Describing Gluons
at zero and finite temperature

Axel Maas

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Quarks, Hadrons, and the QCD Phase Diagram
St. Goar
Germany

UNI GRAZ

Overview

- Describing gluons at zero temperature

Supported by the FWF

See: 0907.5185, 0810.1987, hep-lat/0702022, hep-ph/0408074

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- Describing gluons at zero temperature
    - Fixing an umambiguous gauge

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Overview

- Describing gluons at zero temperature
  - Fixing an umambiguous gauge
- Gluons at finite temperature
  - Resolving the Linde problem
  - Properties of gluons for SU(2) and SU(3)

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Part I

Zero Temperature

Gauge freedom

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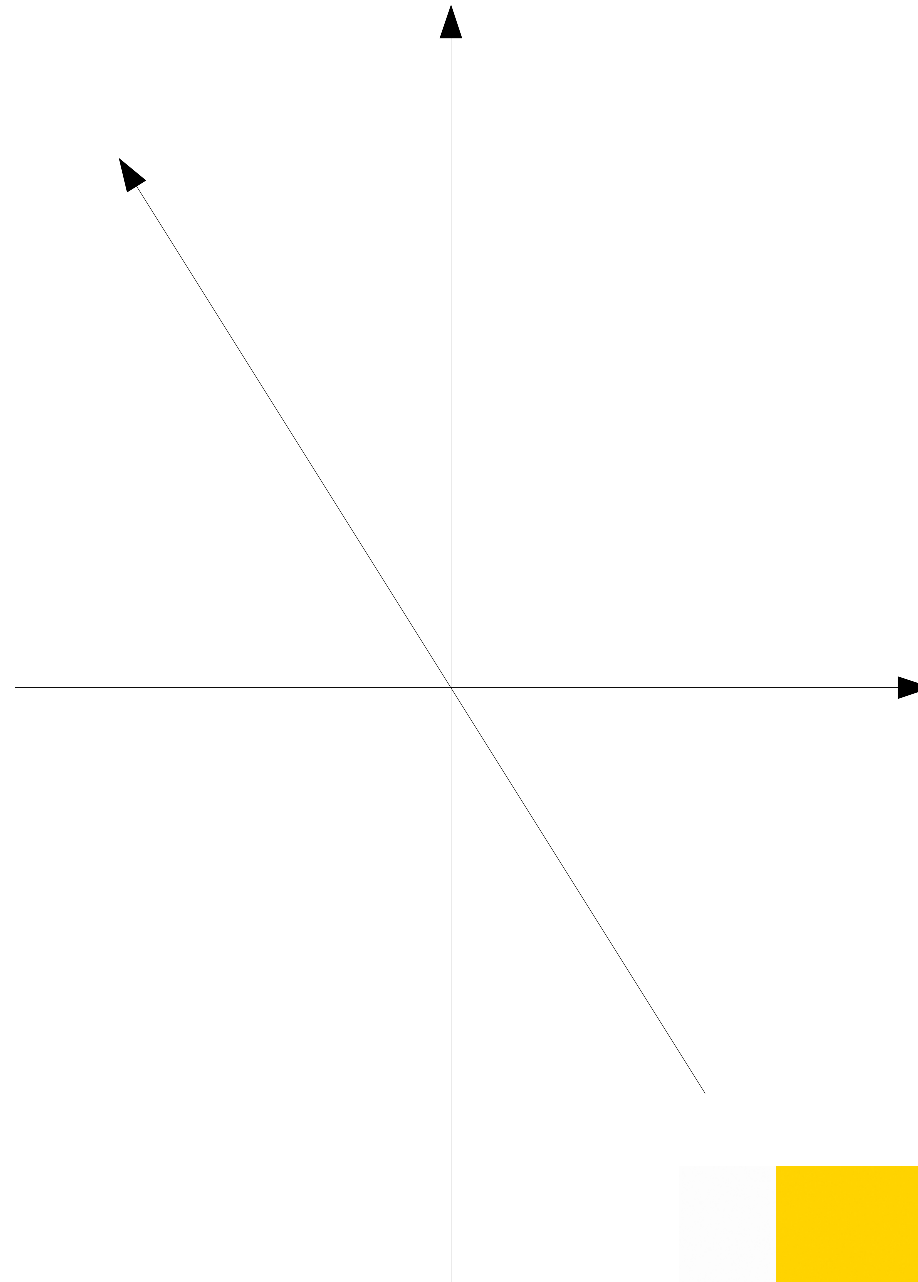
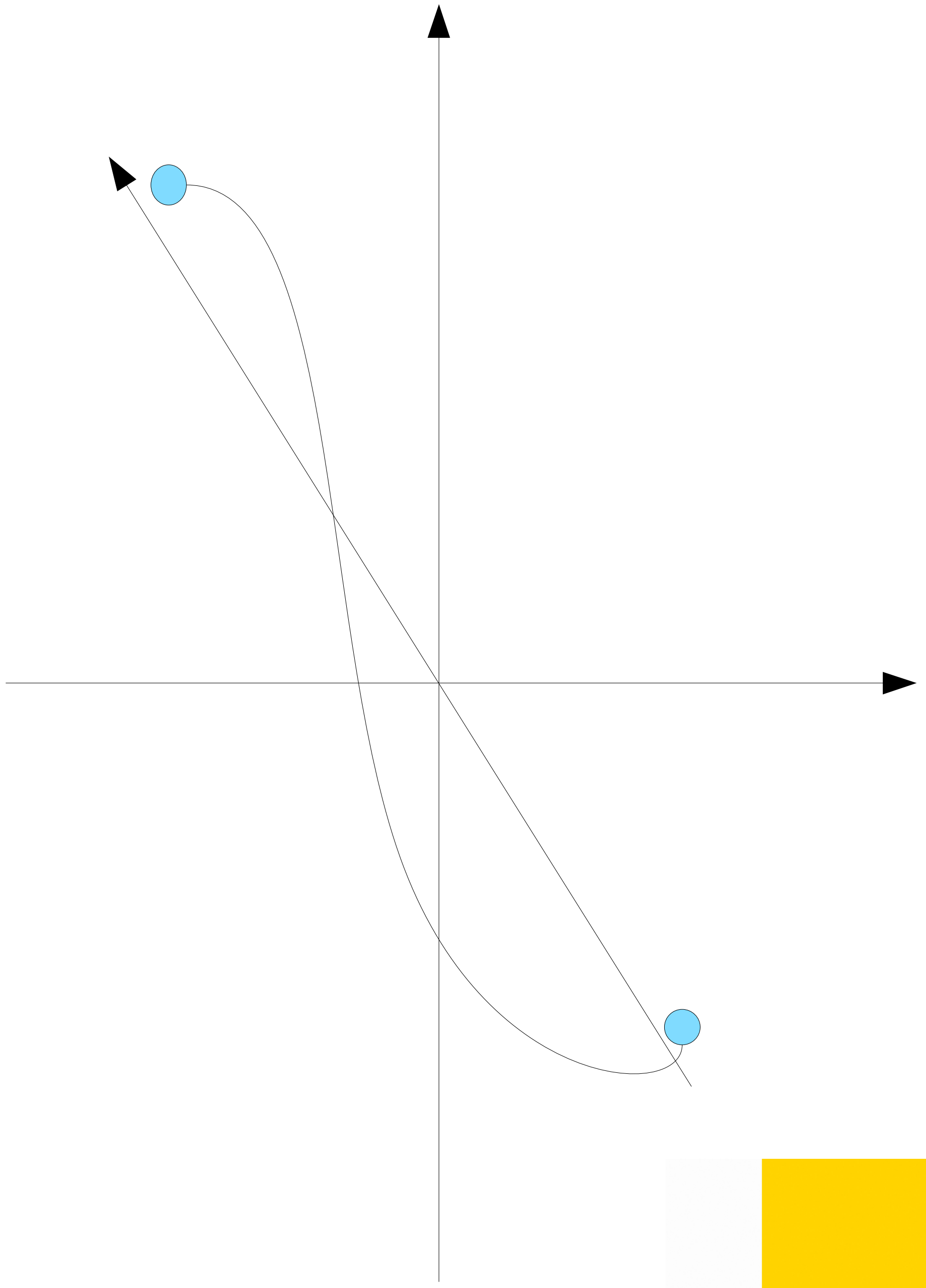
  - Keep only gluons: Yang-Mills theory
- Quarks and gluons are only well-defined in a fixed gauge
  - No concept of a gauge-invariant local color density
  - Like energy density in general relativity
- Describing gluons requires gauge-fixing
  - Comparison of different methods requires the same gauge fixing in all methods

Configuration space (artist's view)



Configuration space (artist's view)

- Gauge fields not unique
  - Gauge transformation does not change physics



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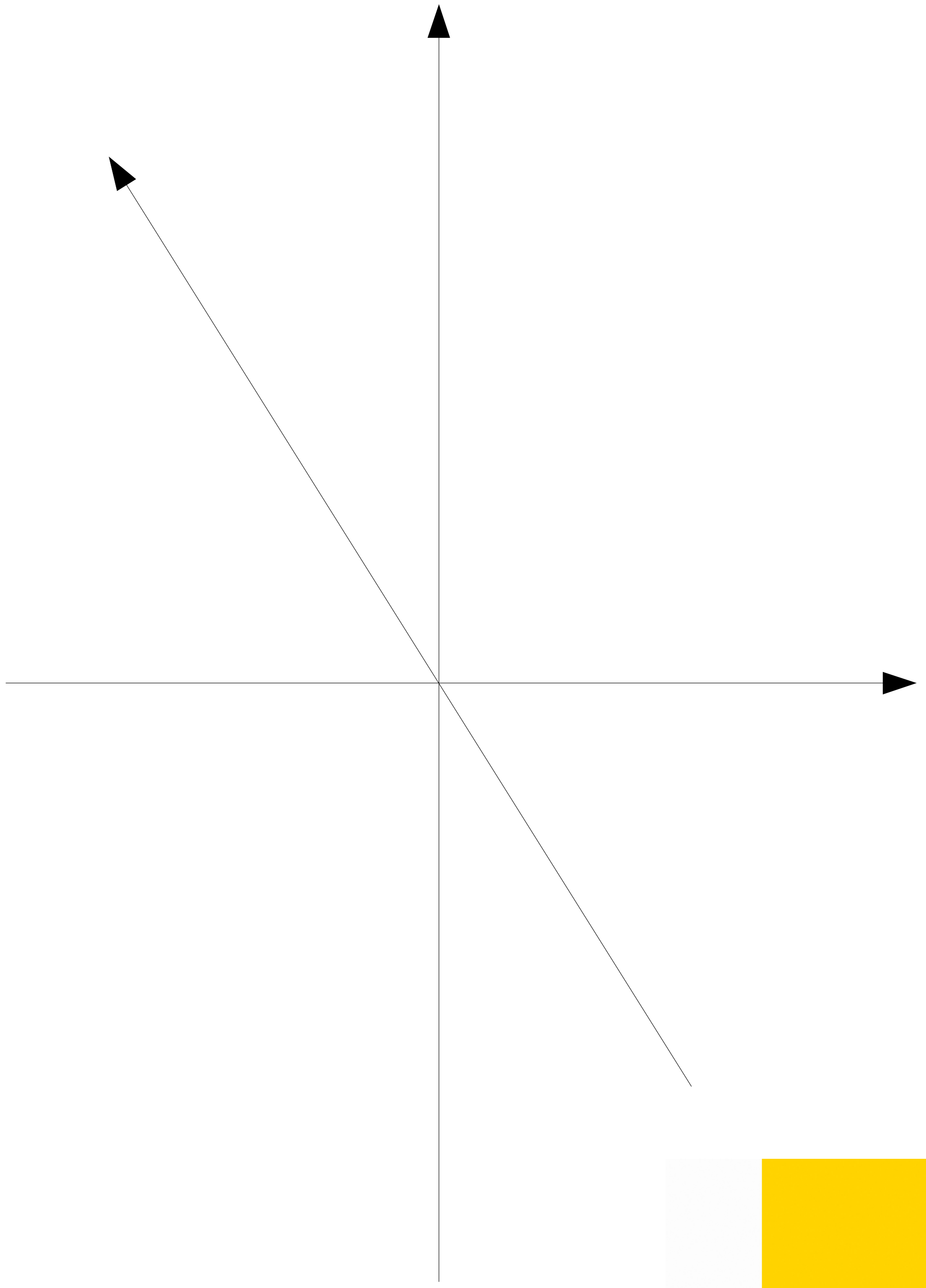

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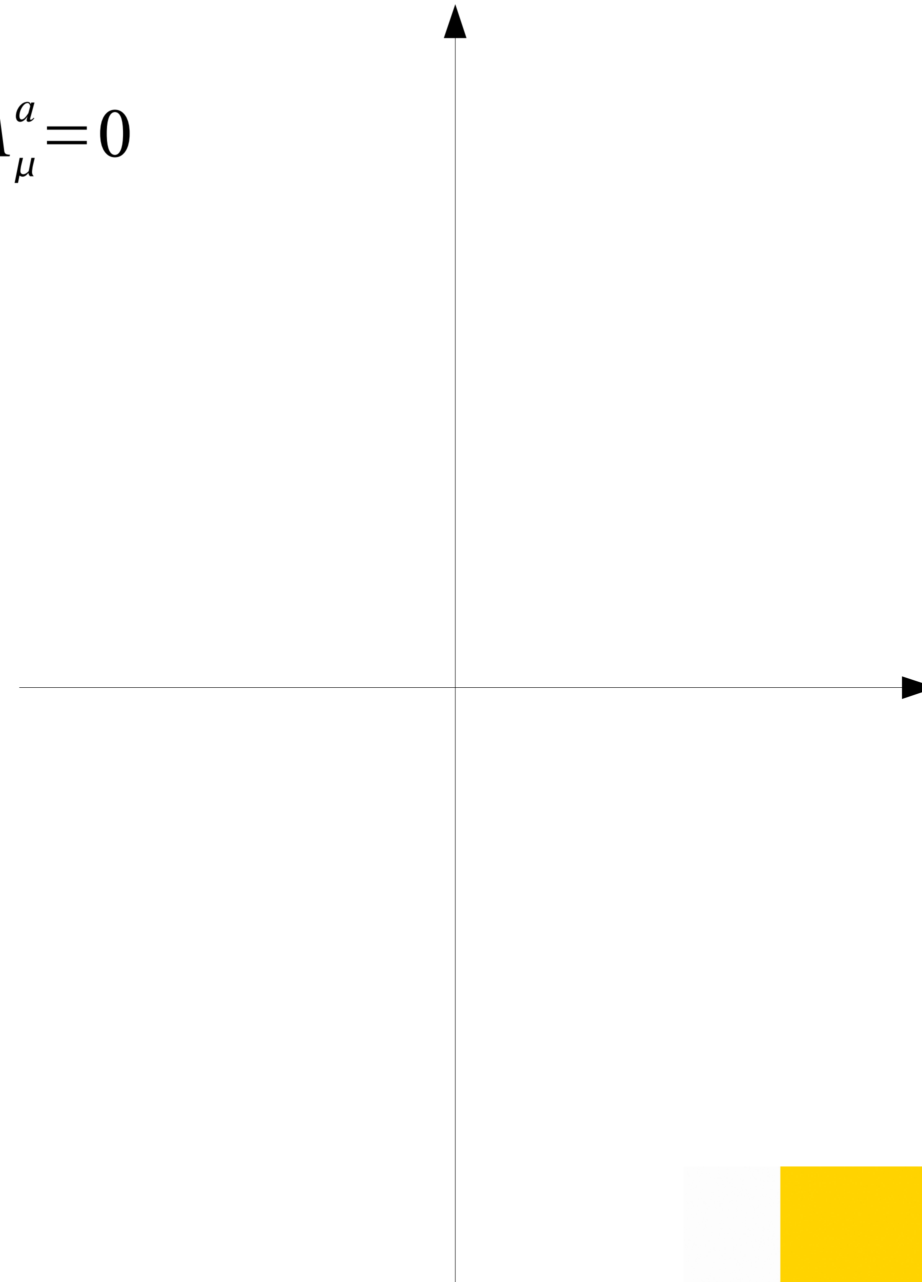
- Impose Landau gauge condition $\partial_\mu A_\mu^a = 0$
  - Reduces configuration space to a hypersurface



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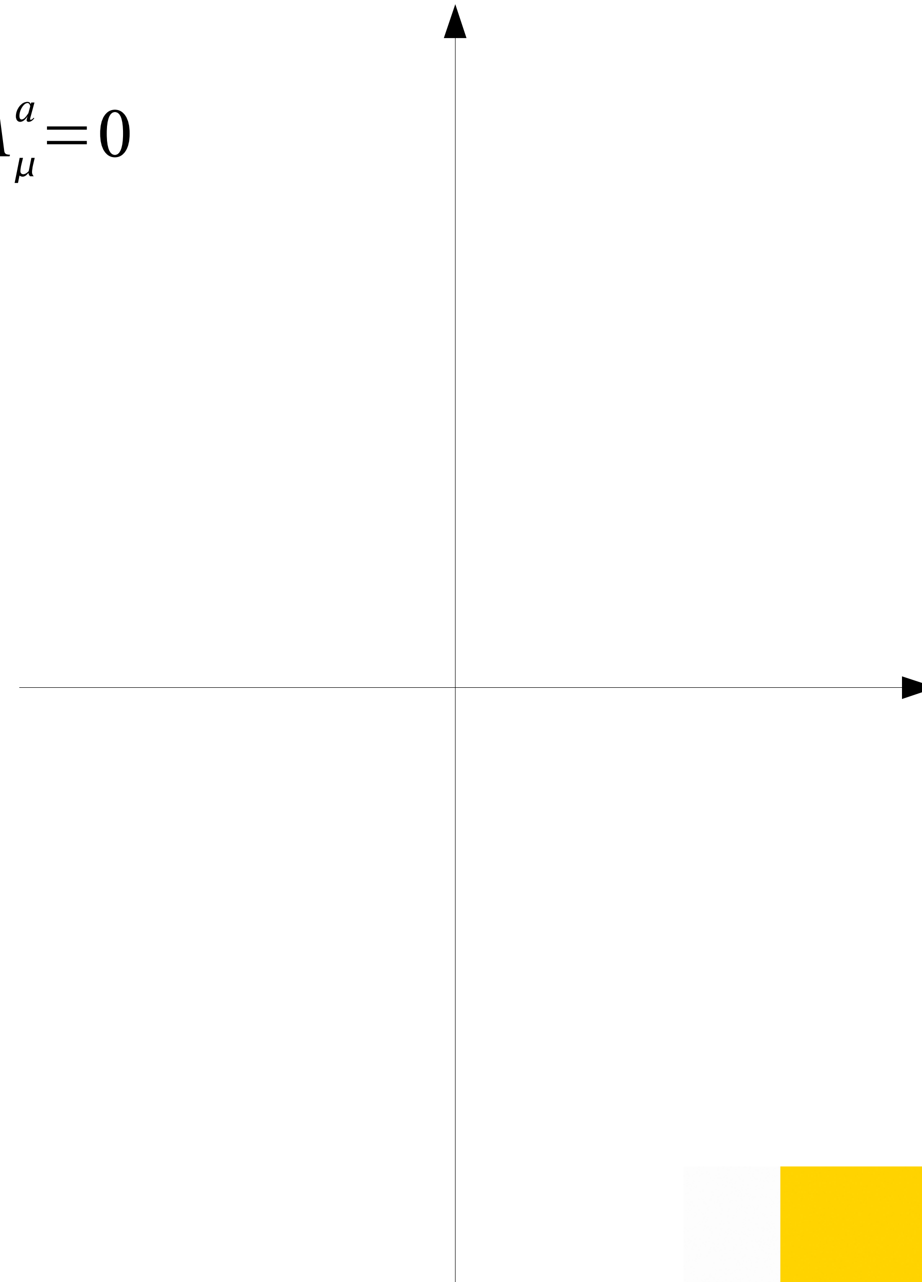

(Perturbative) Landau gauge

- Lagrangian:

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

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

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

- Degrees of freedom:

Gluons: A_{μ}^{a}

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

- Ghosts interact with gluons: They have to be included

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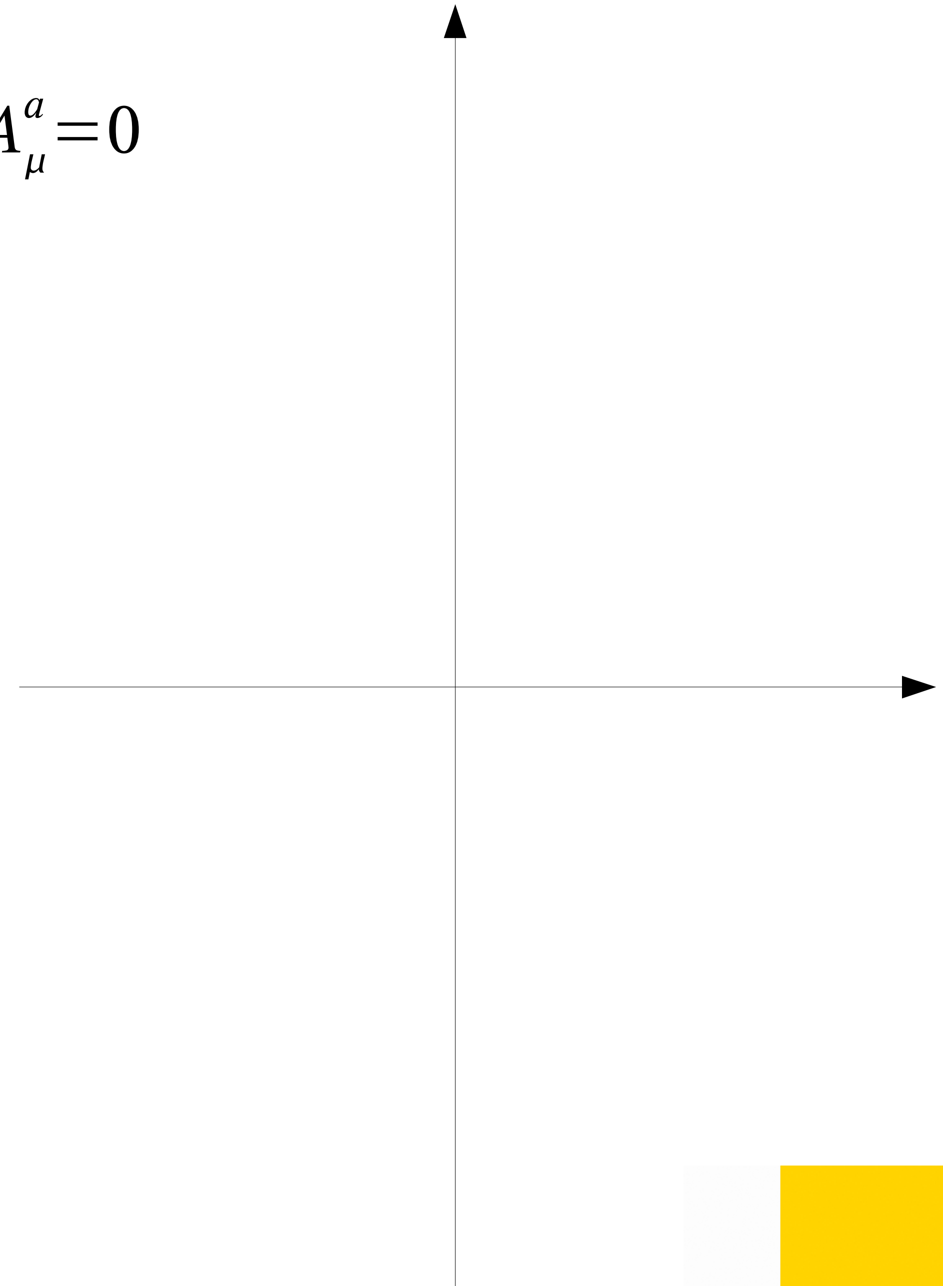

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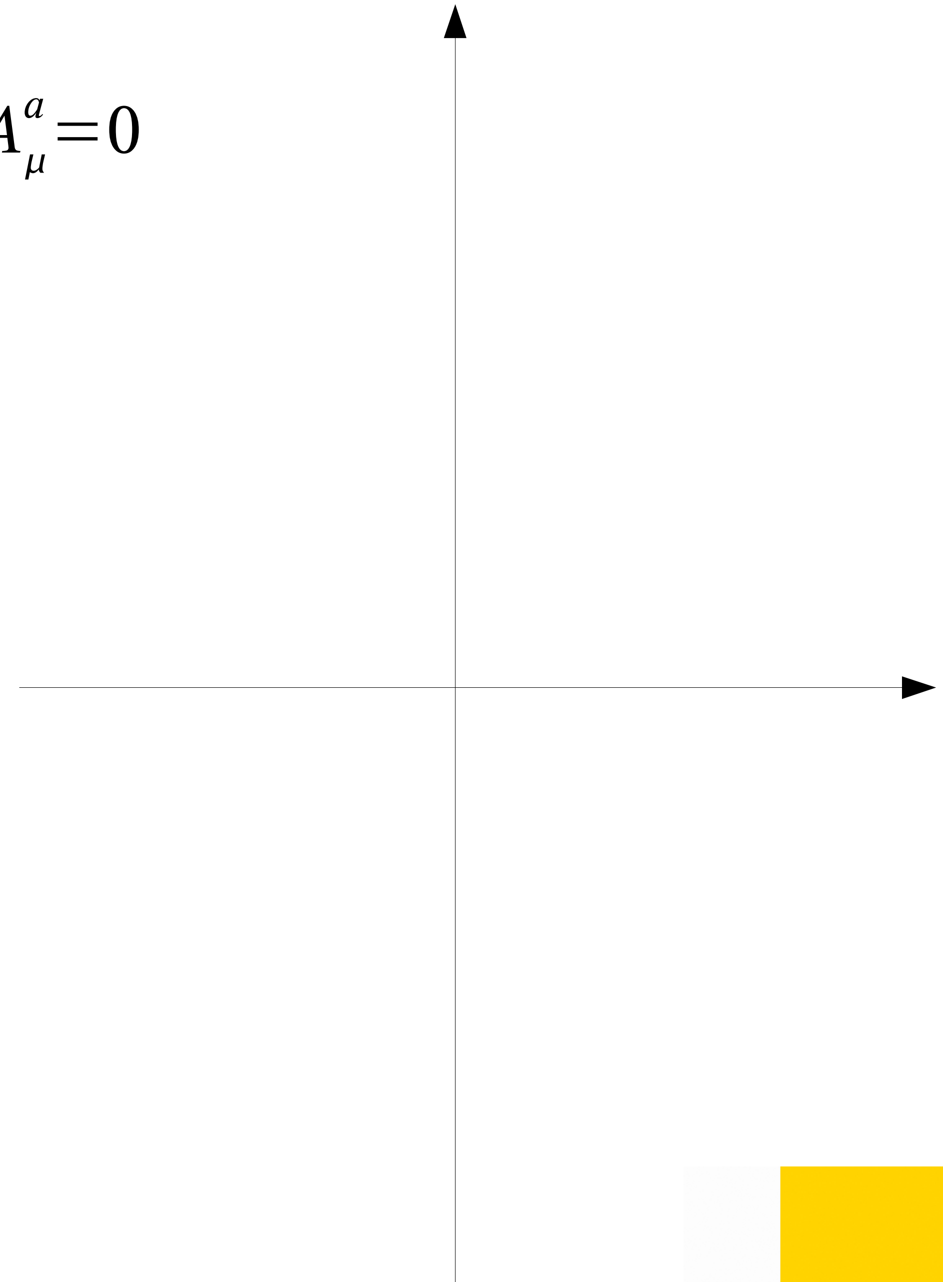
  - Permits to describe gluons using correlation functions



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- Simplest non-zero Green's functions: 2-point functions or propagators
  - Expectation values of products of two field operators
  - 1-point functions vanish

Propagators

- In Landau gauge: Gluon and one auxiliary field: Ghost
- Gluon:

$$D_{\mu\nu}^{ab}(x-y) = \langle A_\mu^a(x) A_\nu^b(y) \rangle$$

$$D_{\mu\nu}(p) = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right)\frac{Z(p)}{p^2}$$

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- G and Z are the dressing functions

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- Also for the non-perturbative physics?

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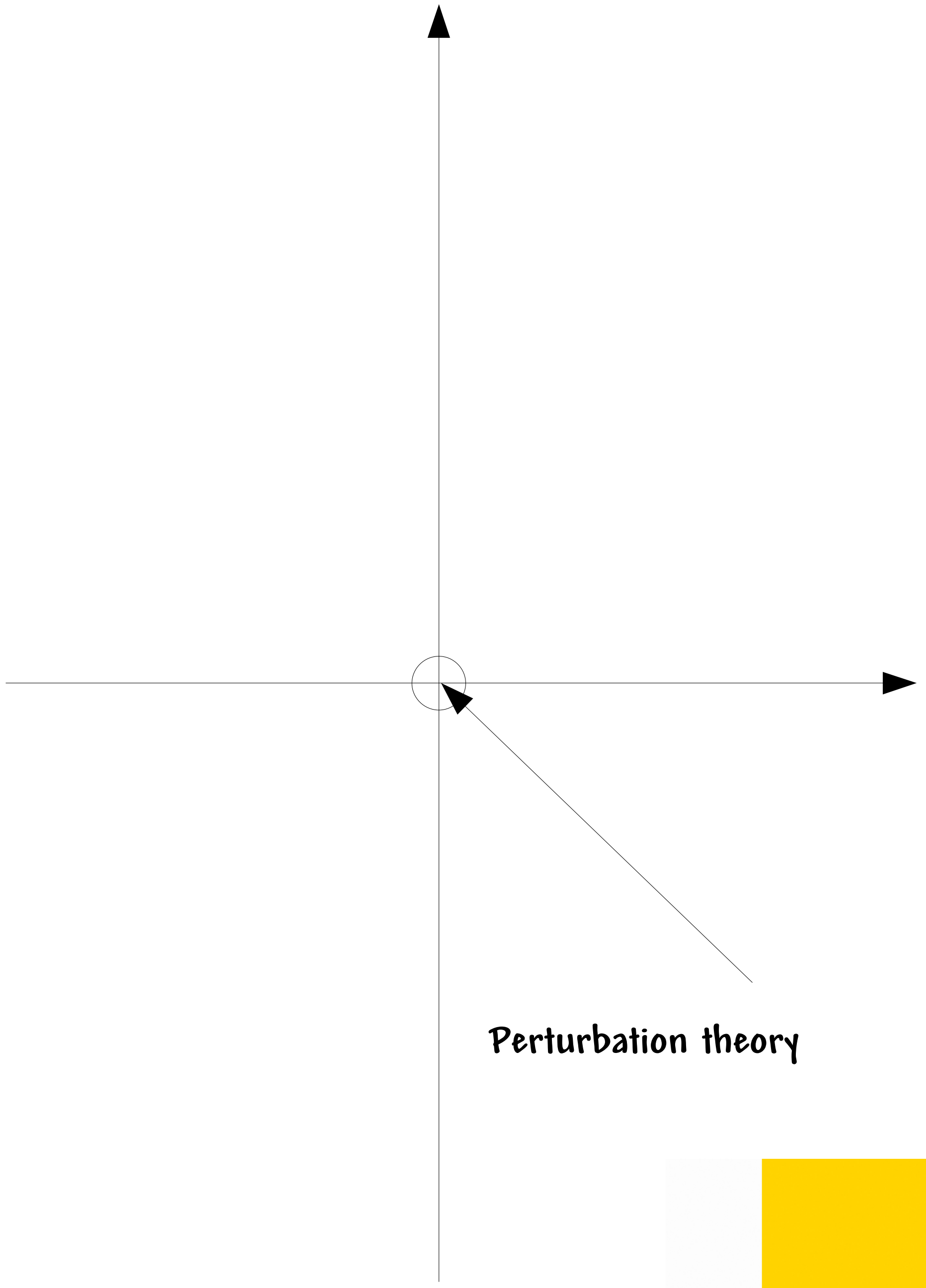

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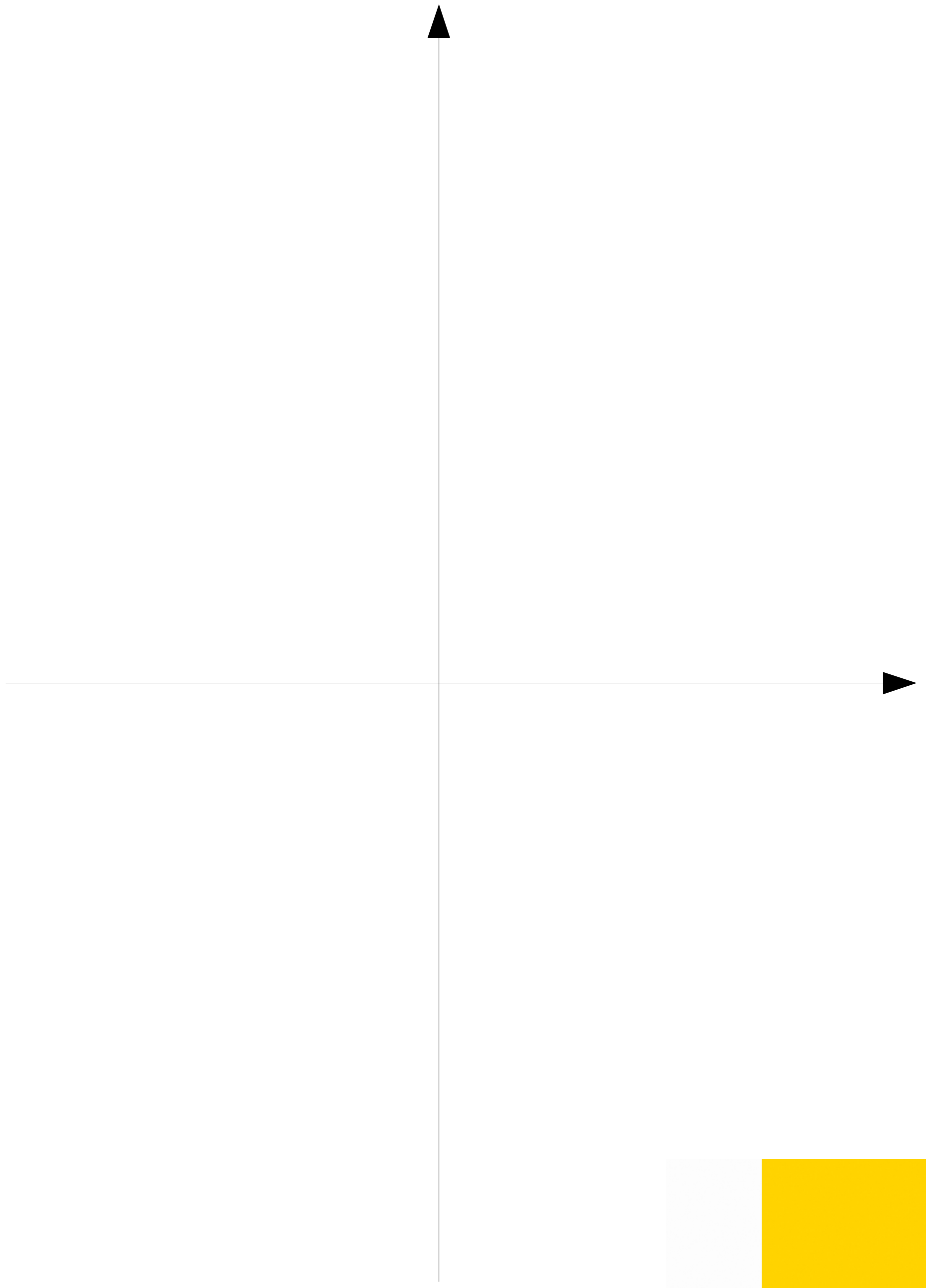
- Non-perturbative physics probes the complete hypersurface



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- There are no local gauge conditions, which select a unique gauge field configuration [Singer 1978]
  - Gribov-Singer ambiguity

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- Resolves the Gribov-Singer ambiguity explicitly

Implementation

- Generates a one-parameter family of Landau gauges, parameterized by the ghost propagator at zero momentum: A second gauge parameter [Maas, 2009; Fischer, Maas, Pawlowski, 2008]

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- Differences only visible in the deep infrared

Ghost propagator from the lattice [3d, Maas, 2009]

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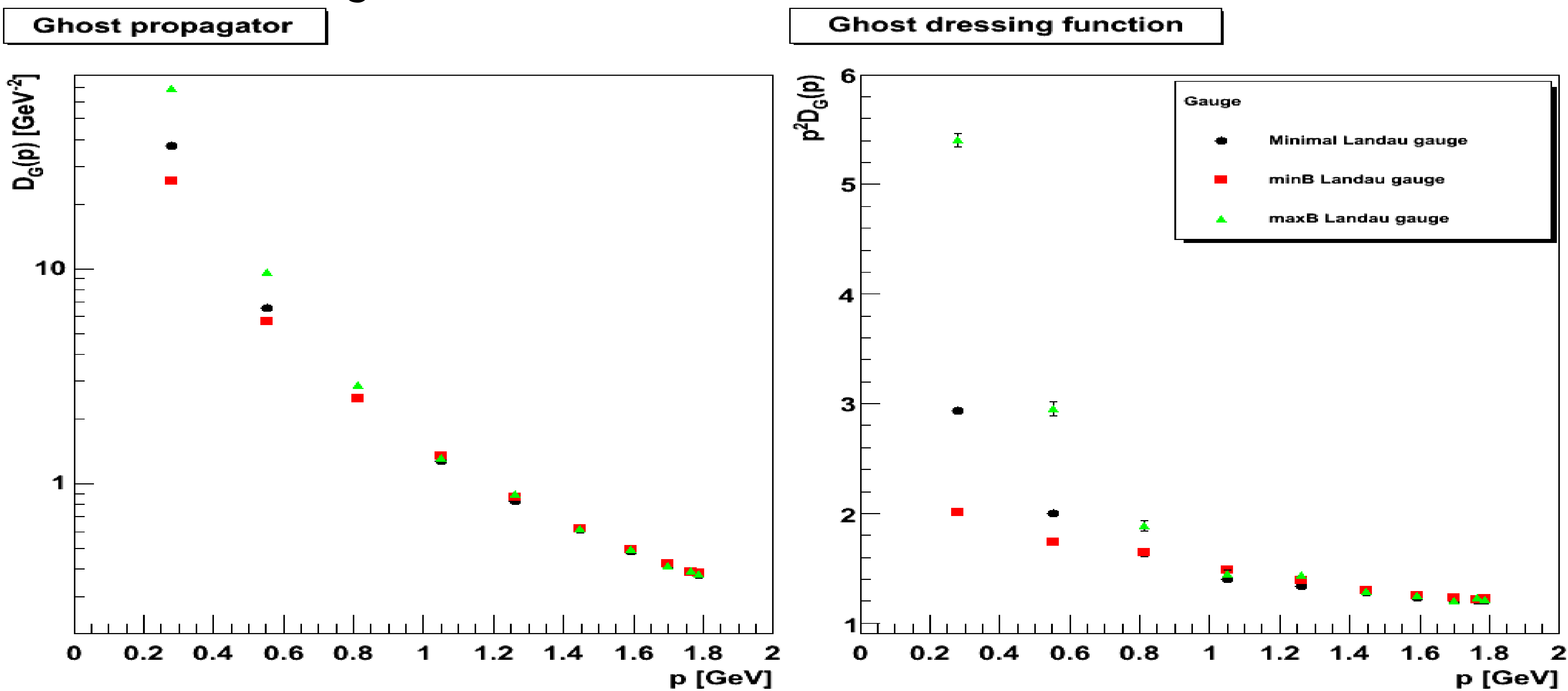

- Results from lattice calculations
- Different gauge choices yield different propagators
- Lattice artifacts still to be studied

Ghost dressing function in the continuum [Fischer, Maas, Pawlowski, 2008]

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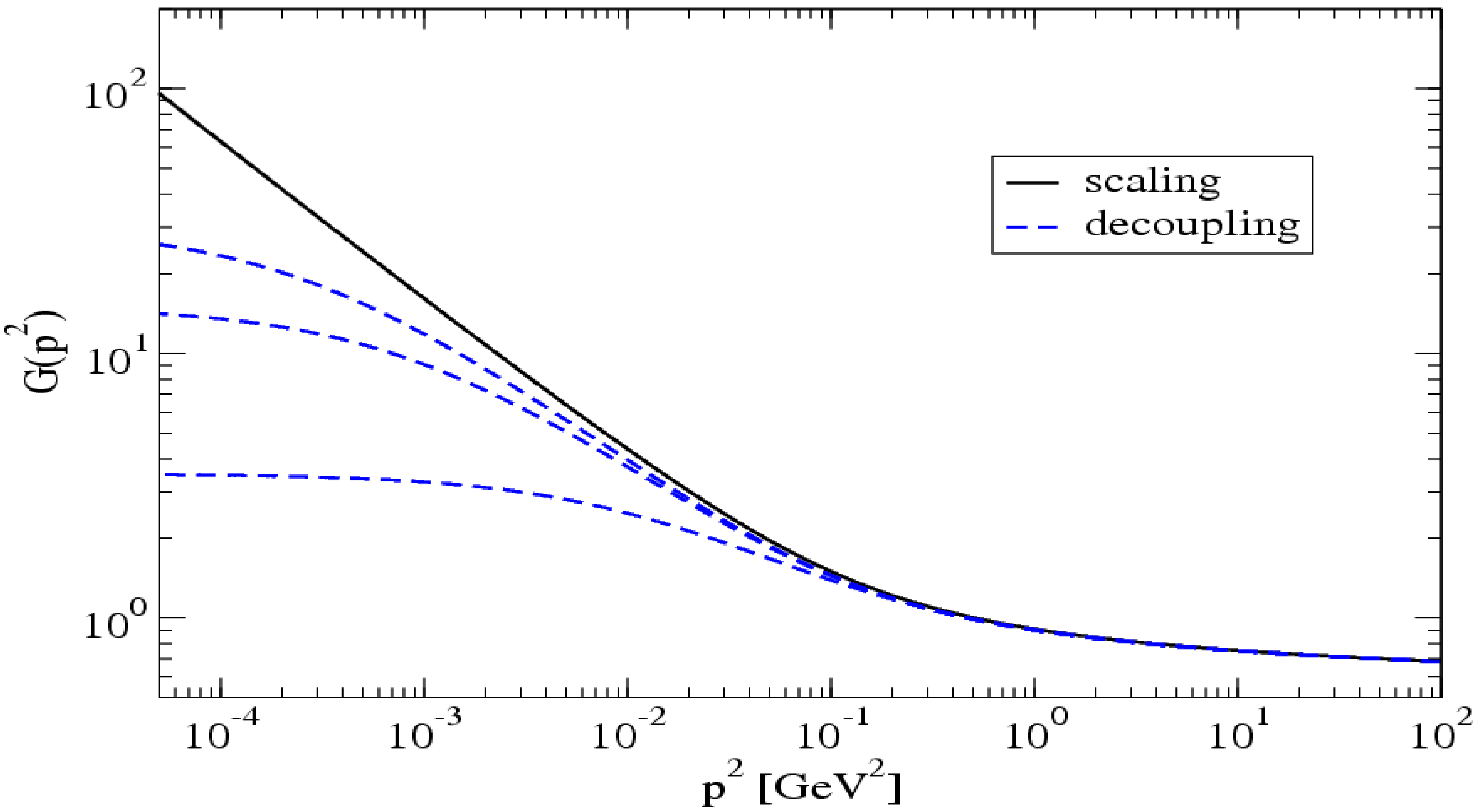

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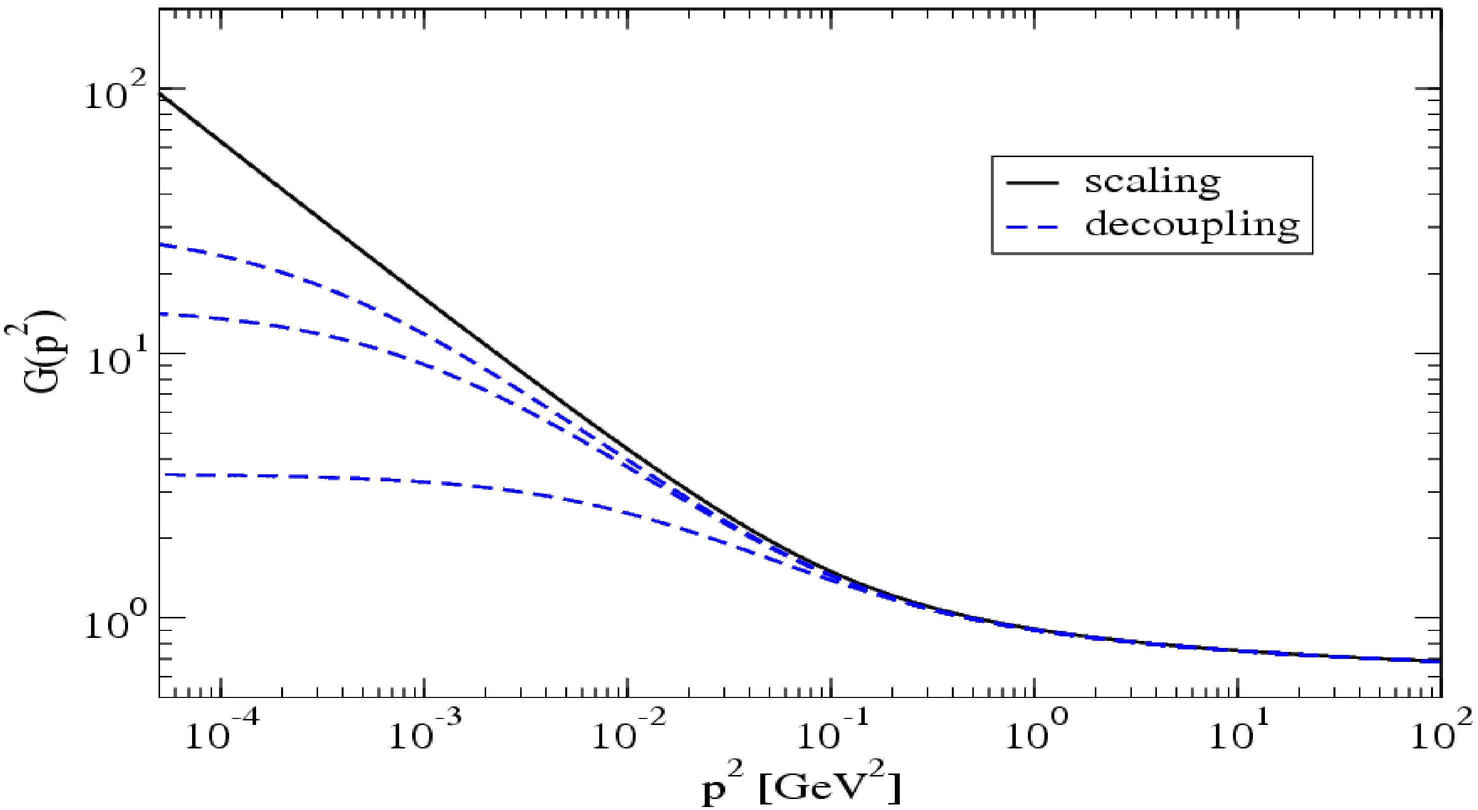

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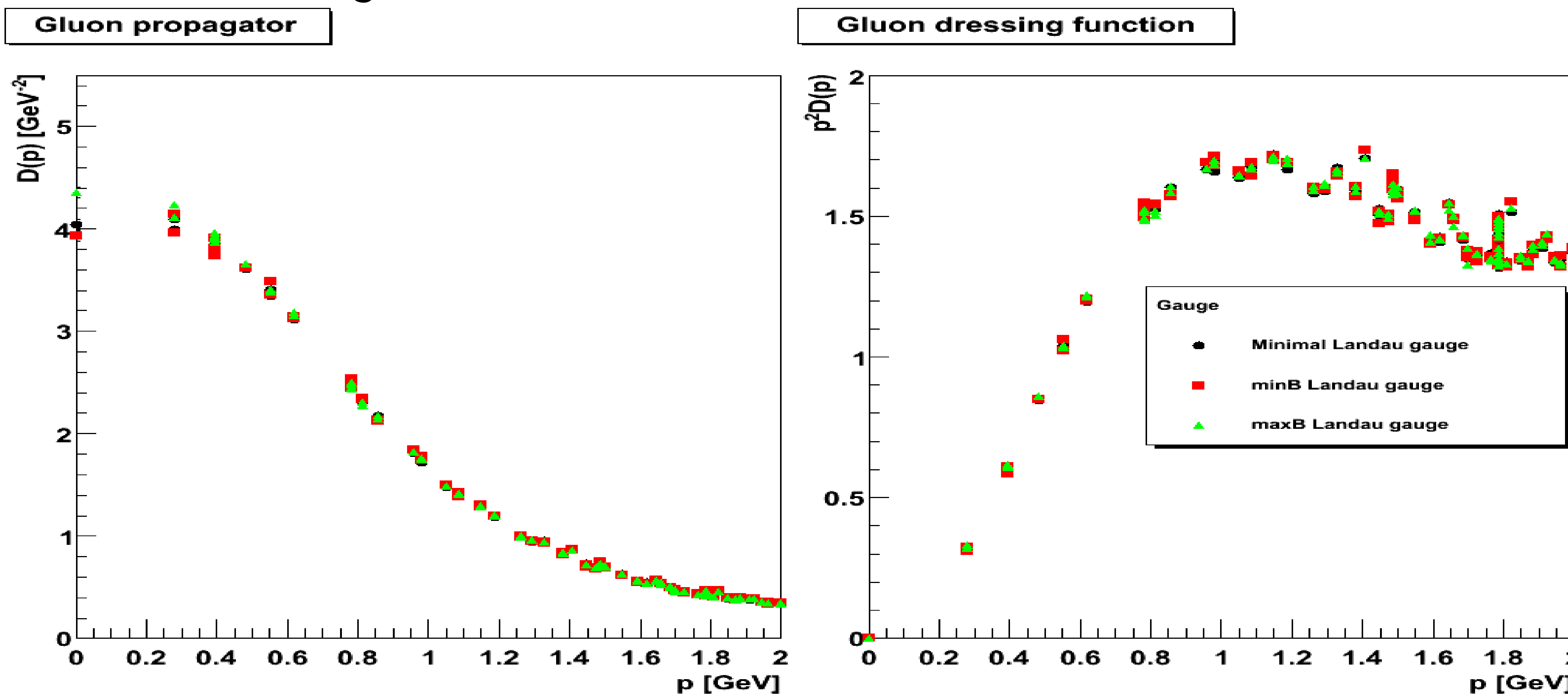
- Scaling: Divergent, Decoupling: Finite dressing function

Gluon propagator from the lattice [3d, Maas, 2009]



- Almost unaffected of the gauge choice at presently accessible volumes
- Effects only expected below 200 MeV

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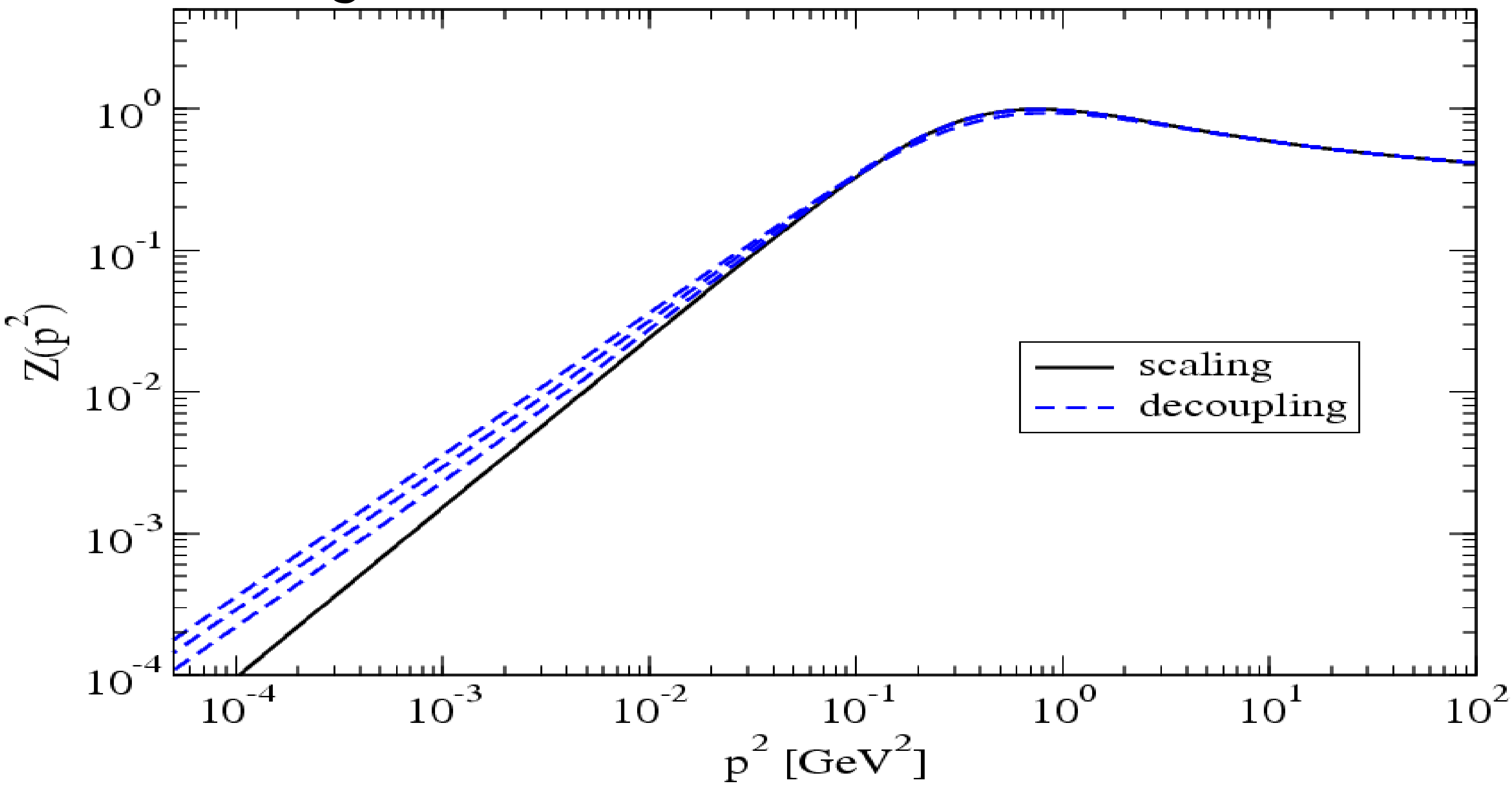

- Scaling case: Vanishing gluon propagator
  - No positive spectral function: Gluons confined [Zwanzgier, '90s]
- Decoupling case: Screened gluon
  - No positive spectral function [Fischer, Maas, Pawlowski, 2008; Cucchieri, Mihara, Mendes, 2004]

Part II

Finite Temperature

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Infinite-temperature case: See poster of Veronika Macher

Finite-Temperature Propagators

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- Gluon

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  - Here: Only soft

Splitting of electric and magnetic sectors

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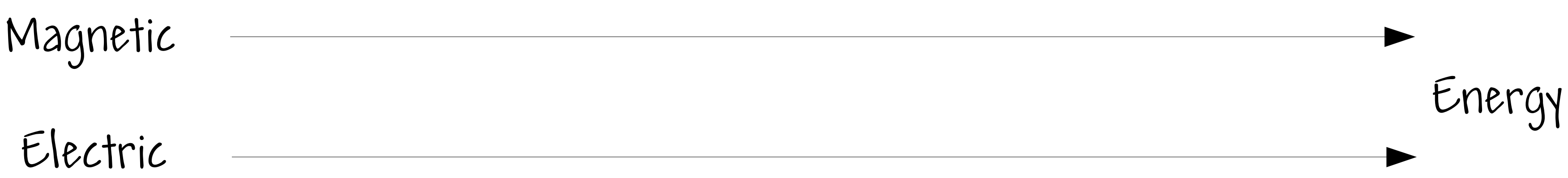

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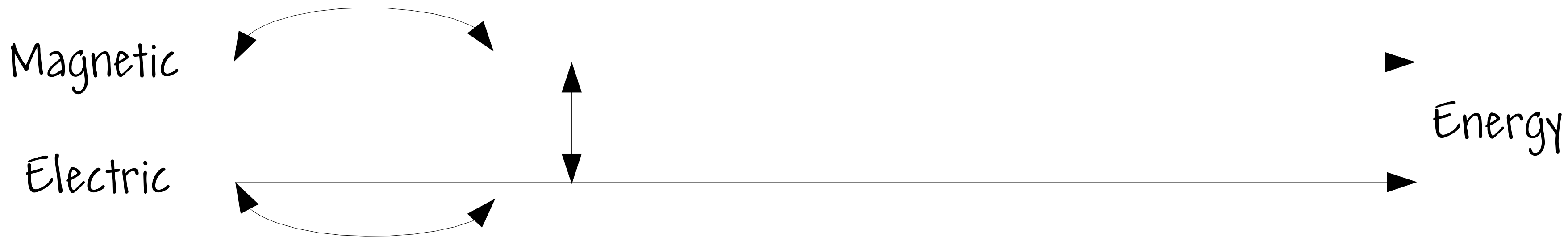

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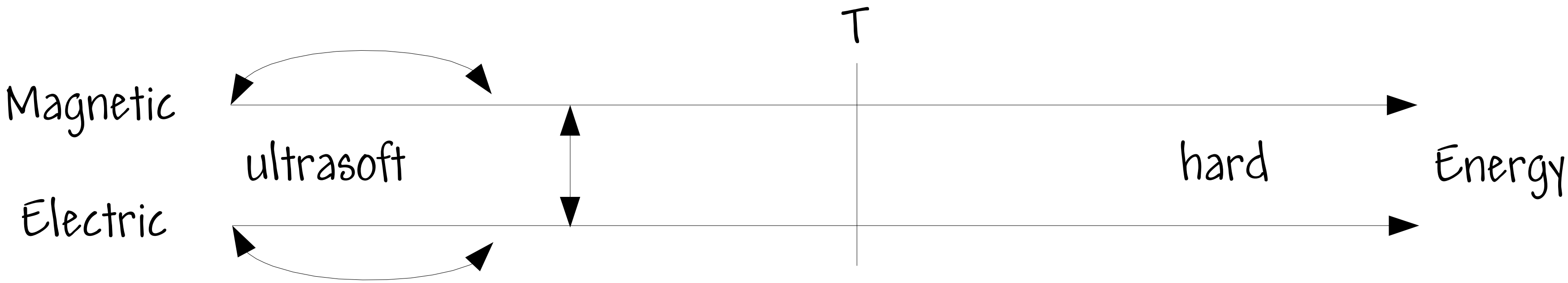

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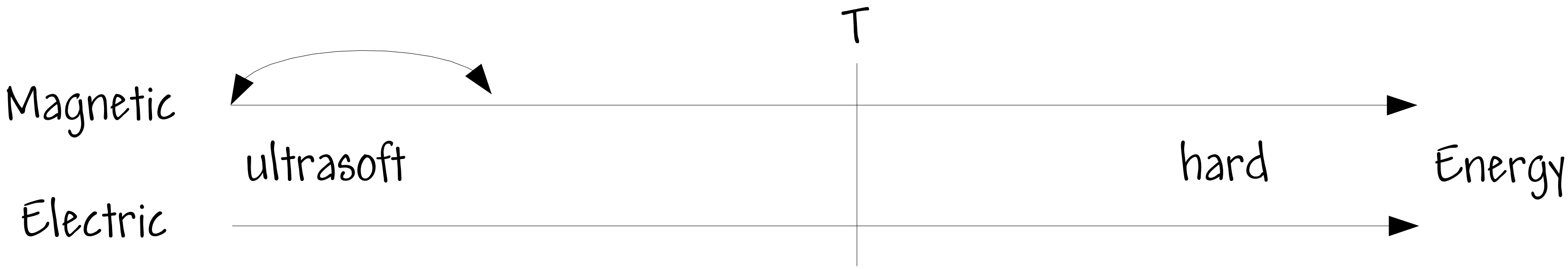

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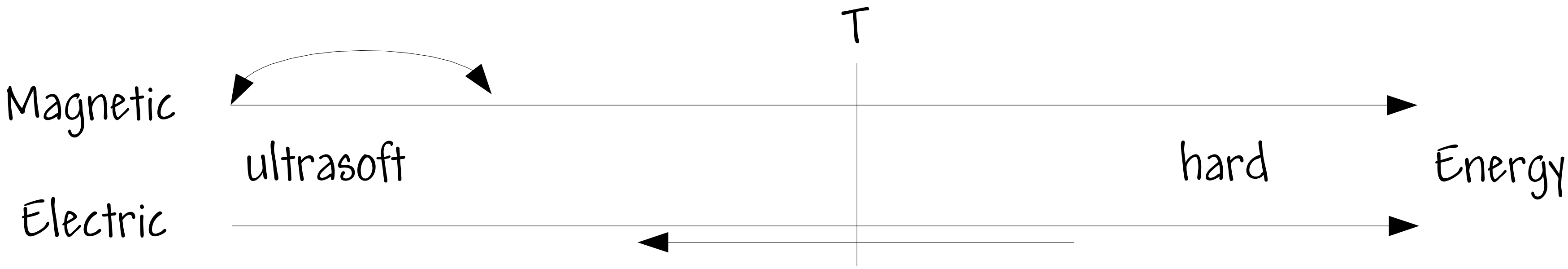

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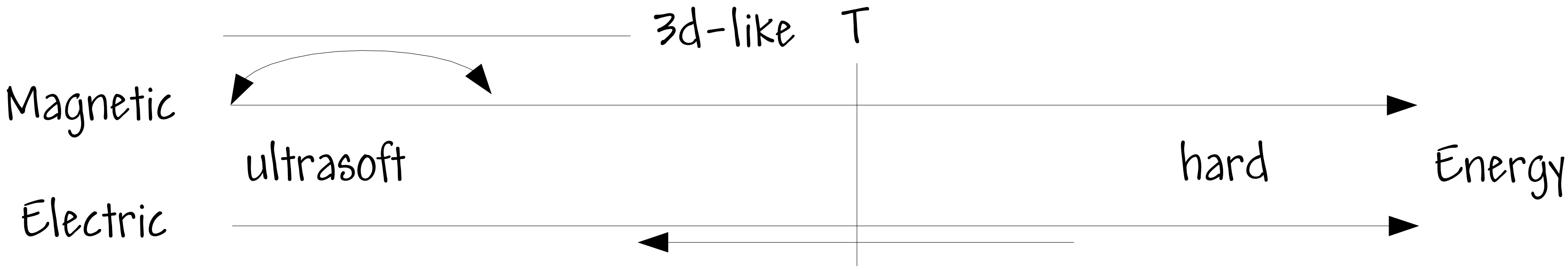

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- The ultrasoft magnetic sector behaves essentially as in a dimensionally reduced (3d) theory

Resolving the Linde problem

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- The deep infrared of the magnetic sector behaves as in a pure zero-temperature 3d-Yang-Mills theory

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- Electric sector is screened by hard interactions
- No infrared divergencies left: No Linde problem

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- Solution at all temperatures possible
- Deep infrared qualitatively independent of temperature!
- Magnetic gluon propagator is infrared vanishing
  - No positive-definite spectral function
  - Magnetic sector not part of the physical spectrum
- Electric gluon part of a BRST quartet already in perturbation theory
  - Not part of the physical spectrum either
- Gluons are not deconfined!
- Gauge-invariant statement

Imprint of the phase transition [Cucchieri, Maas, Mendes, 2007]

- Non-perturbative contribution to the free energy scale as T^3
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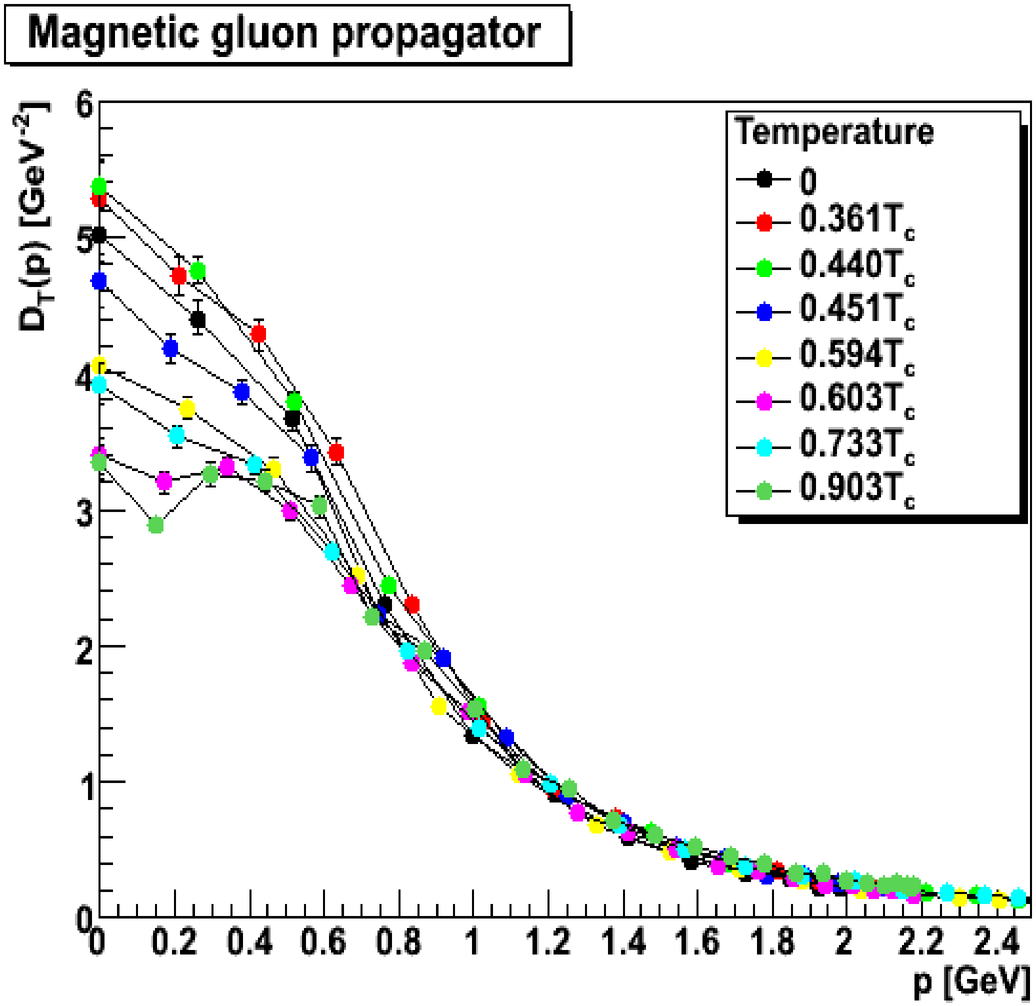
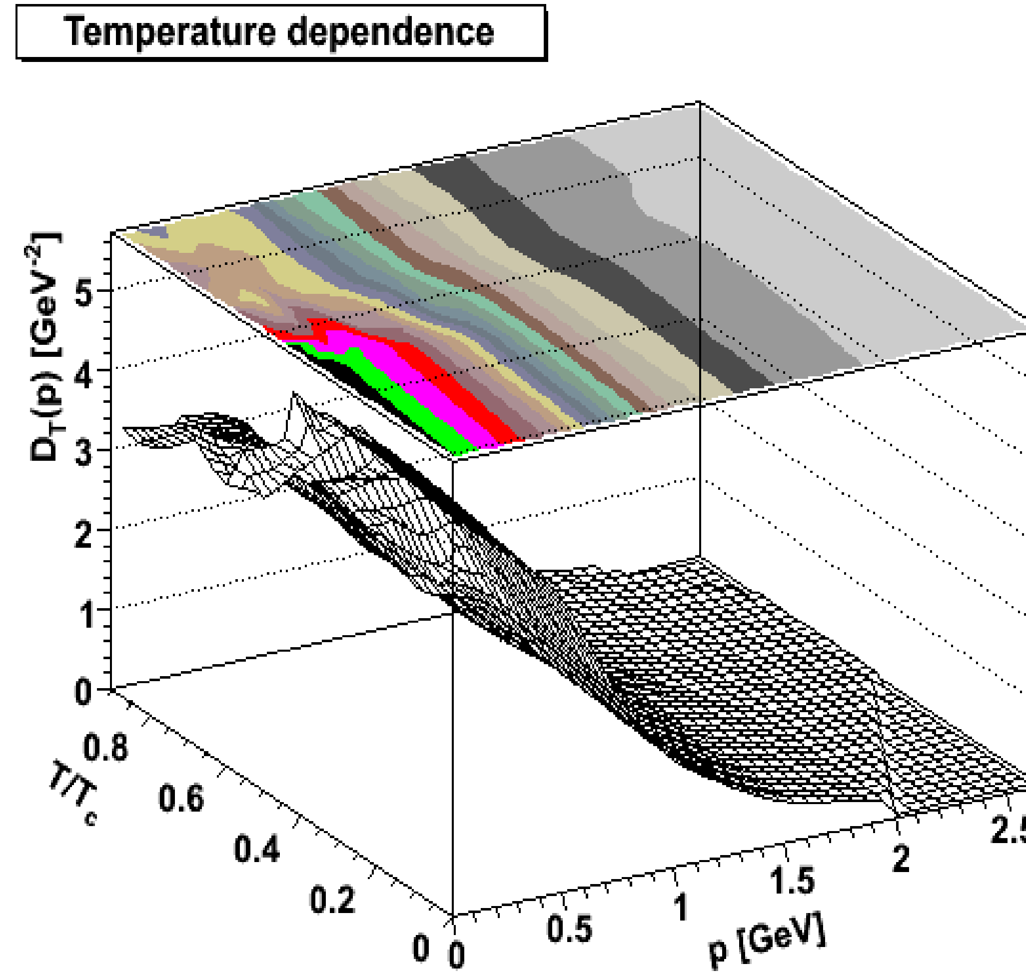
Magnetic gluon at low temperature

[SU(2), Maas, unpublished]



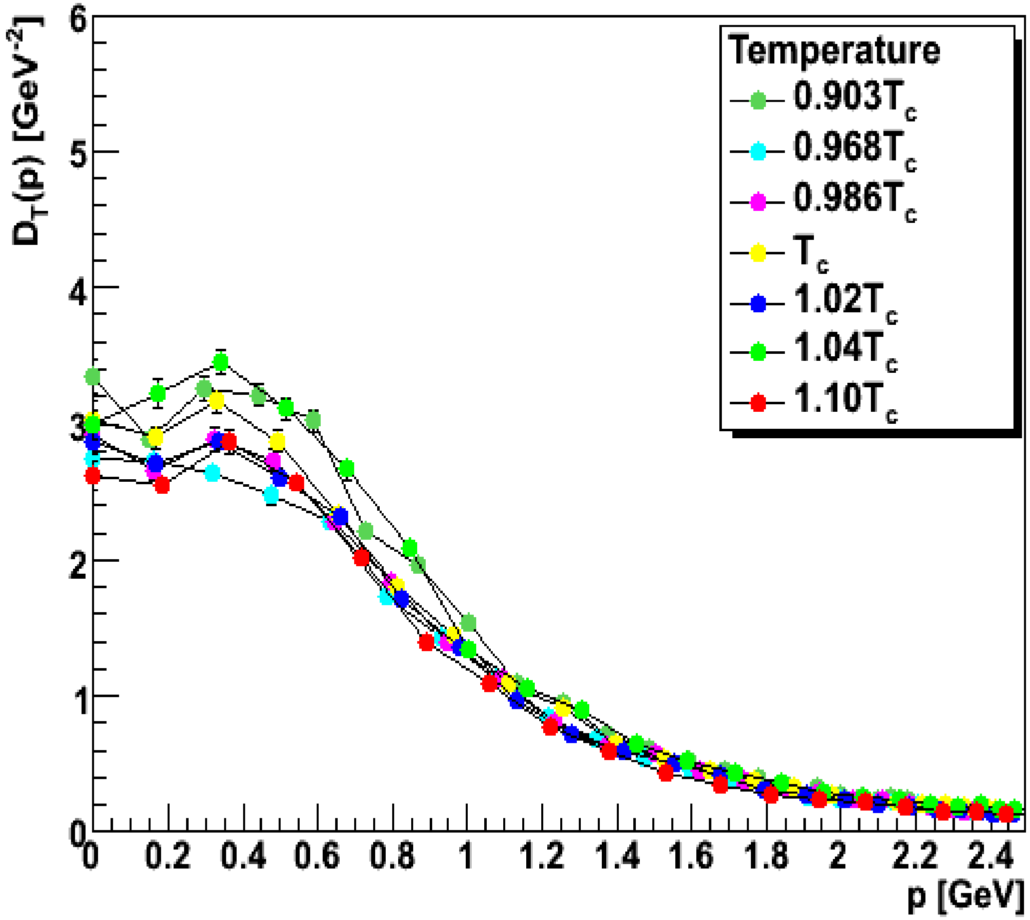


- Very small changes only
- Ultraviolet almost unchanged
- Somewhat stronger infrared suppressed with increasing temperature

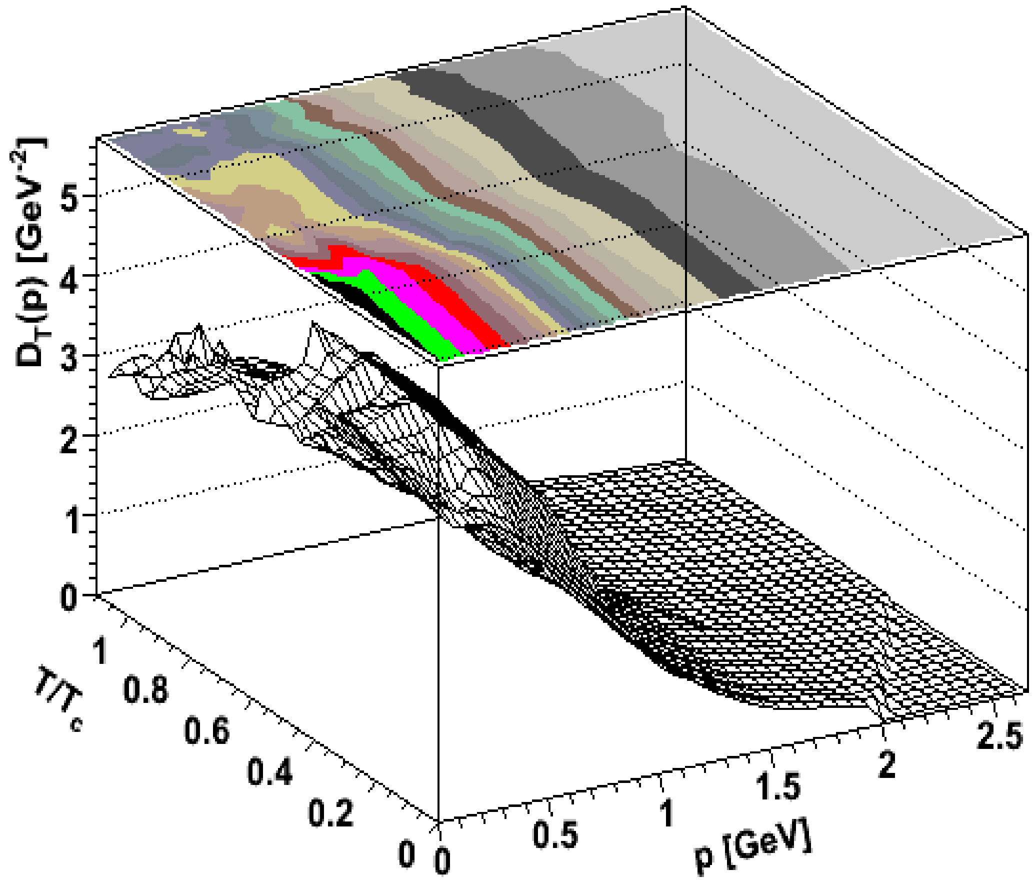
Magnetic gluon at the phase transition

[SU(2), Maas, unpublished]

Magnetic gluon propagator



Temperature dependence

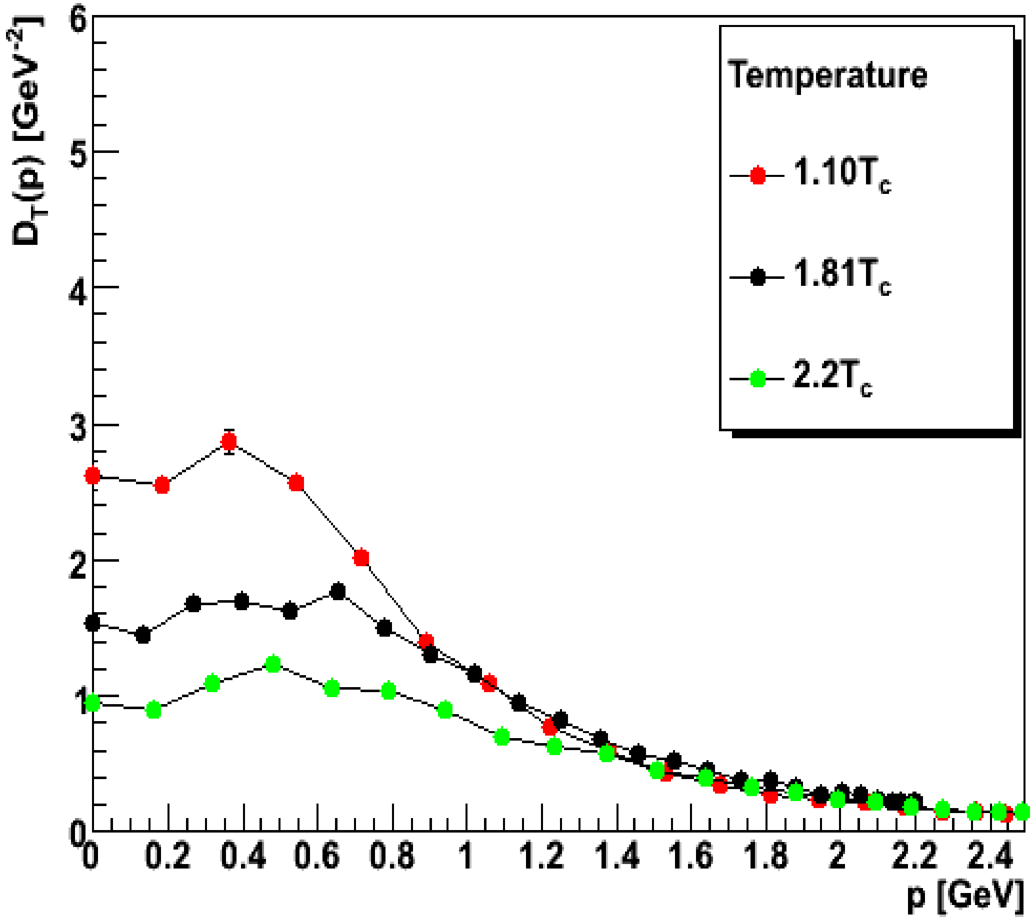


- No response to the phase transition visible

Magnetic gluon at high temperature

[SU(2), Maas, unpublished]

Magnetic gluon propagator



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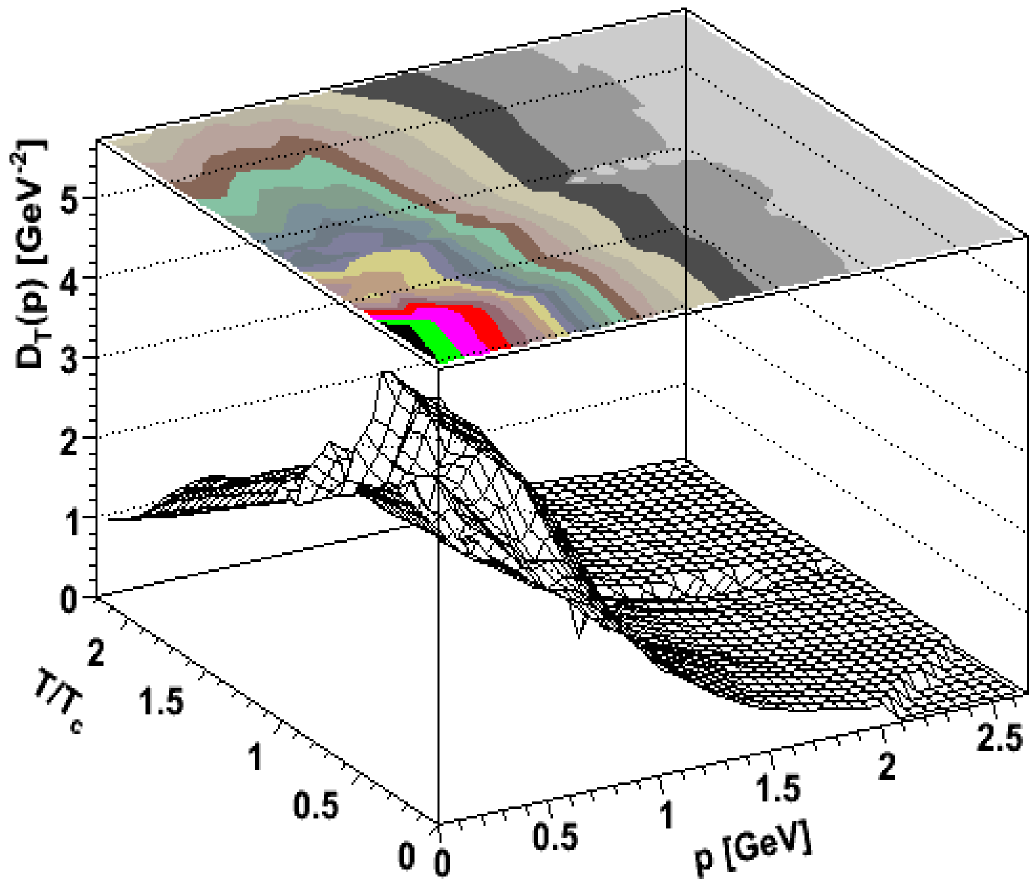

- Continued infrared suppression
- Possibly emergence of a maximum structure around 0.5 GeV

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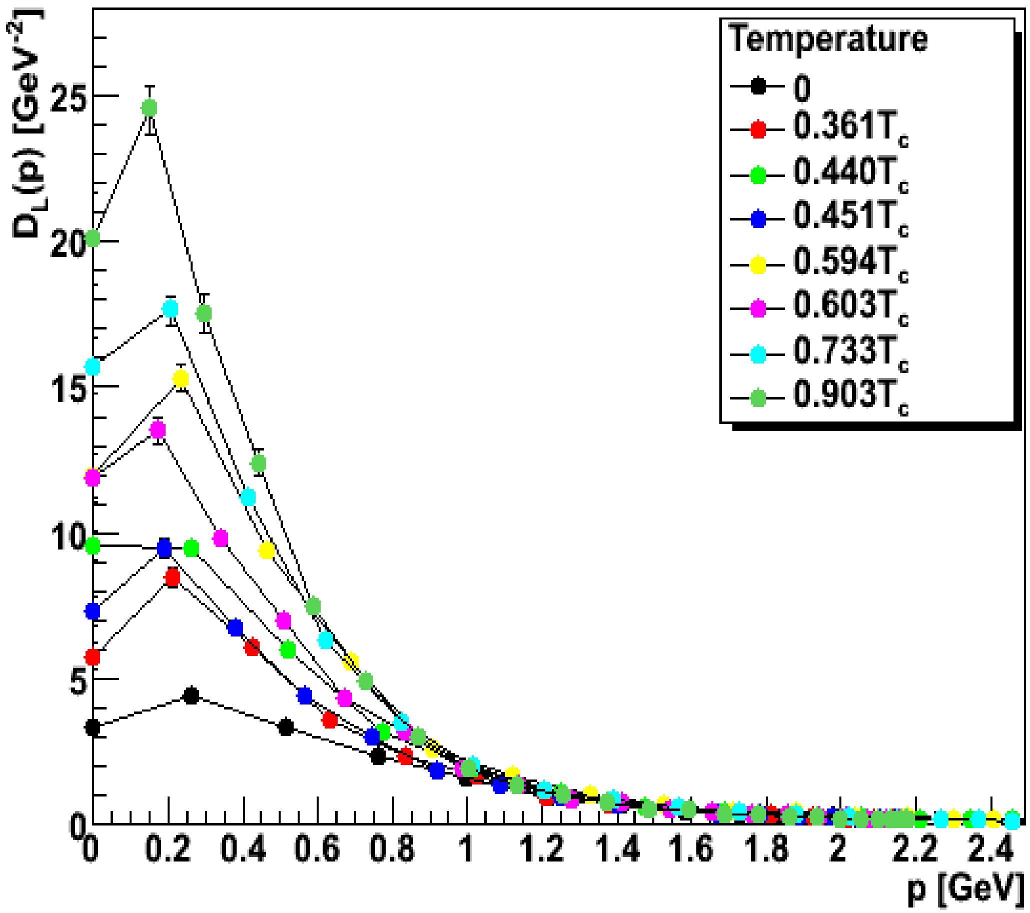
- Temperature essentially a perturbative scale for the ultrasoft magnetic sector: No qualitative impact of the phase transition in the magnetic sector at low momenta expected
- Electric sector sensitive to hard interactions: Impact expected

Electric gluon at low temperature

[SU(2), Maas, unpublished]

Electric gluon propagator



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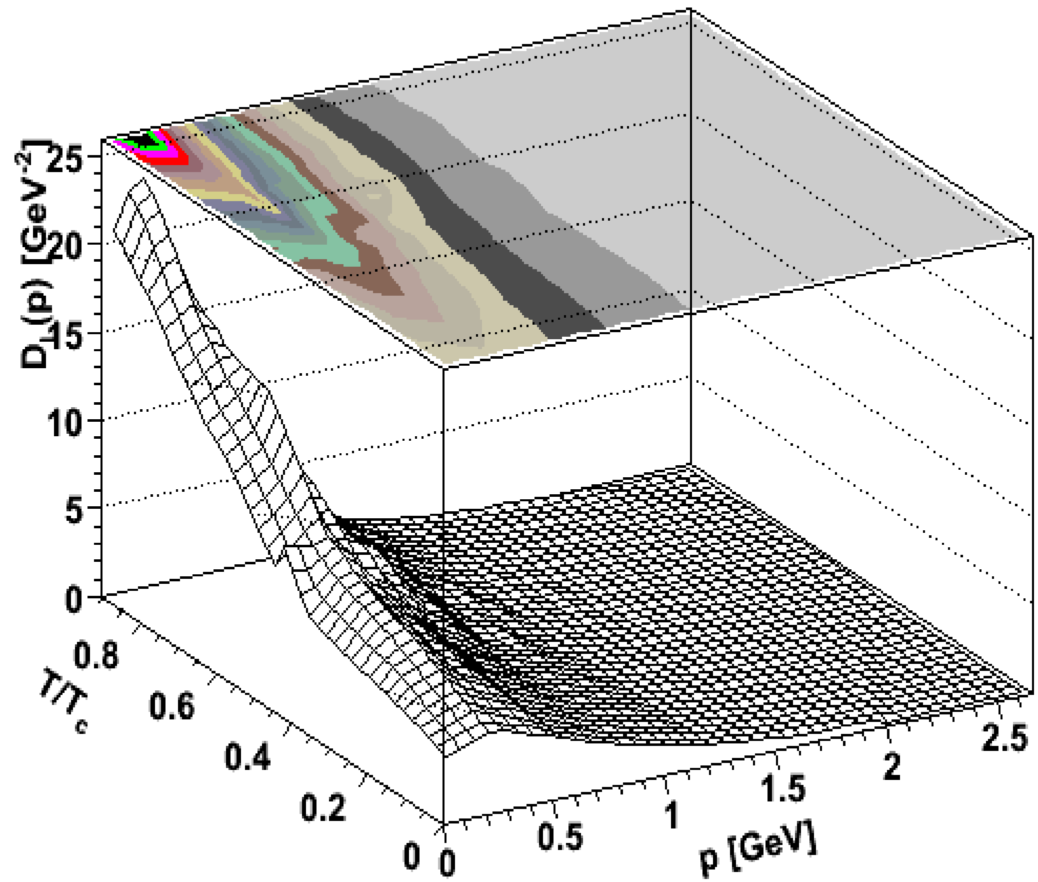
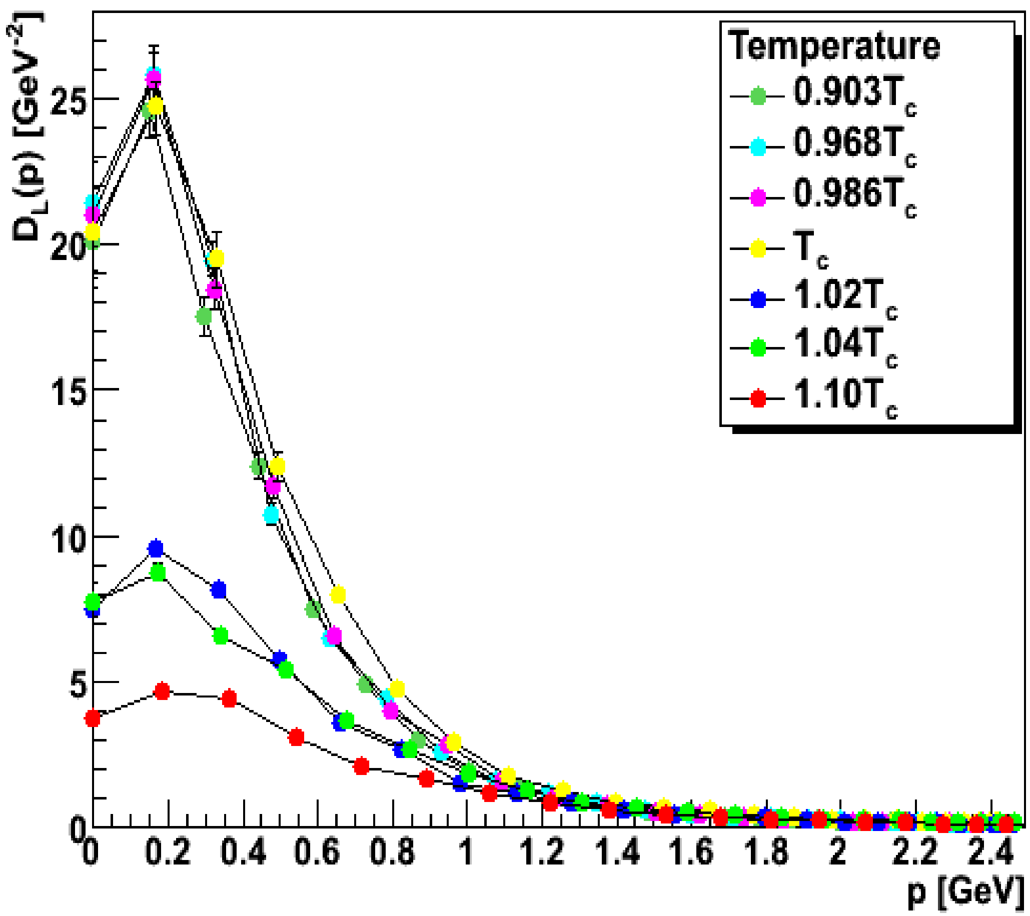


- Becomes infrared enhanced with temperature
- Already significant effects at low temperature

Electric gluon at the phase transition

[SU(2), Maas, unpublished]

Electric gluon propagator



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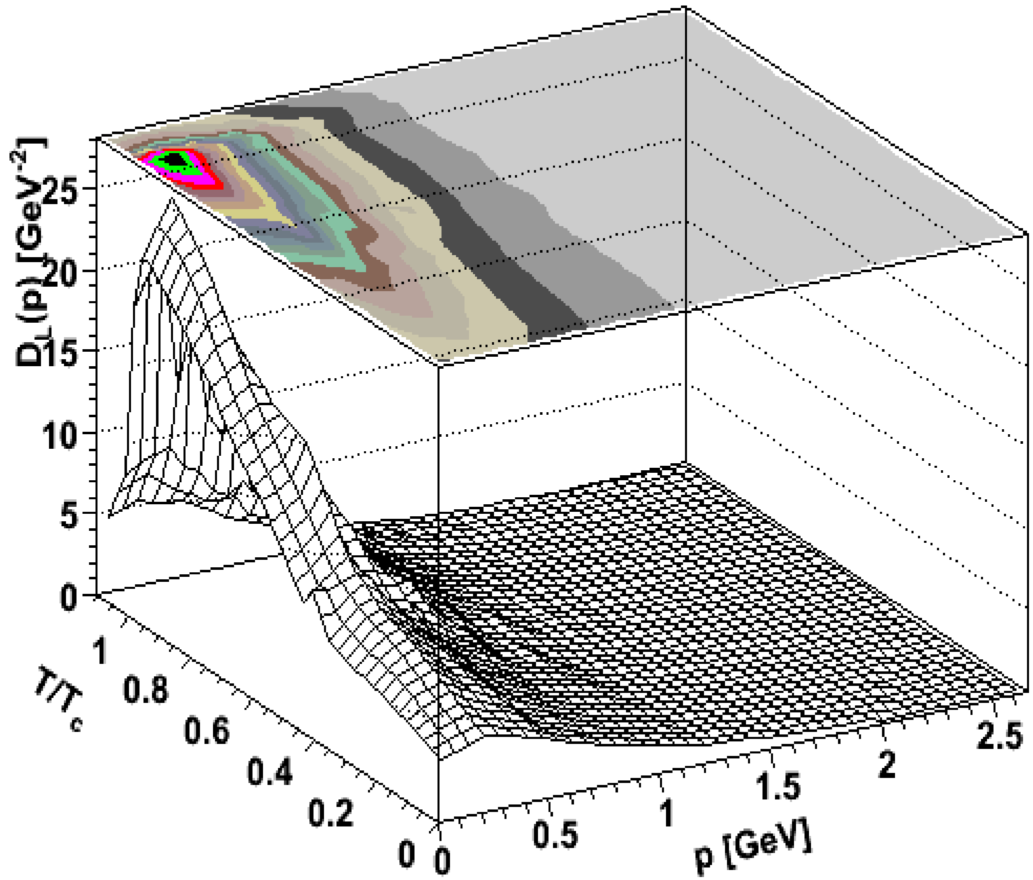
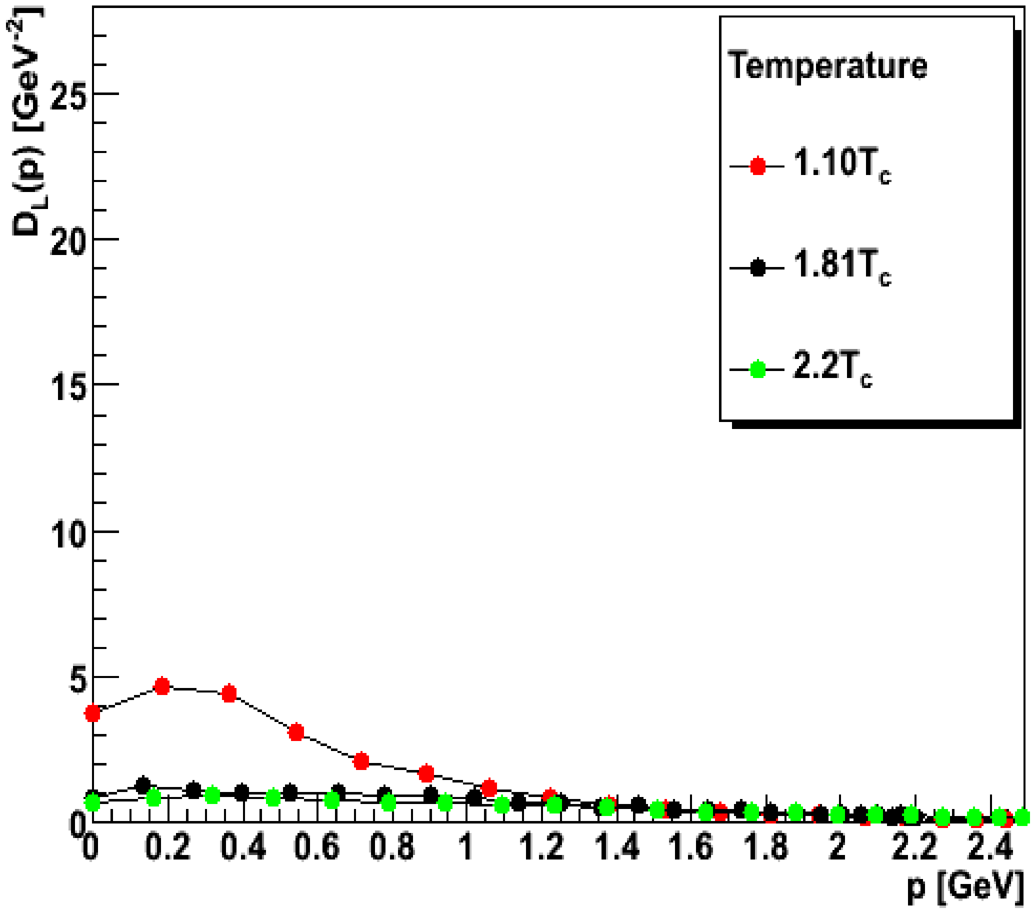


- Maximum at the phase transition temperature
- Sharp drop afterwards
- Very sensitive to the phase transition

Electric gluon at high temperature

[SU(2), Maas, unpublished]

Electric gluon propagator



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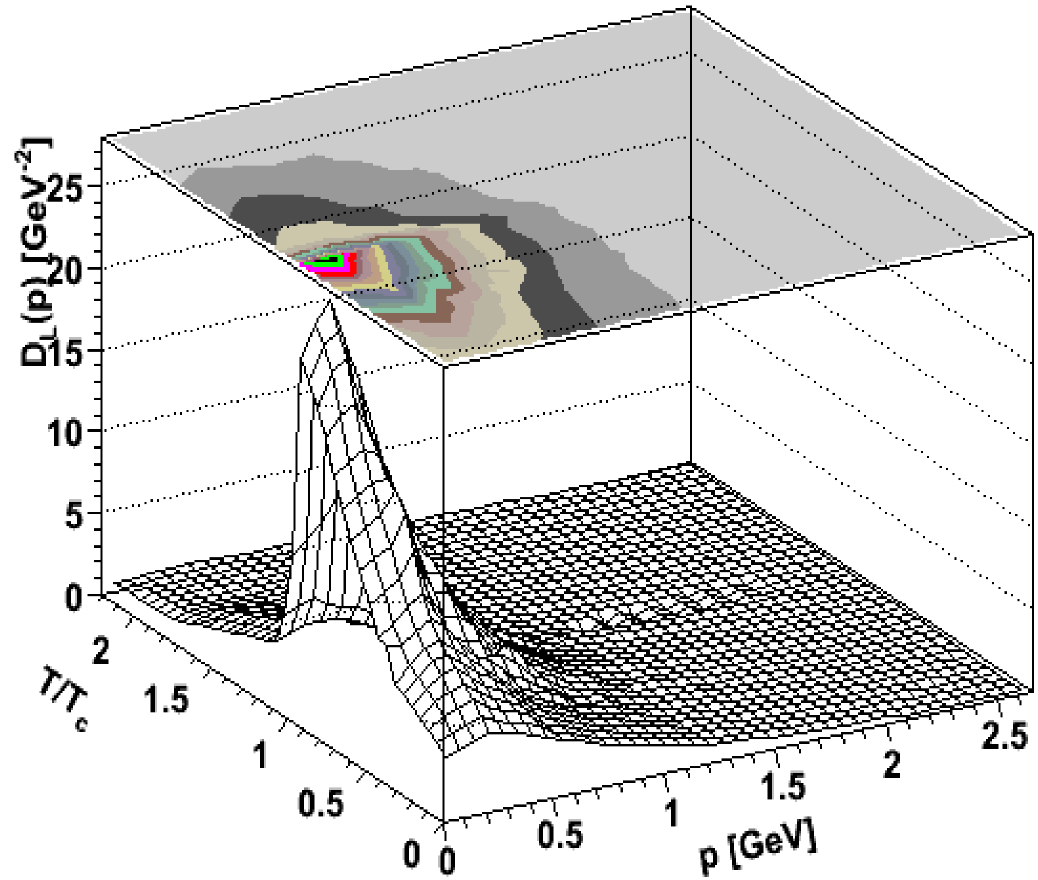

- Further drop
- Less dramatic
- Becomes compatible with a massive particle

Electric screening mass

[Cucchieri, Maas, Mendes, 2007; Maas, unpublished]

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UNI GRAZ

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UNI GRAZ

SU(2) vs. SU(3) electric screening mass [Maas, unpublished]

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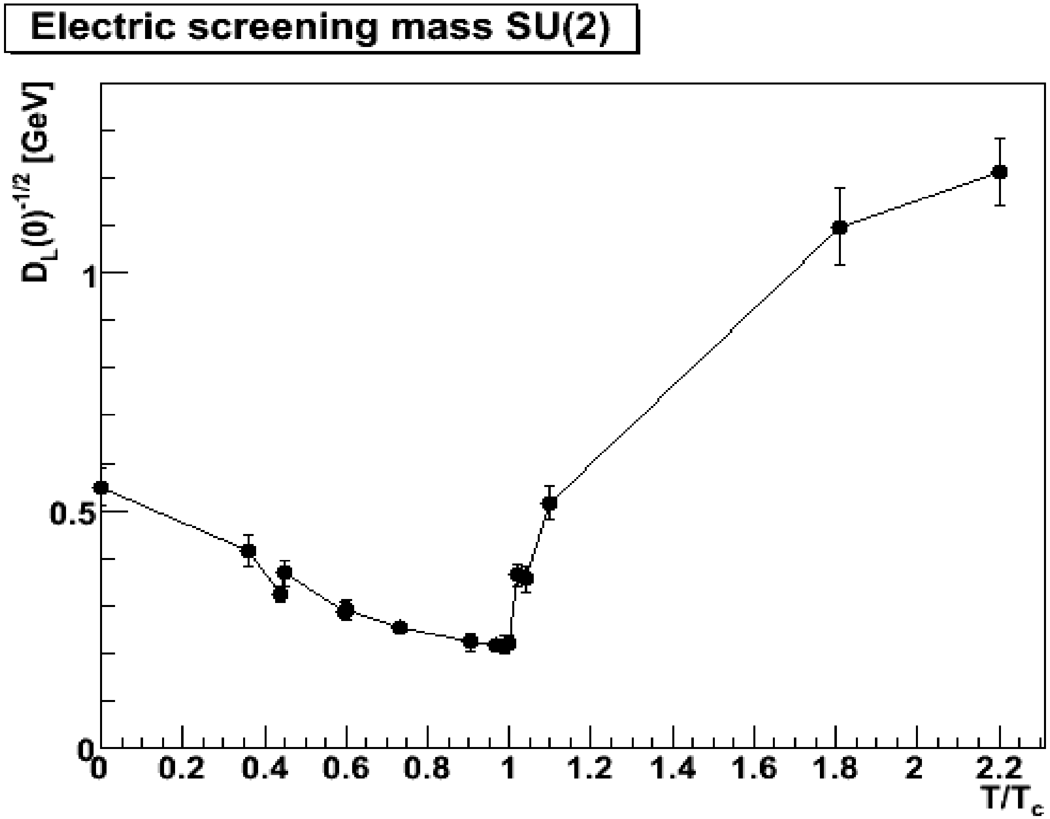
[Maas, unpublished]



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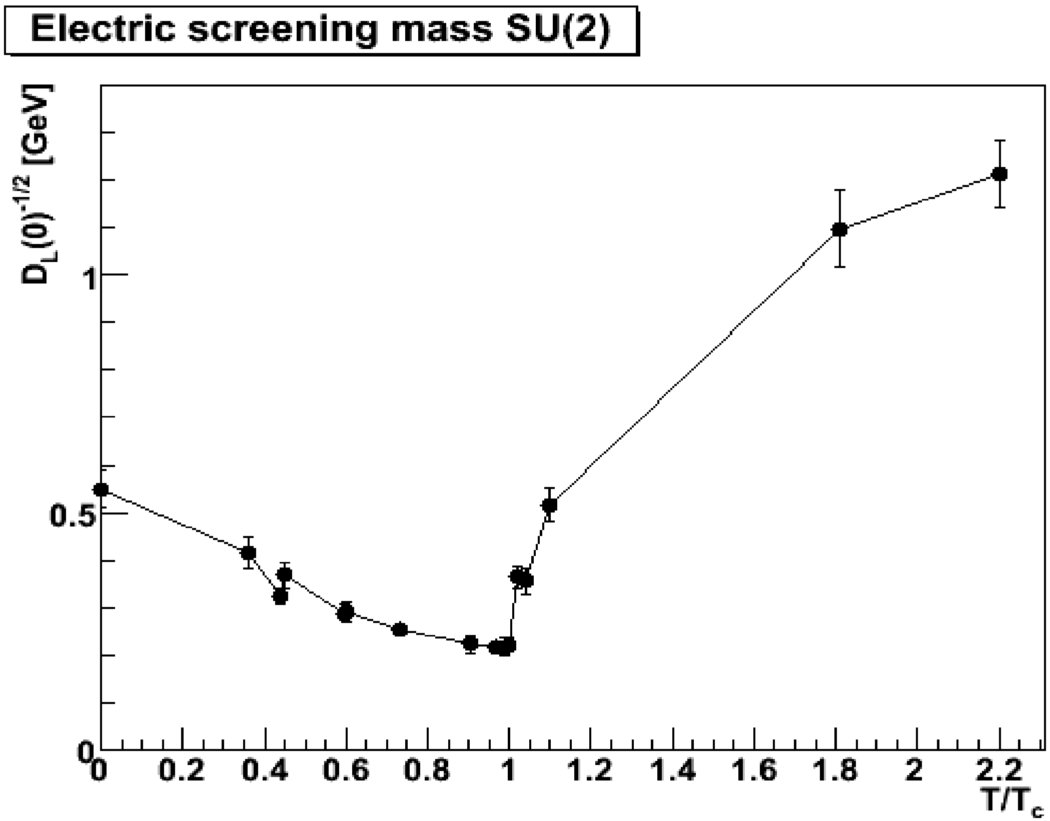

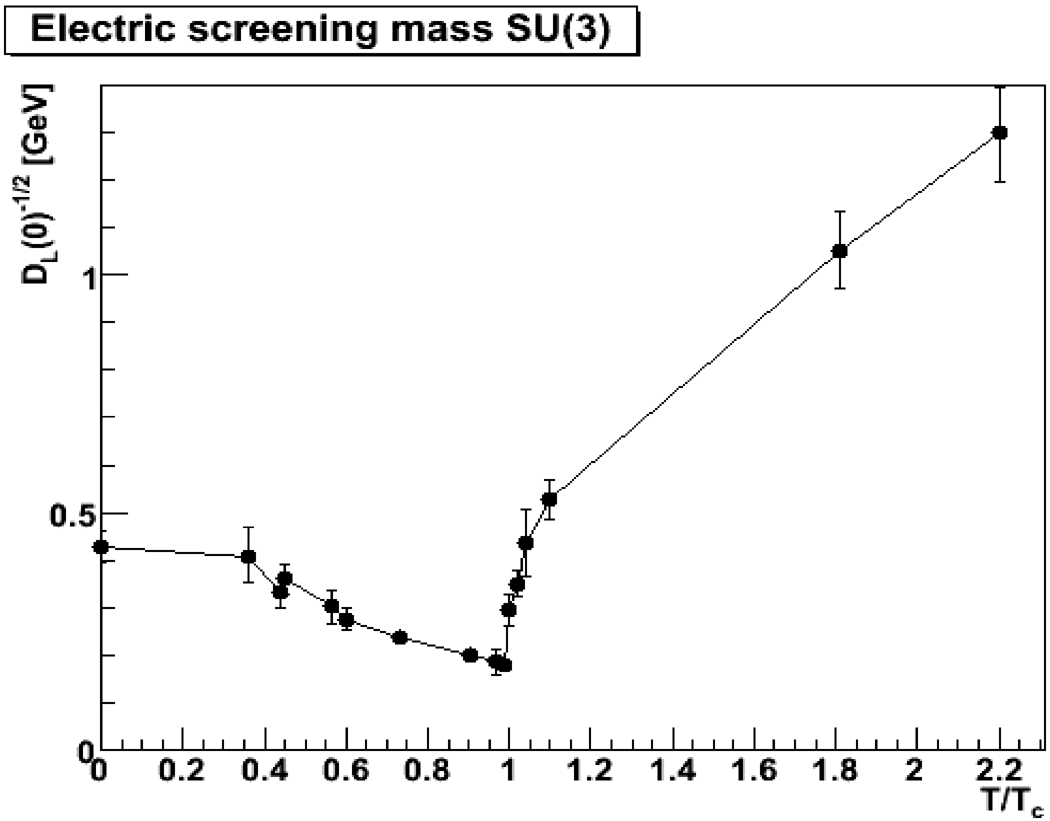

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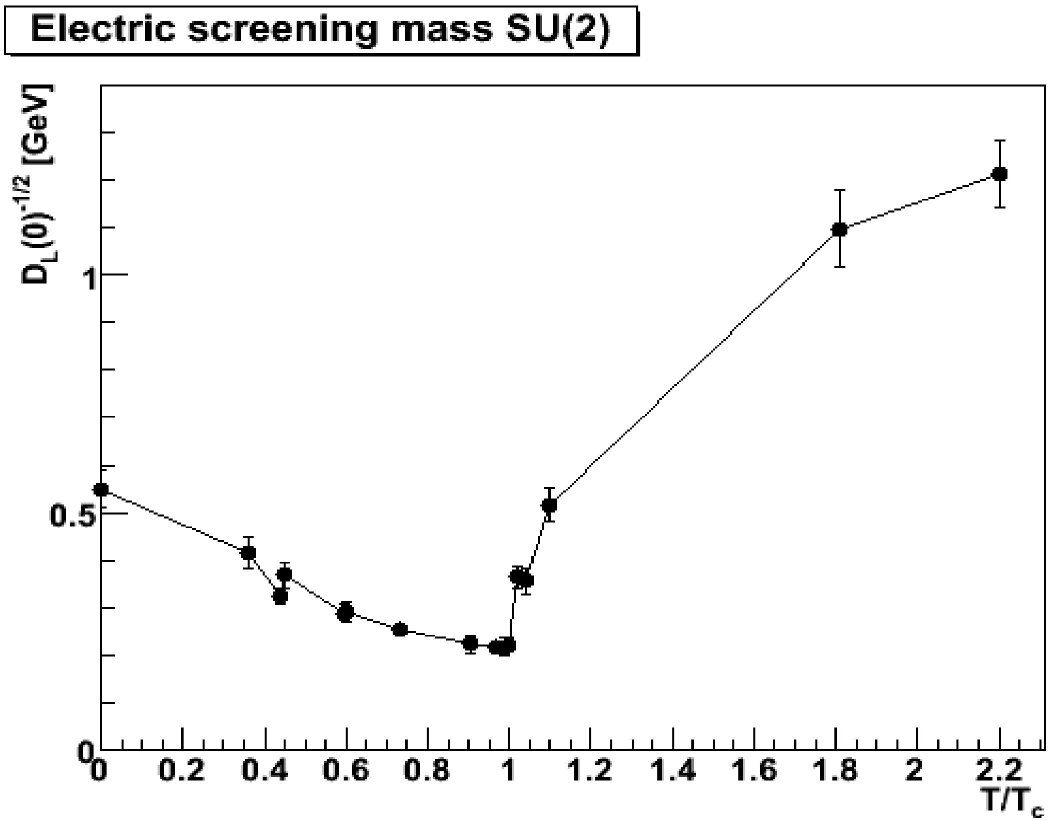

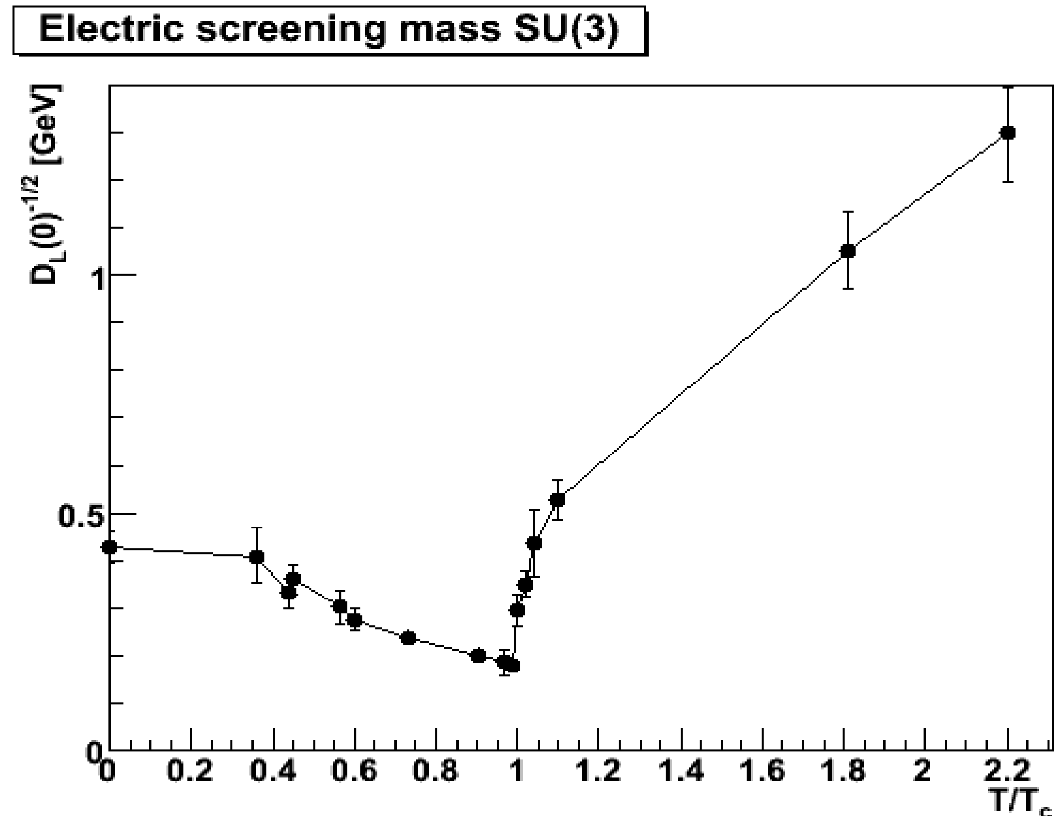

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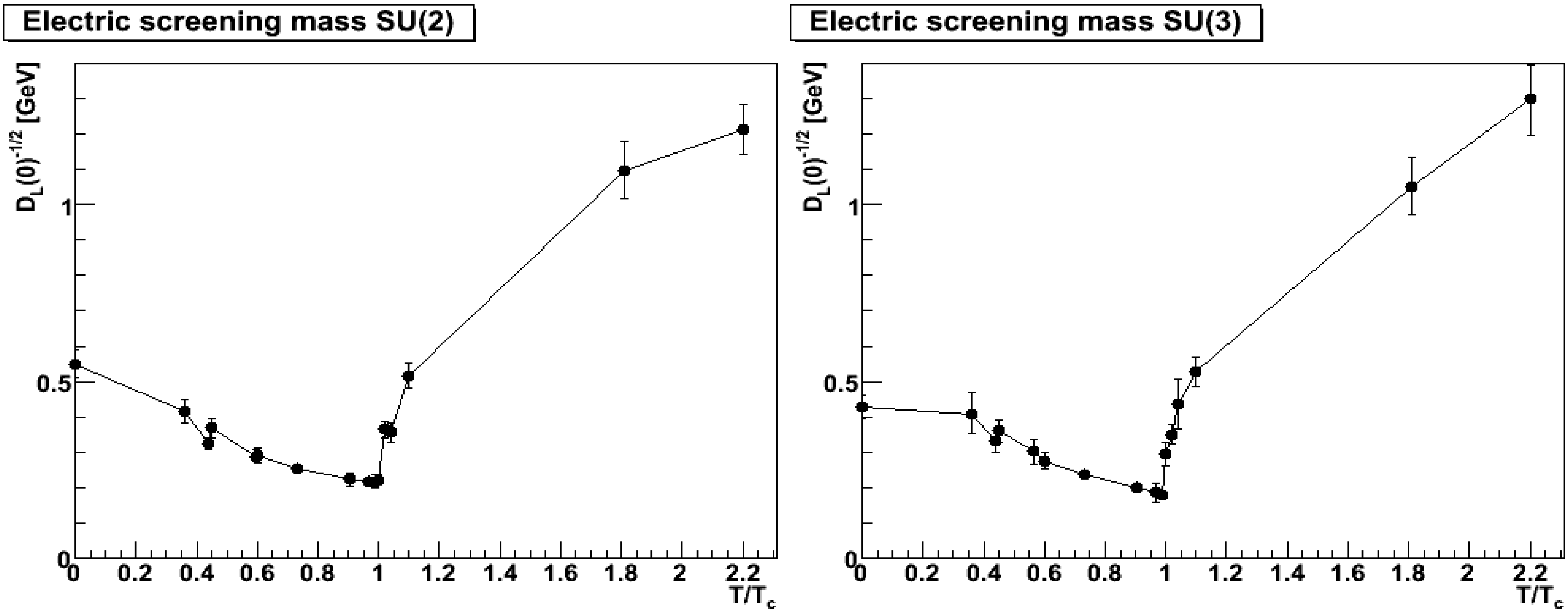

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  - Jump instead of rapid change? - Could distinguish the order

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- Application to quarks and mesons: See talks by J. Braun, C. S. Fischer, L. Haas, J. Müller, J. M. Pawlowski