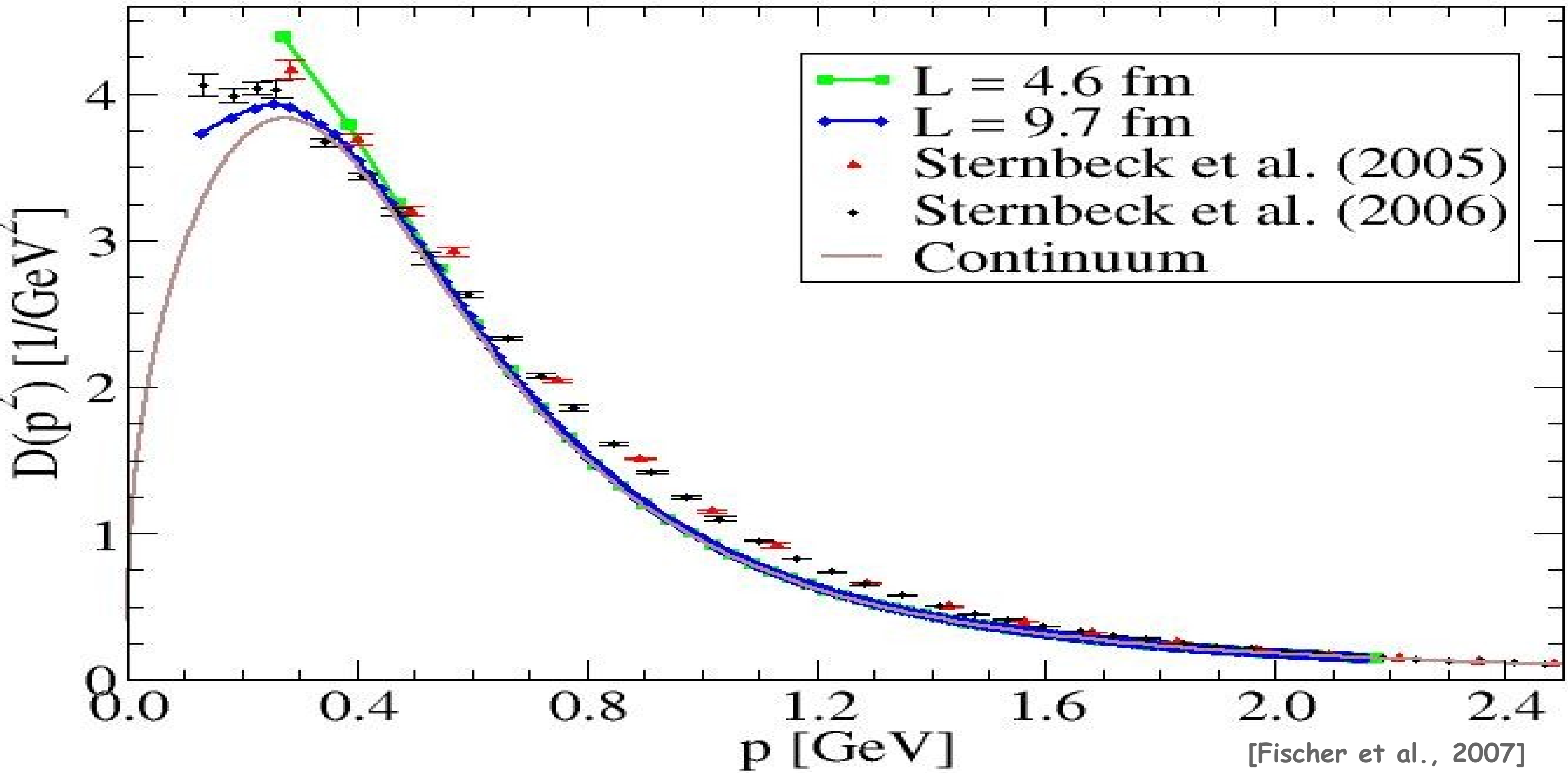

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- Qualitative similar behavior
- Relevant length scale about 10-15 fm

Lambda gauges

- **Gauge condition** $\lambda_0 \partial_0 A_0^a + \ldots + \lambda_d \partial_d A_d^a = 0$

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  - $\lambda = 0$ (under-constrained) Coulomb gauge
- Lorentz invariance not manifest
  - Two (continuous) variables: Energy, 3-momentum
  - Gluon propagator: two tensor structures
    - Temporal: $D_{00}(k_{0,} |\vec{k}|)$
    - Spatial: $D^{tr}(k_{0,} |\vec{k}|) = P_{ij} D_{ij}(k_{0,} |\vec{k}|)$

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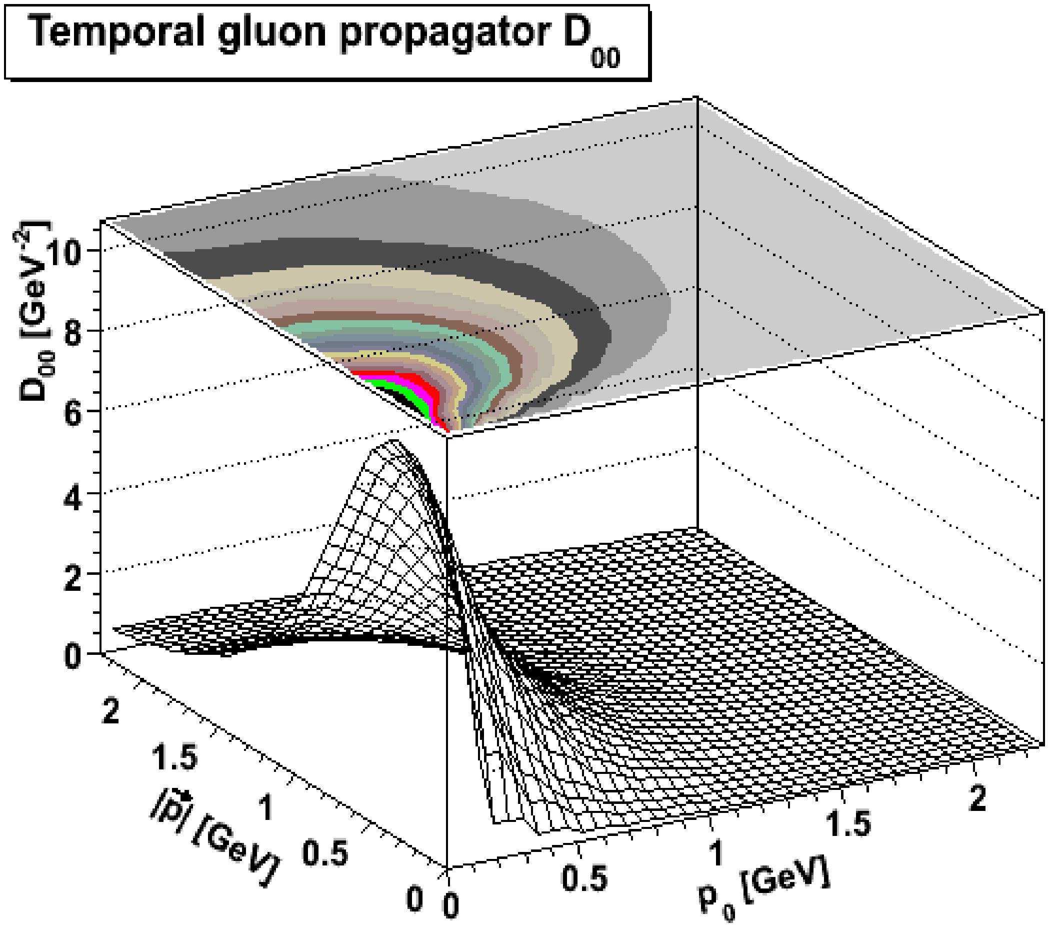
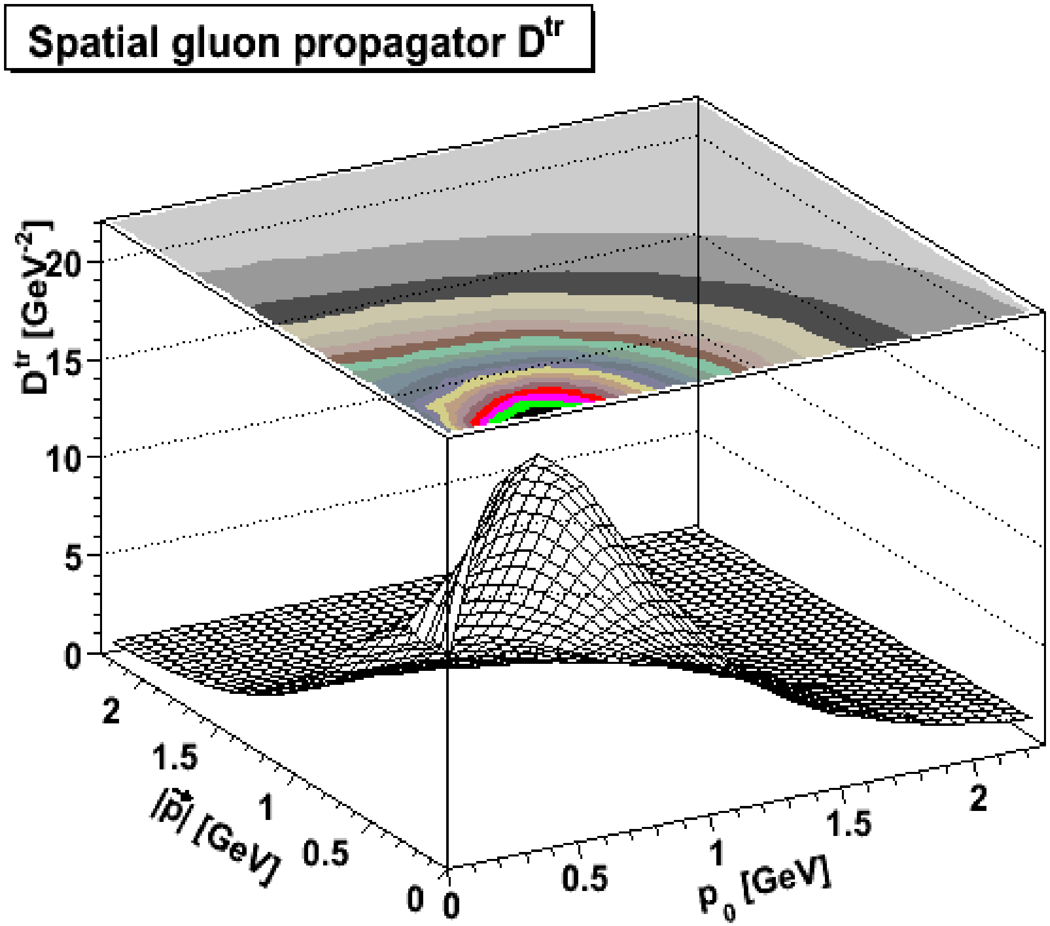
    - Transverse gluon propagator vanishing

Gluon propagator - Landau

[Lattice 40^3, beta=4.2, λ=1: Cucchieri et al., unpublished]





•Different in Landau gauge because the gluon is a vector particle

•Distinct maximum and infrared suppressed

Gluon propagator

[Lattice 40^3, beta=4.2, λ=1/2:
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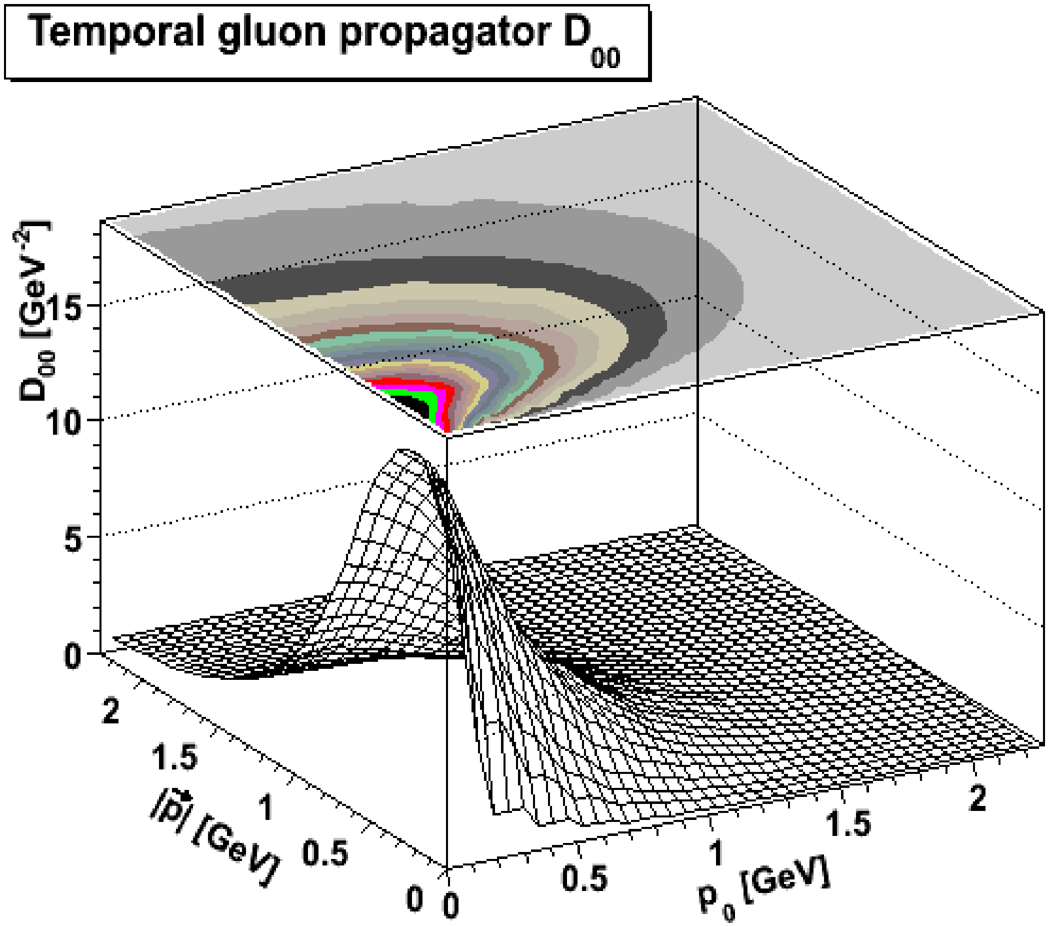
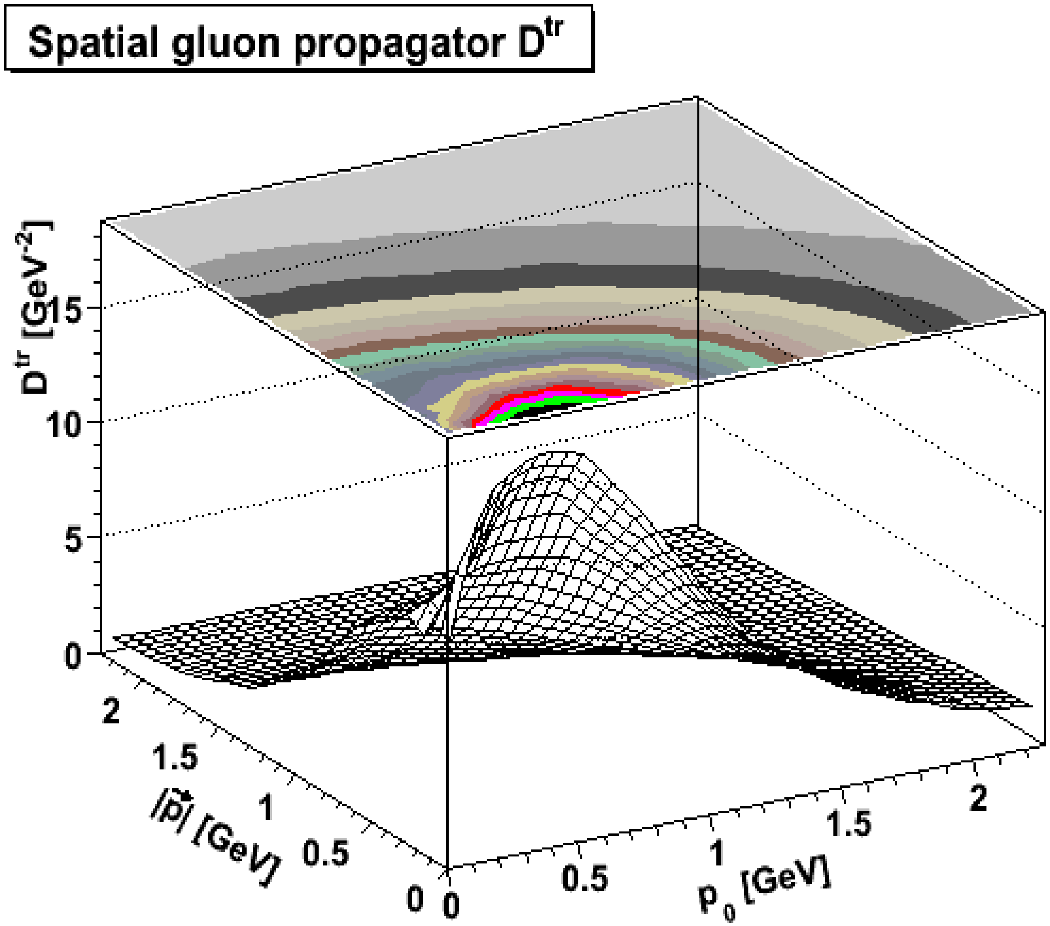
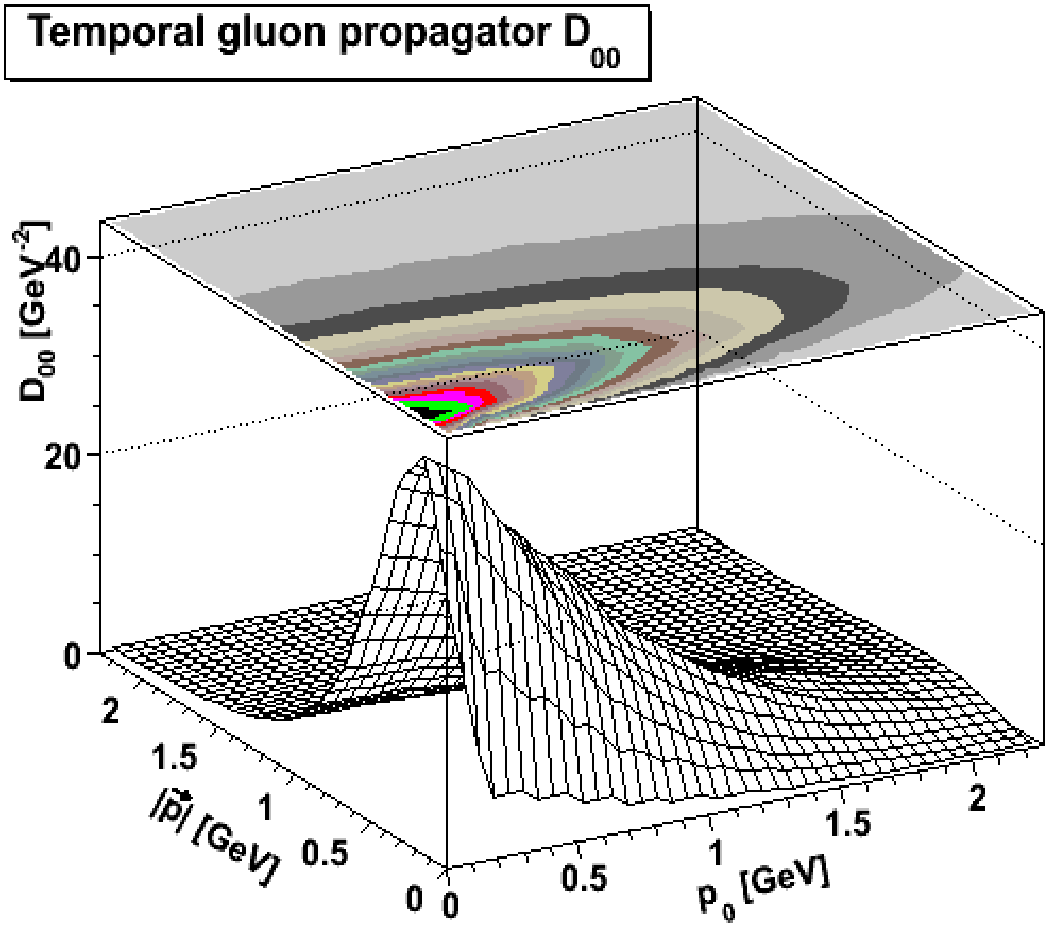


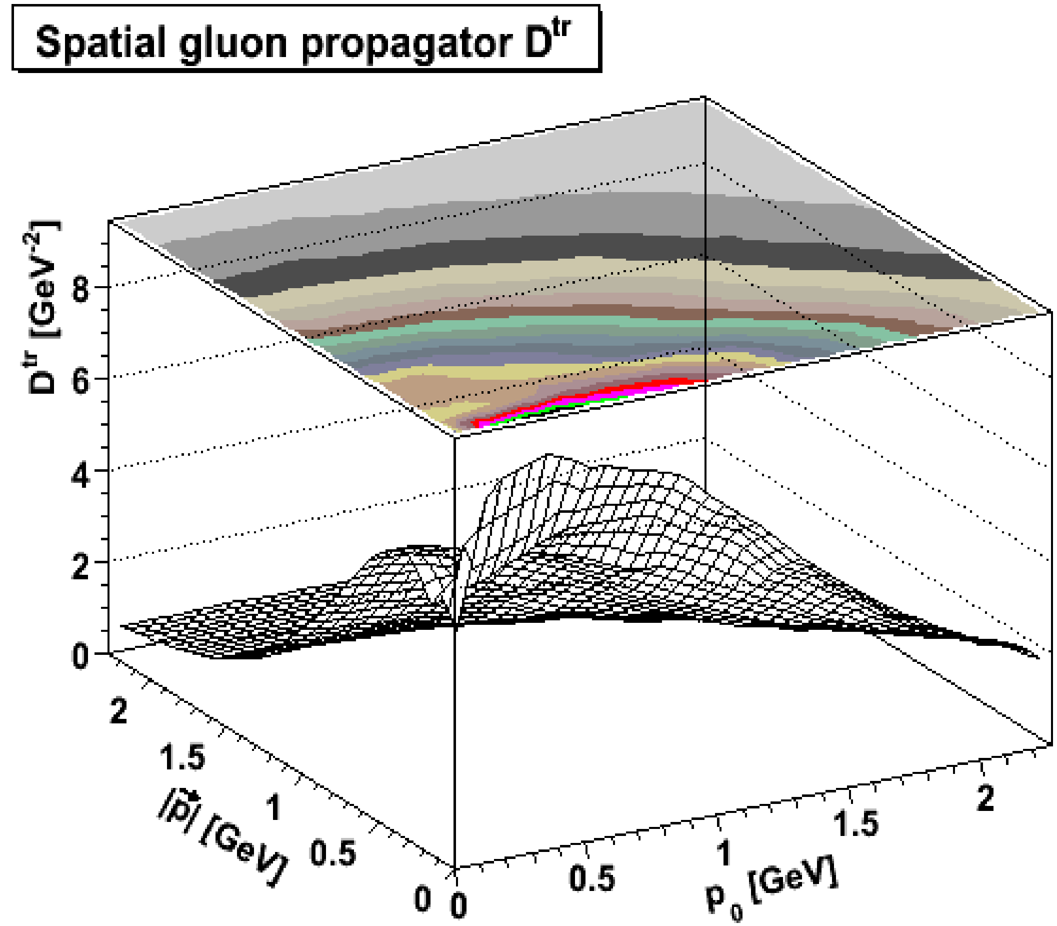


- No visible changes

Gluon propagator

[Lattice 40^3, beta=4.2, λ=1/10: Cucchieri et al., unpublished]

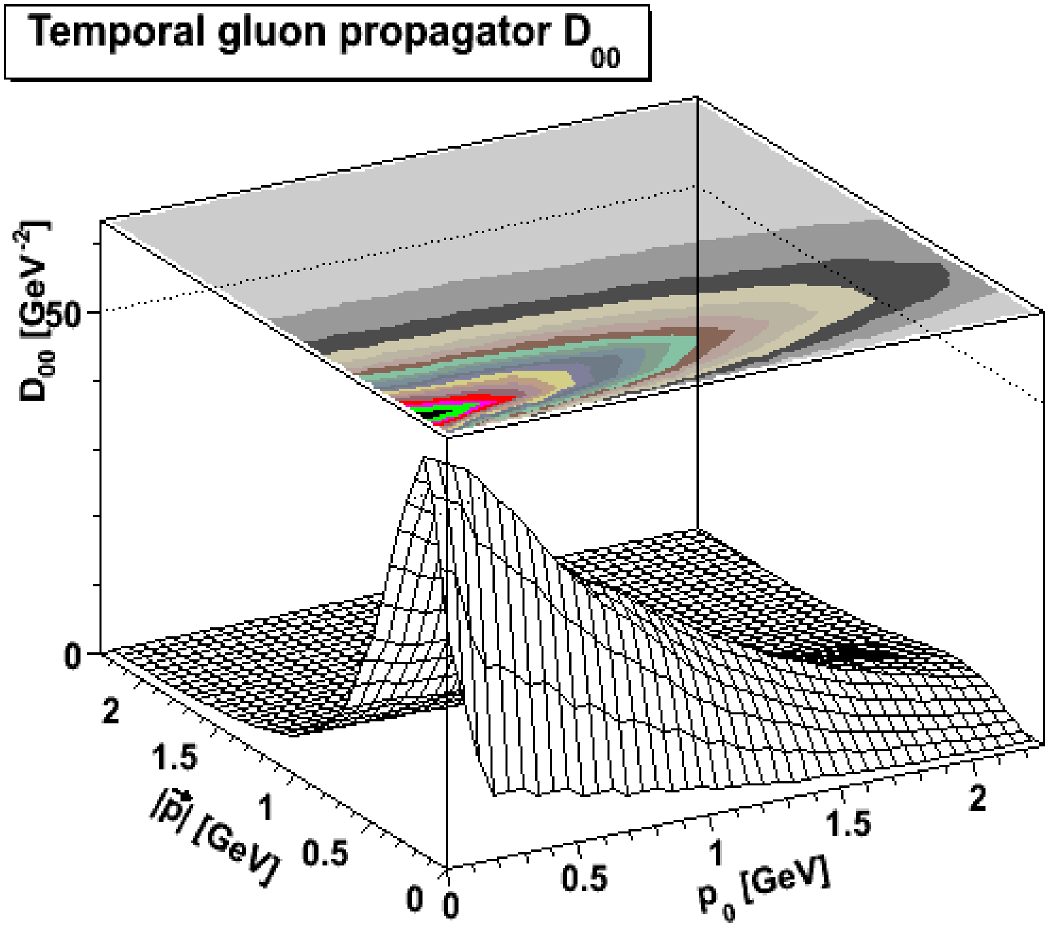


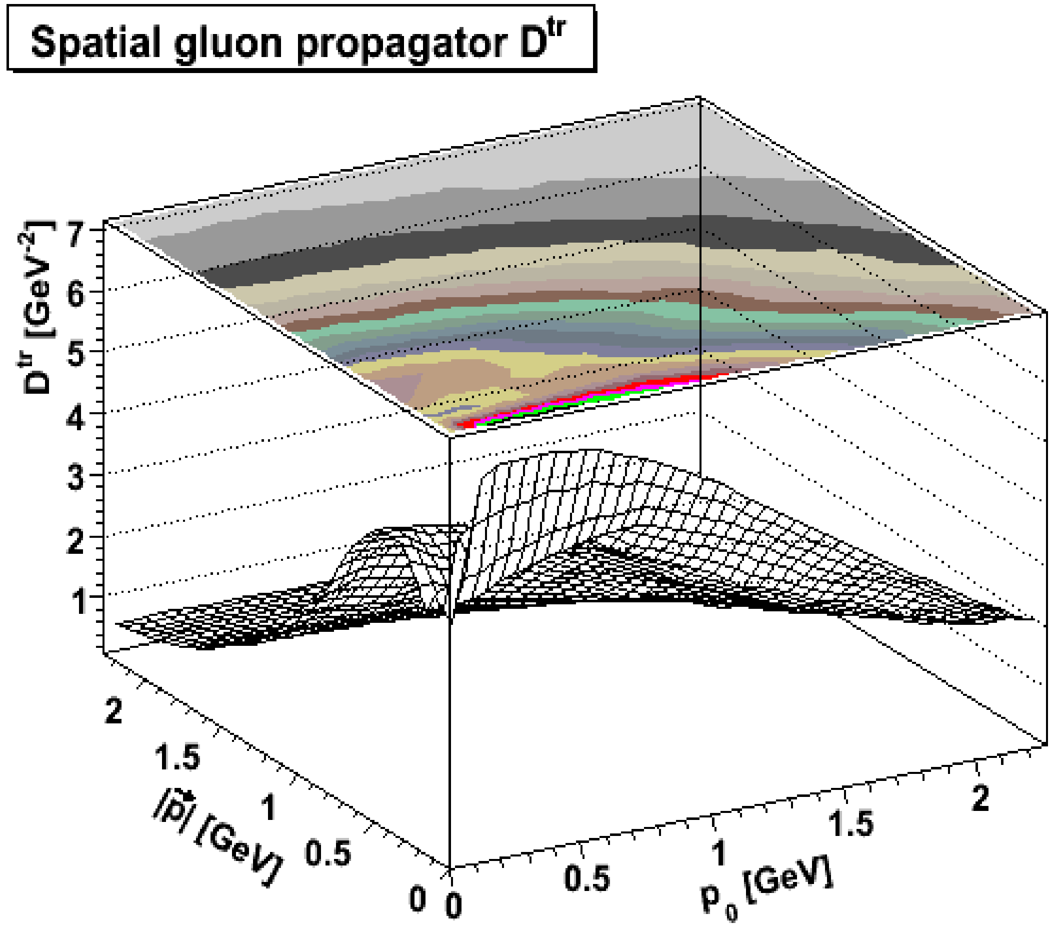


- Temporal: Maximum becomes more pronounced, more infrared
- Spatial: Spatial maximum at larger momenta

Gluon propagator

[Lattice 40^3, beta=4.2, λ=1/20: Cucchieri et al., unpublished]

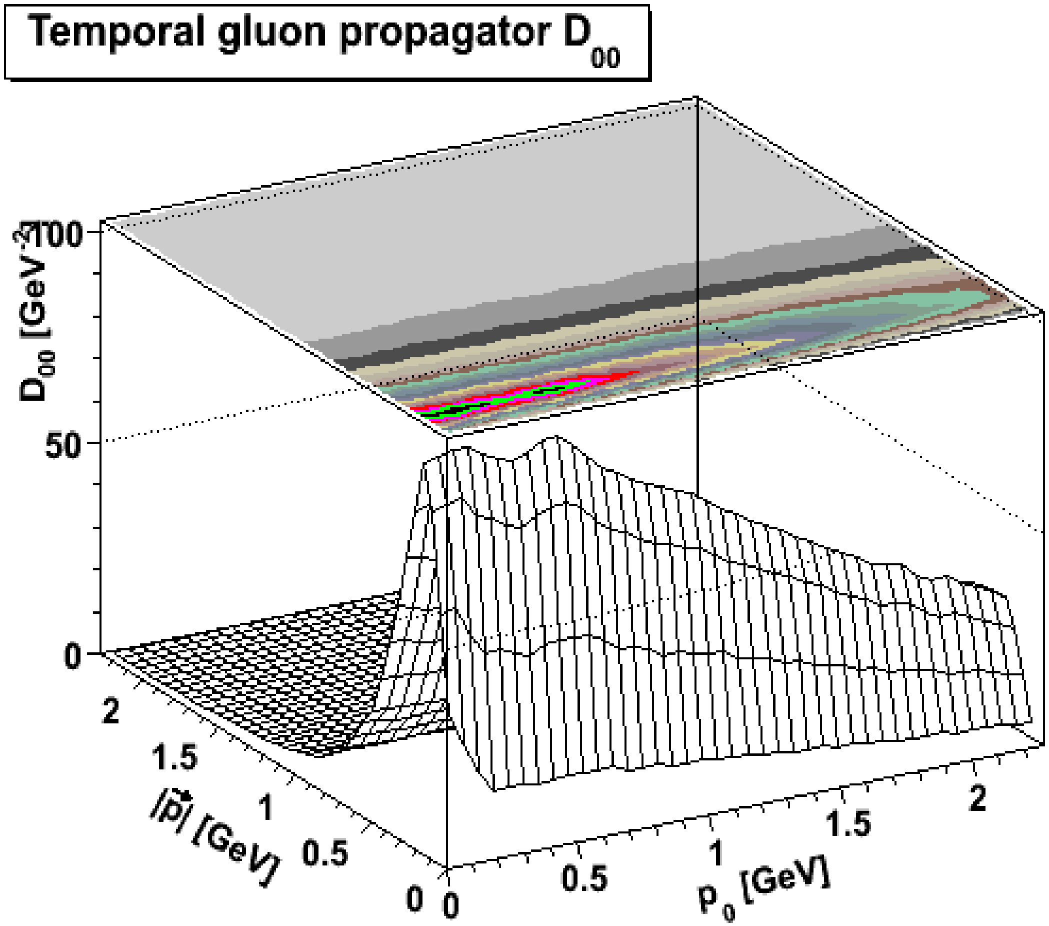


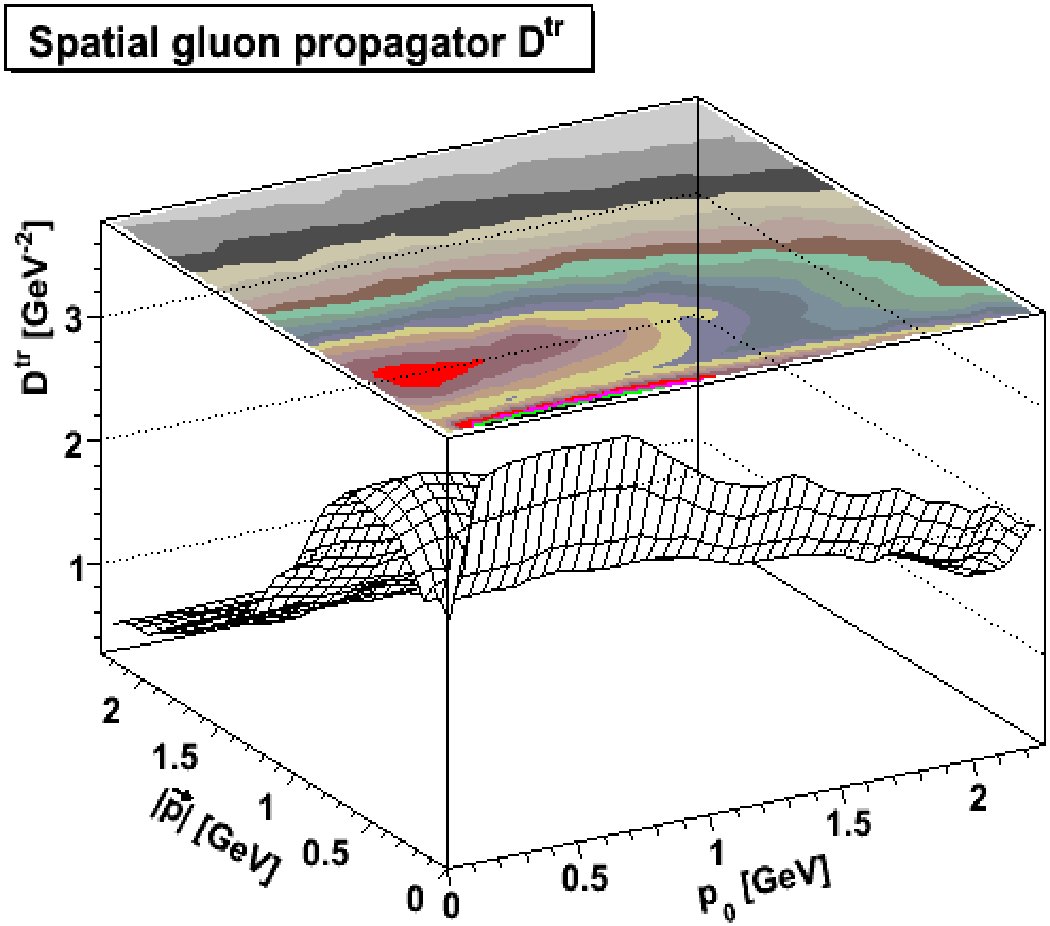


- Resolution of maxima more complicated
- Larger volumes required

Gluon propagator

[Lattice 40^3, beta=4.2, λ=1/100:
Cucchieri et al., unpublished]

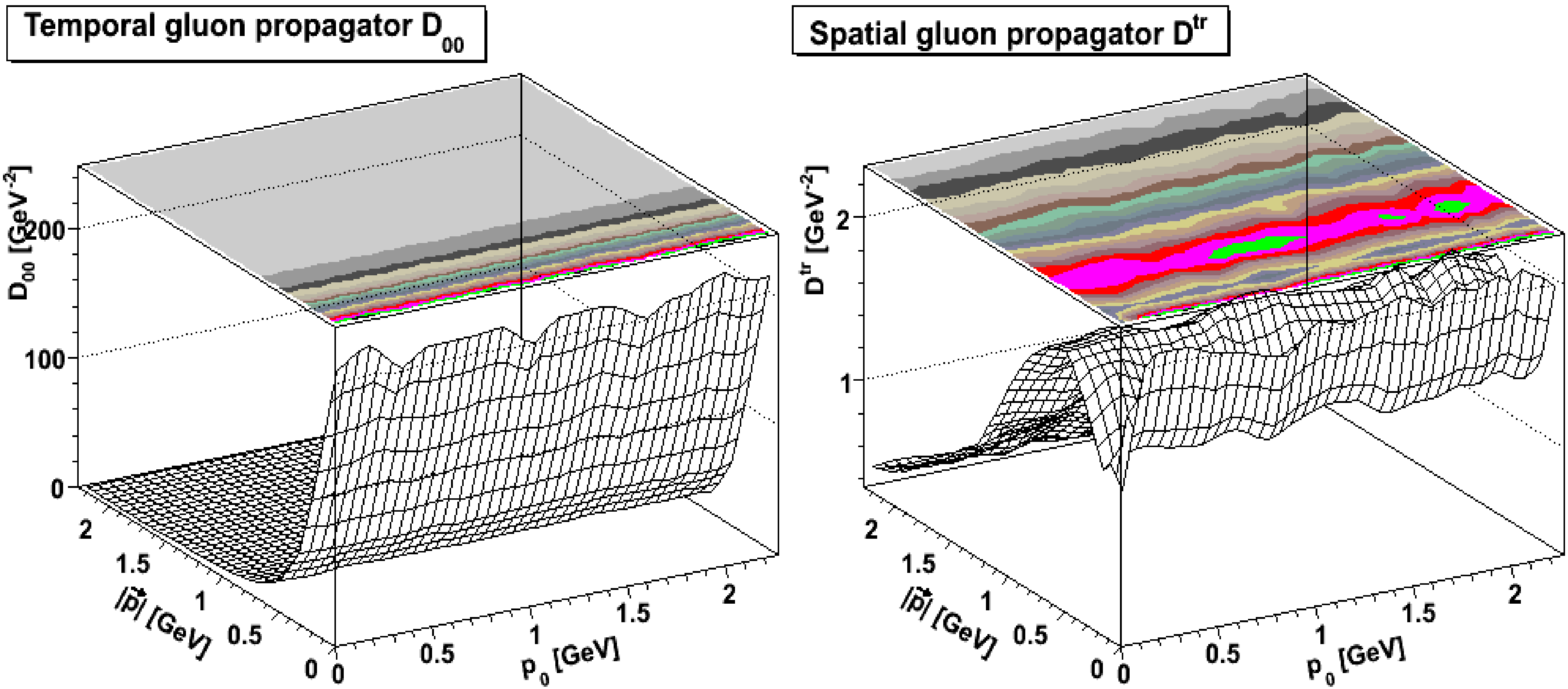




- Coulomb-like at large momenta - Landau-like at small momenta
- Separation momentum, decreasing with λ

Gluon propagator - Coulomb

[Lattice 40^3, beta=4.2, Coulomb: Cucchieri et al., unpublished]

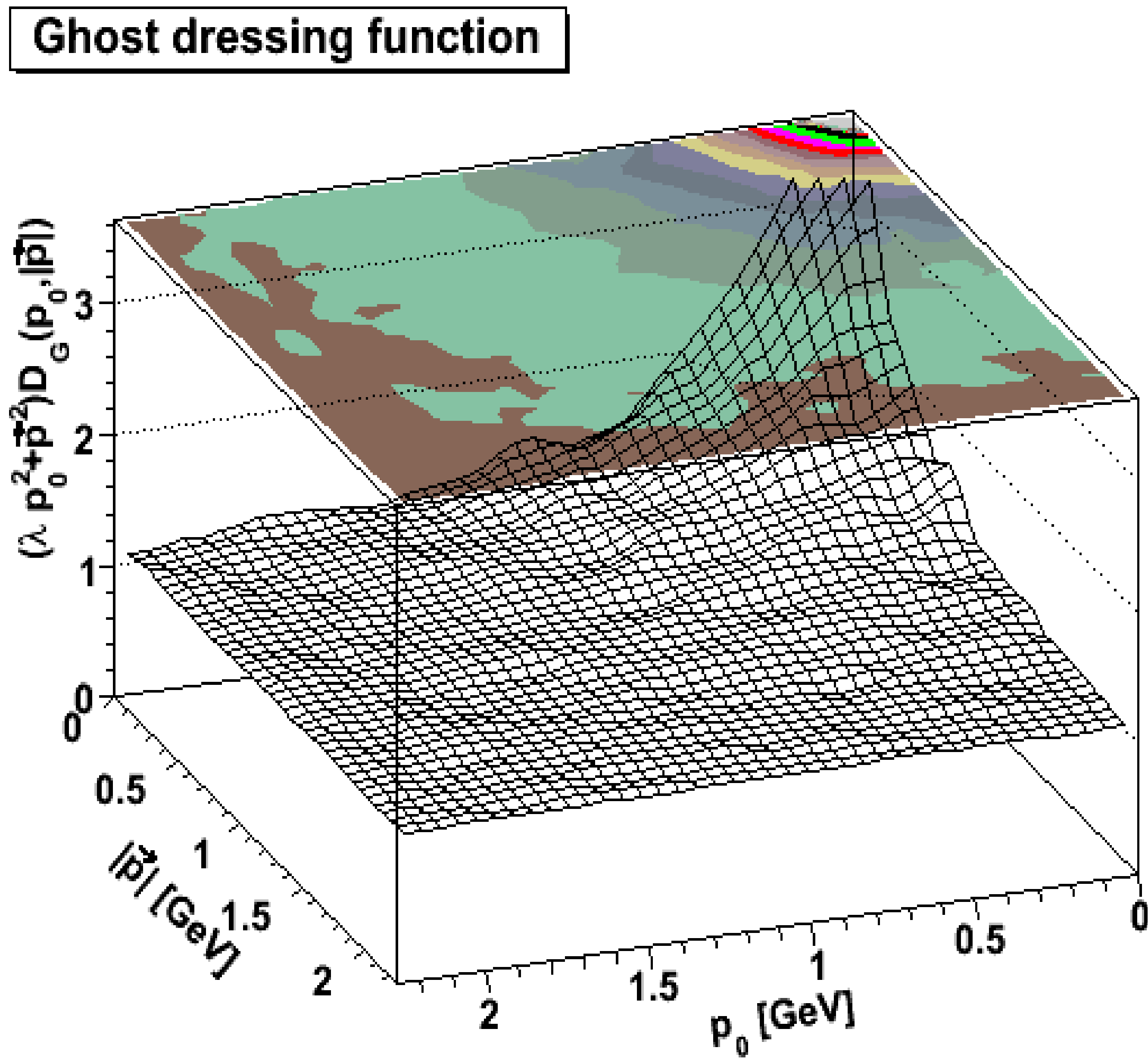


- Temporal propagator infrared divergent – discontinous change
- Spatial propagator only vanishing at zero energy

Ghost dressing function

[Lattice 40^3, beta=4.2, Λ=1: Cucchieri et al., unpublished]

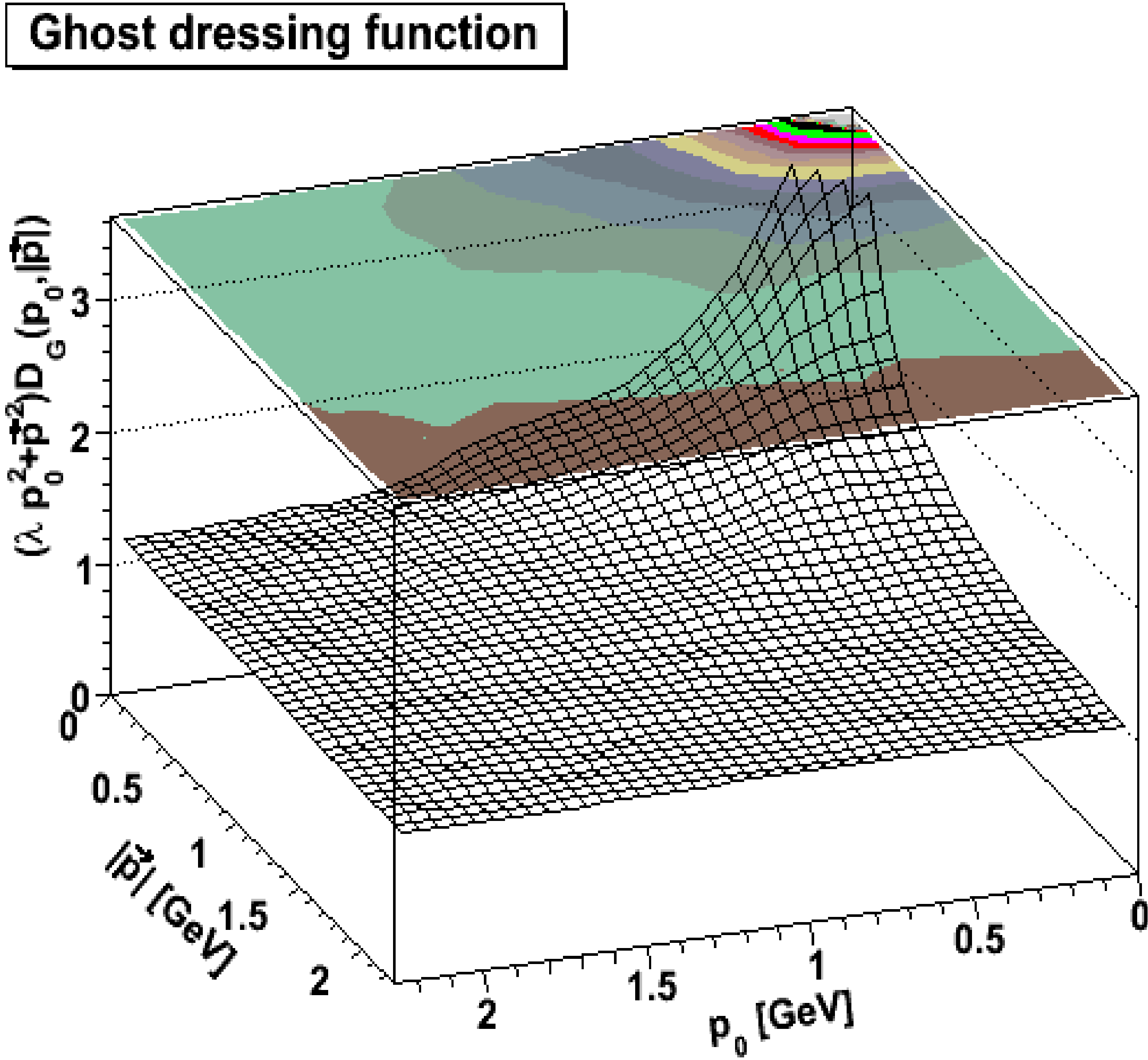
- Scalar particle
  - Isotrope
- Infrared strongly enhanced



Ghost dressing function

[Lattice 40^3, beta=4.2, λ=1/2: Cucchieri et al., unpublished]

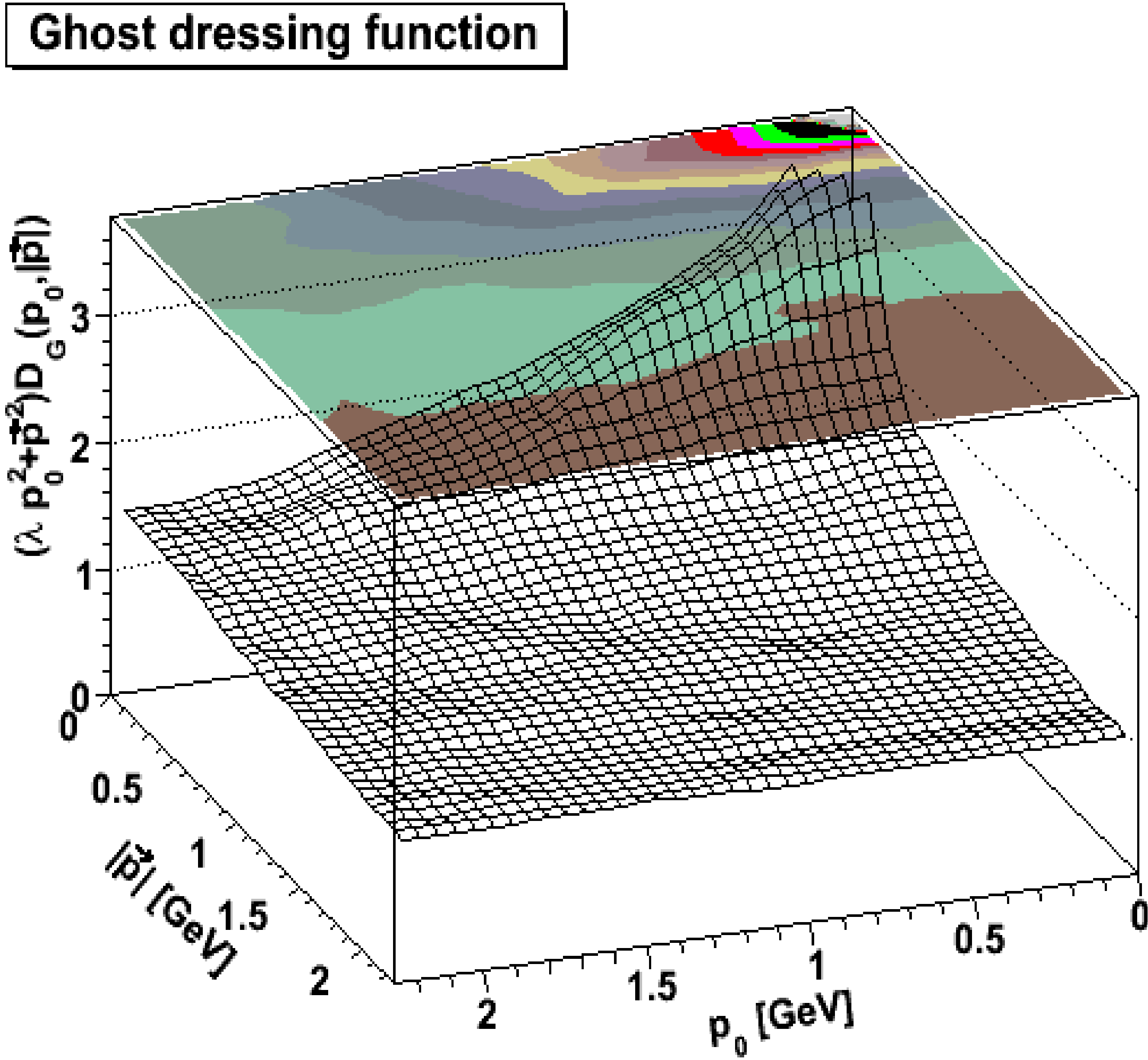
- No visible change



Ghost dressing function

[Lattice 40^3, beta=4.2, λ=1/10: Cucchieri et al., unpublished]

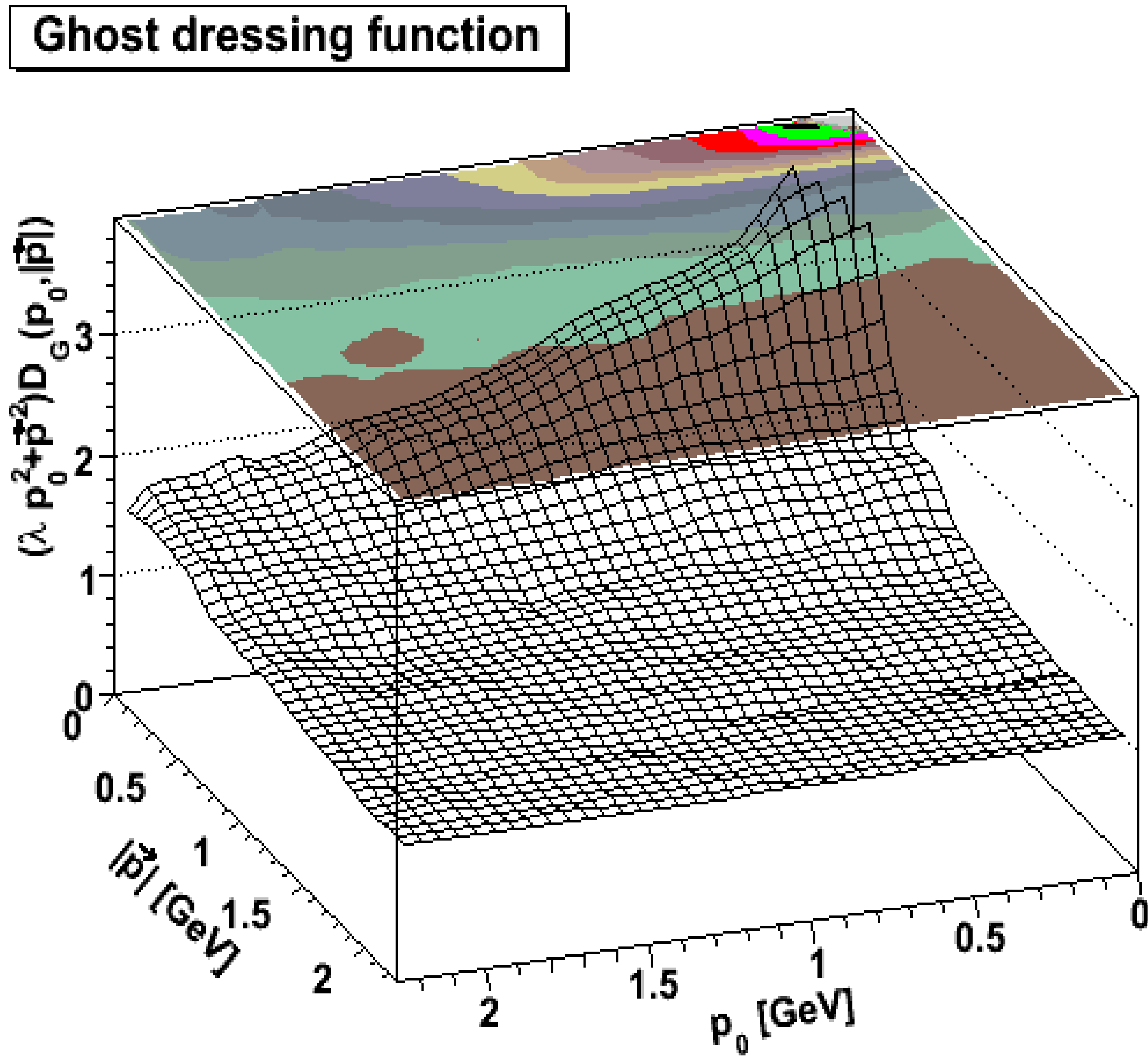
- Increase at all temporal momenta for infrared spatial momenta



Ghost dressing function

[Lattice 40³, beta=4.2, λ=1/20: Cucchieri et al., unpublished]

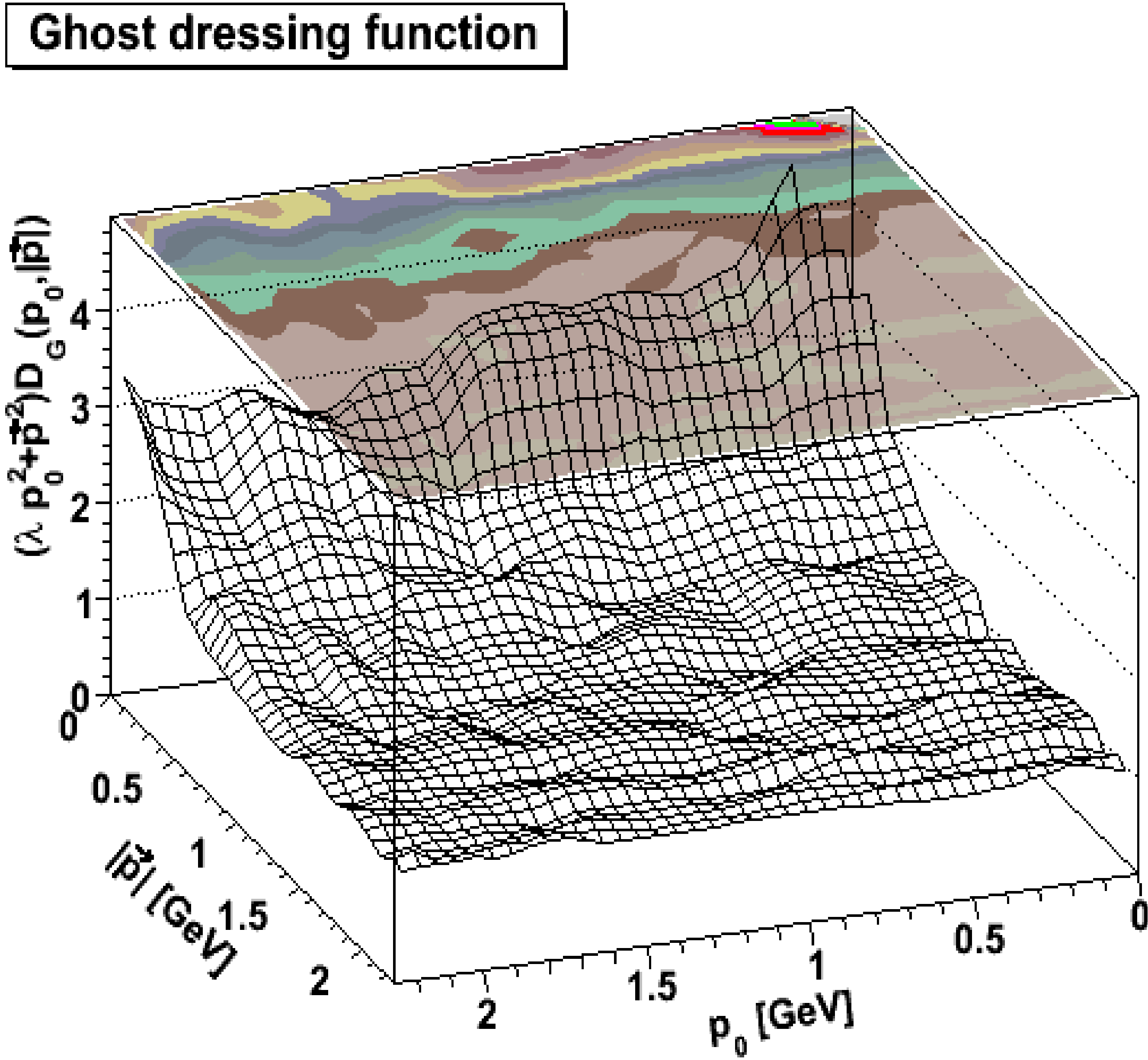
- Effects increase



Ghost dressing function

[Lattice 40^3, beta=4.2, λ=1/100: Cucchieri et al., unpublished]

- Strong enhancement at all temporal momenta for infrared spatial momenta



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- Change of Green's functions under gauge transformation
- Results in agreement with the Gribov-Zwanziger scenario
- Results in 4d similar [Cucchieri et al., 2007]
  - Smaller volumes – stronger finite volume effects

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    - Determine connection to the source of the potential

Topological configurations

- Vortices

Topological configurations

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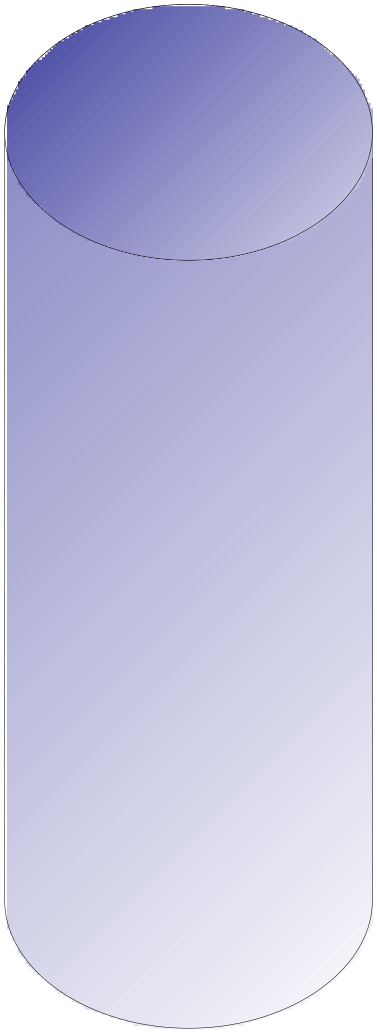
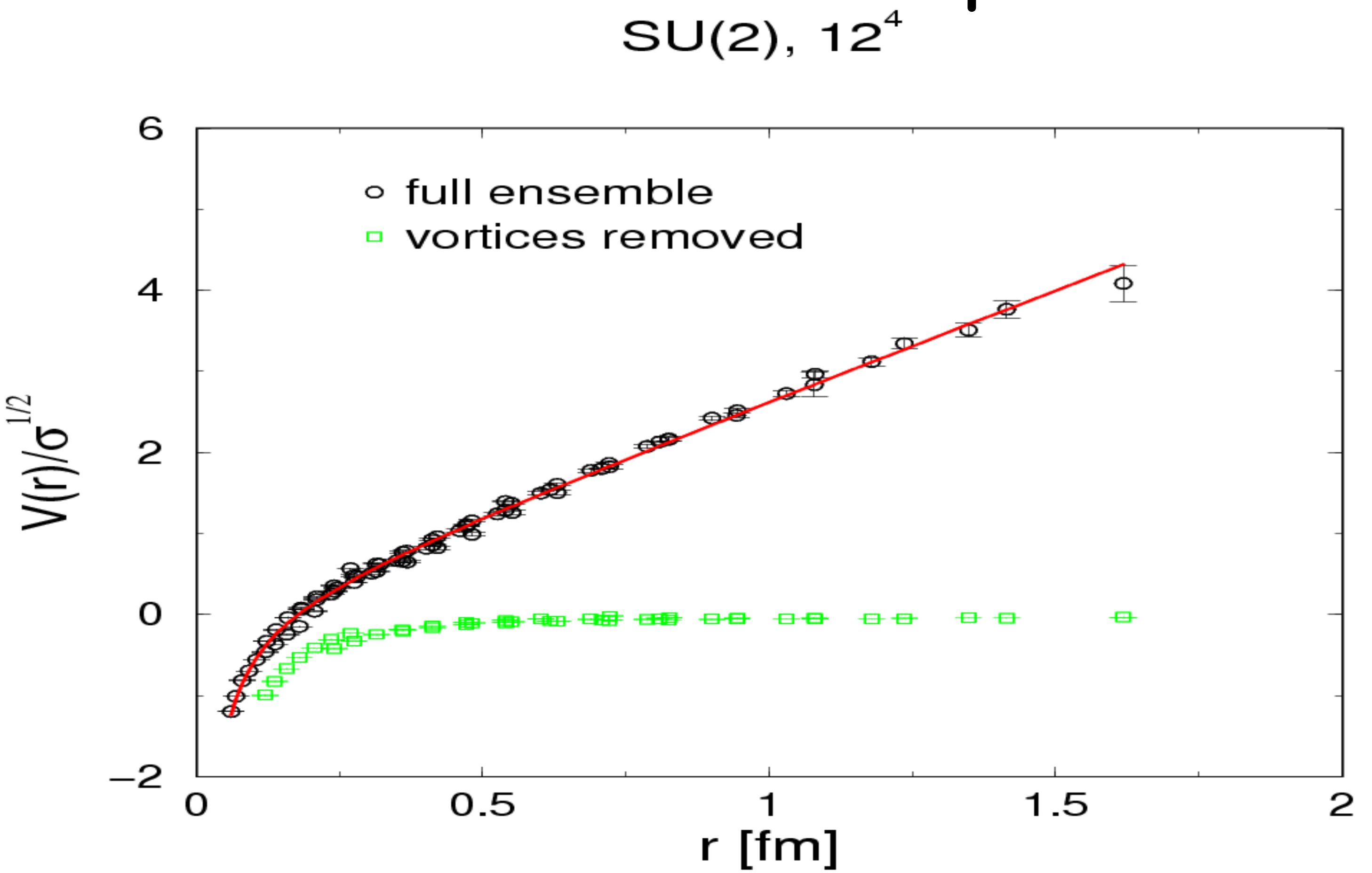
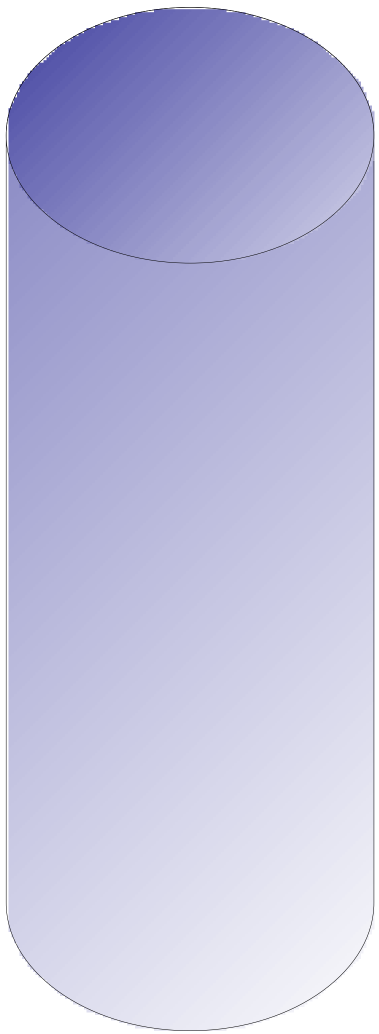
  - String-like objects – world surface



Topological configurations

- Vortices
  - String-like objects - world surface
  - Influence the confinement potential





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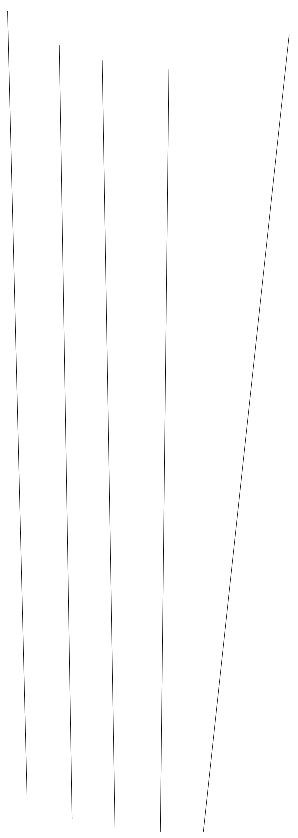

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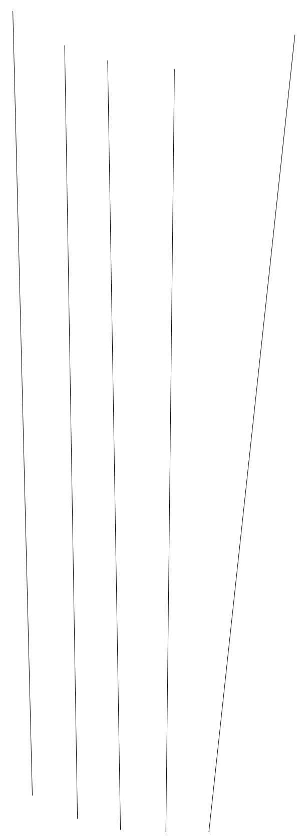

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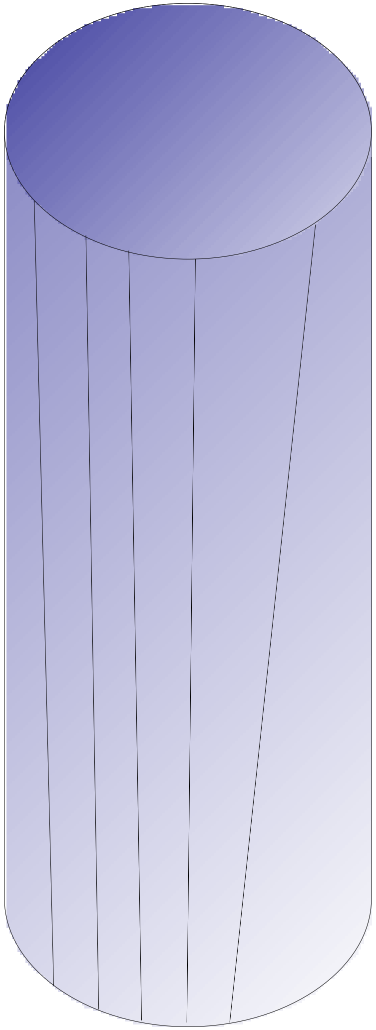
    - Monopoles move on the surface of vortices

[Greensite, 2003, Reinhardt, NPB 2002, Boyko et al., NPB 2006]



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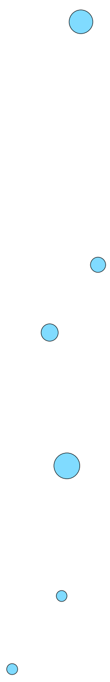

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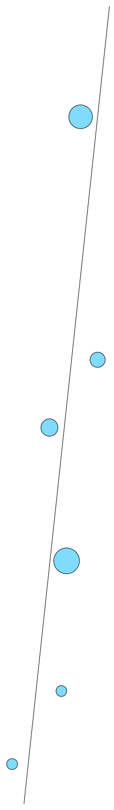

Topological configurations

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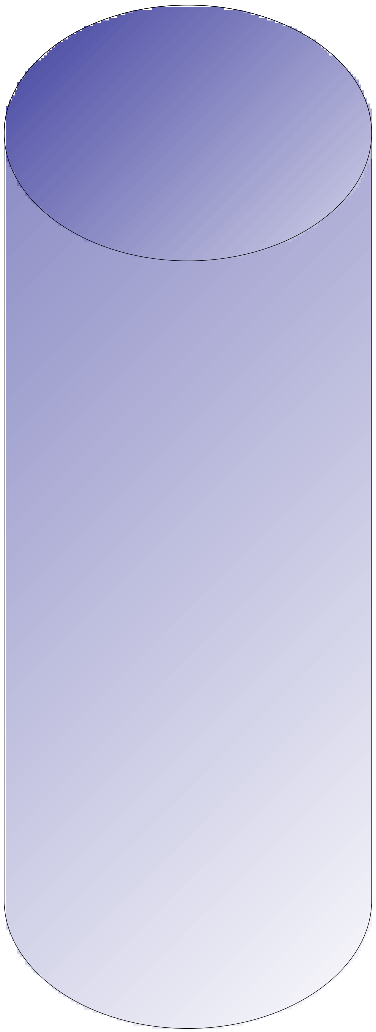

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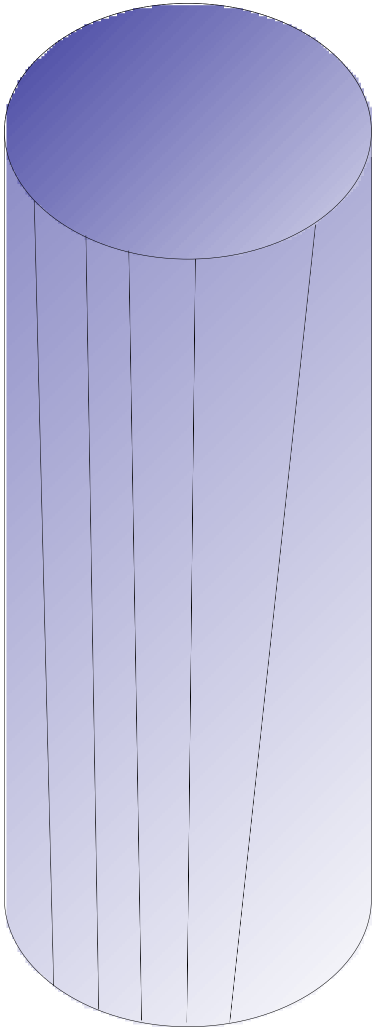
    - Likely more than listed here



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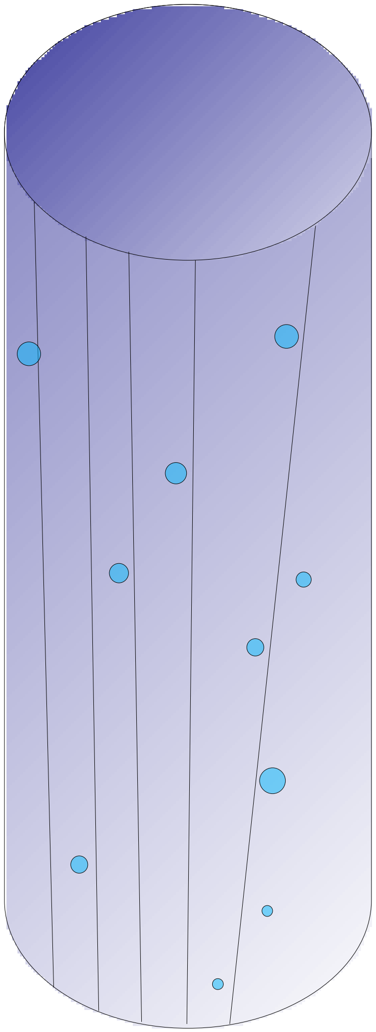

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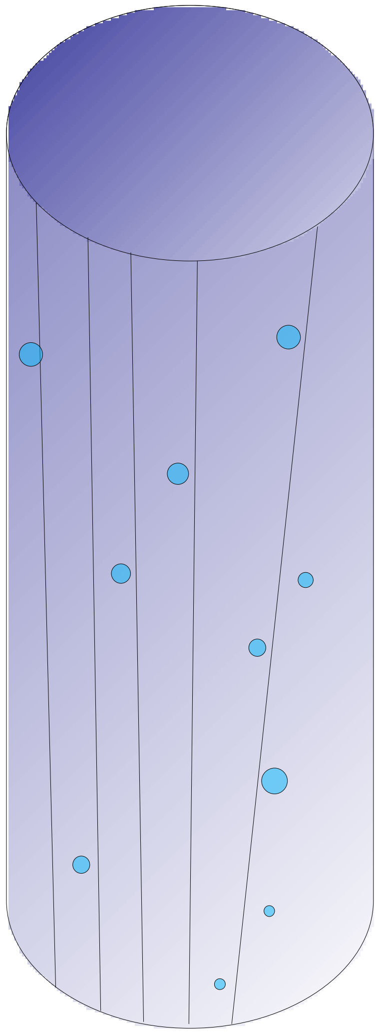

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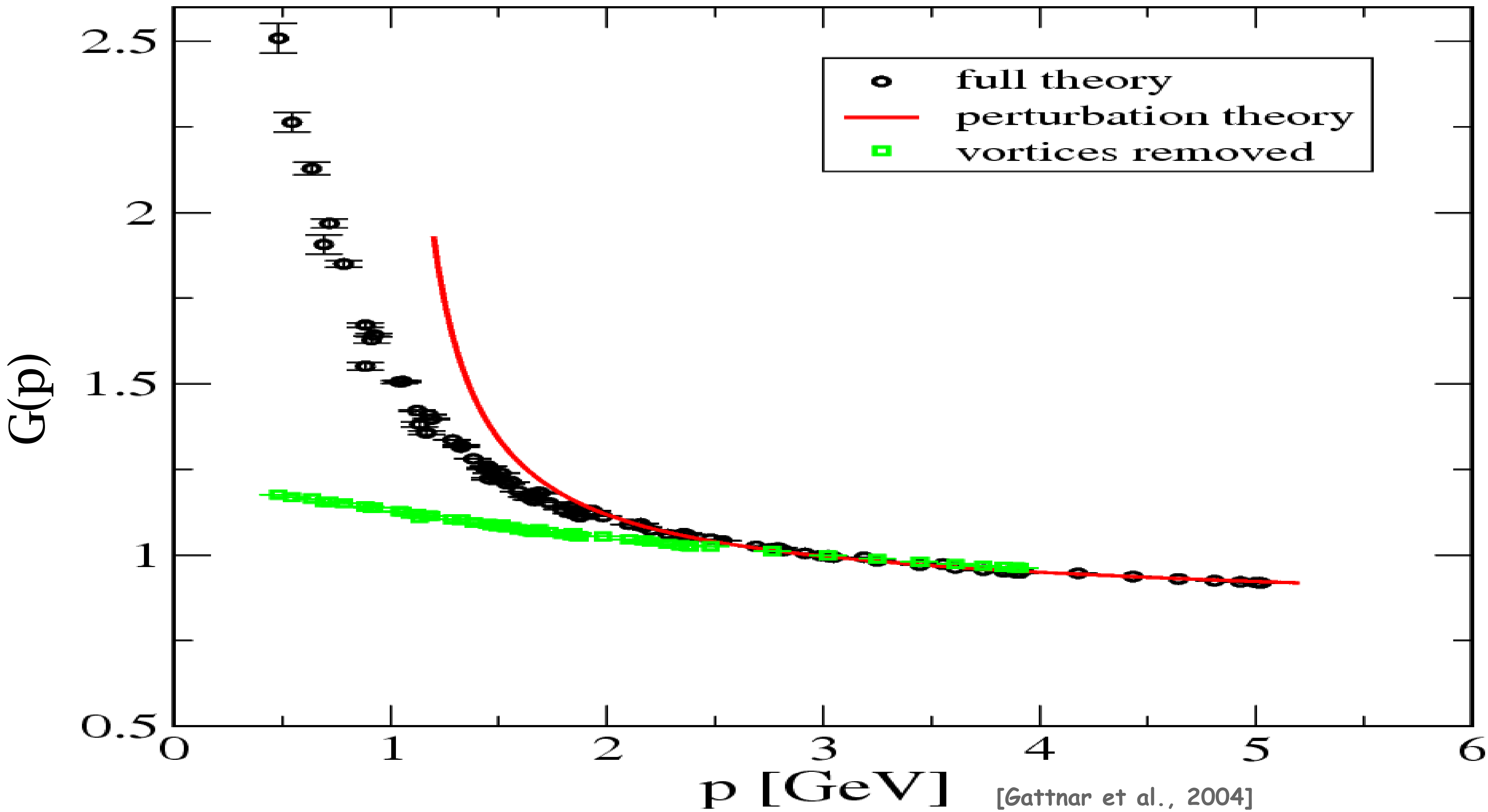
- How relates this to the gluons?

To answer: Return to the Faddeev-Popov operator

Ghost propagators and vortices

- Removal of vortices tames infrared divergence



[Gattnar et al., 2004]

Ghost propagators and vortices

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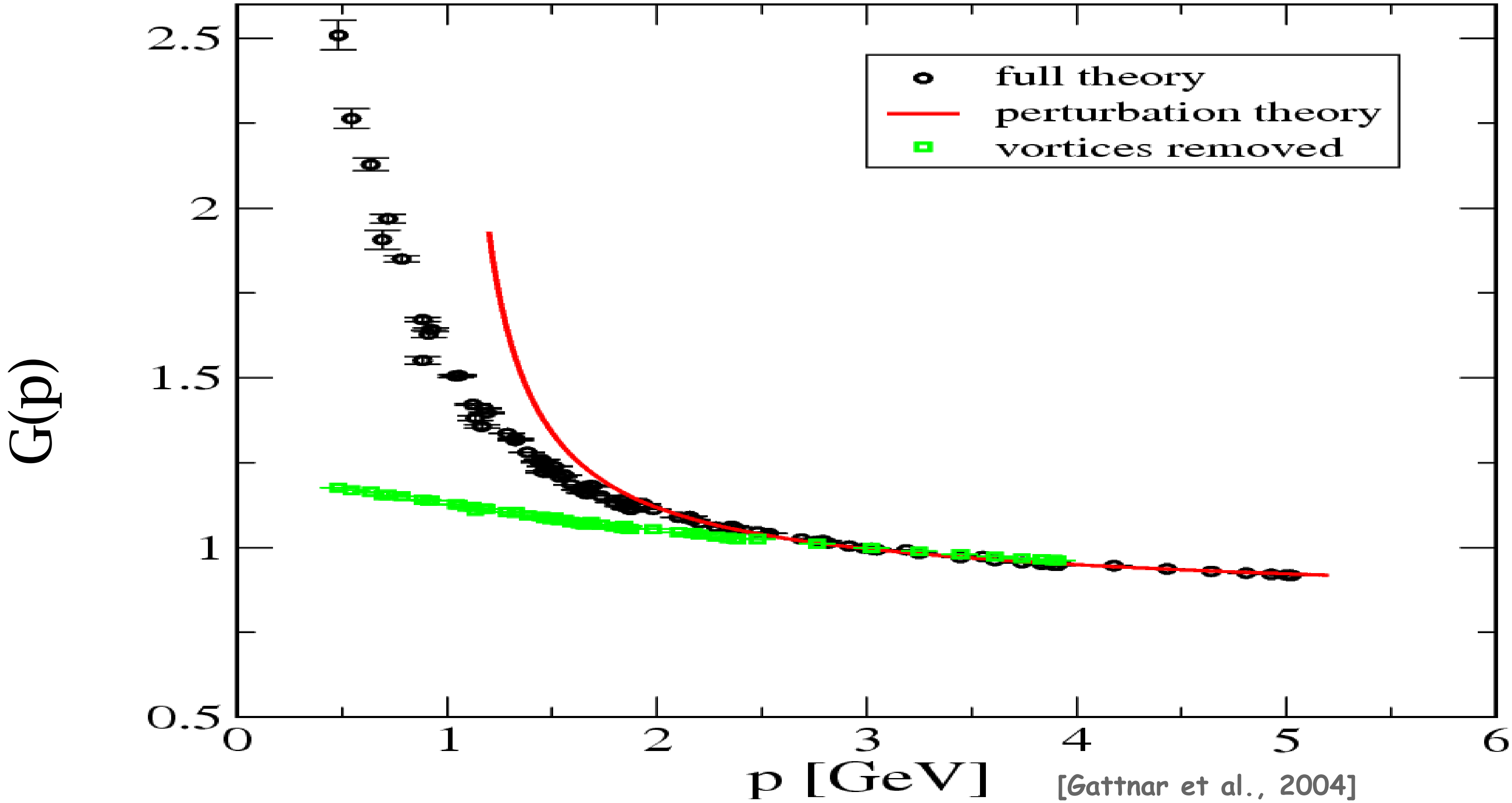
- Hints to a change of the FP-eigenspectrum



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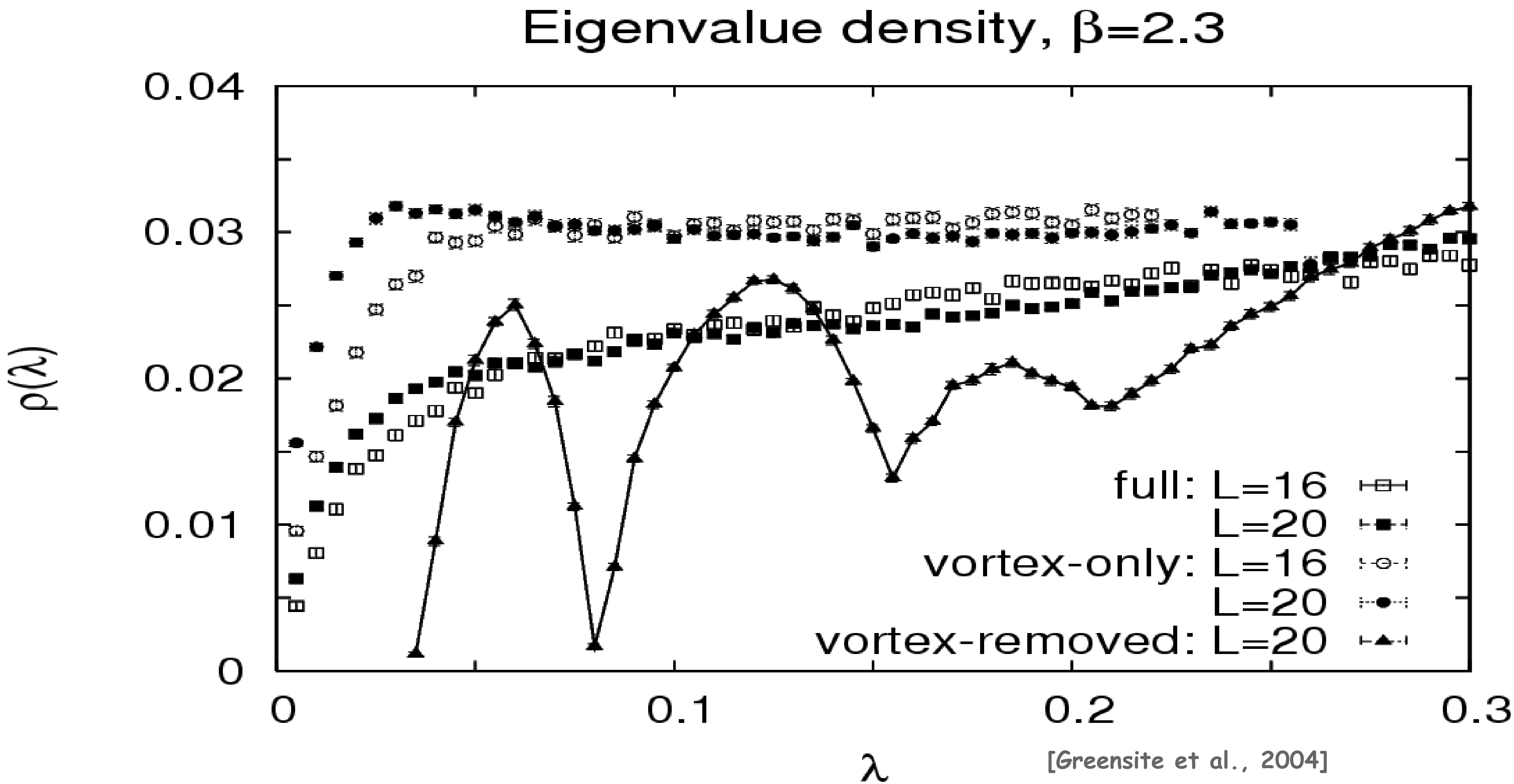
Vortices and the eigenspectrum of the FPO

- Removal of vortices in Coulomb gauge reduces enhancement of near-zero modes



[Greensite et al., 2004]

Analytical approach

- Study analytically the eigenspectrum of the FP-operator in topological background fields
- Use as background fields the field of
- Instantons [Maas, EPJC 2006]
- Monopoles [Maas, 2006]
- (Center) Vortices [Maas, EPJC 2006]

Eigenvalue equation

- **General form (for transverse fields)**

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- Non-localized: Correspond to scattering states in quantum mechanics

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    - Instanton and vortex: Non-trivial radial behavior
    - Monopole: Non-trivial angular behavior

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- Results for a more complicated system?

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- More on the connection to topological objects
- Different gauge groups and more gauges

Collaborations

- A. Cucchieri, T. Mendes (Uni. of São Paulo, Brazil)
  - Lattice results on interpolating gauges and Landau gauge Faddeev-Popov operator
  - hep-lat/0701011, hep-lat/0610123, hep-lat/0610006, hep-lat/0605011
- C. S. Fischer (Darmstadt Uni. of Technology), J. M. Pawlowski (Uni. of Heidelberg), L. von Smekal (Uni. of Adelaide, Australia)
  - Finite volume DSEs
  - hep-ph/0701050
- Supported by the DFG and VEGA