

Gluons at finite temperature

-

Confinement, screening and all that

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In collaboration with

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Overview

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 - Confinement of gluons at **zero temperature**

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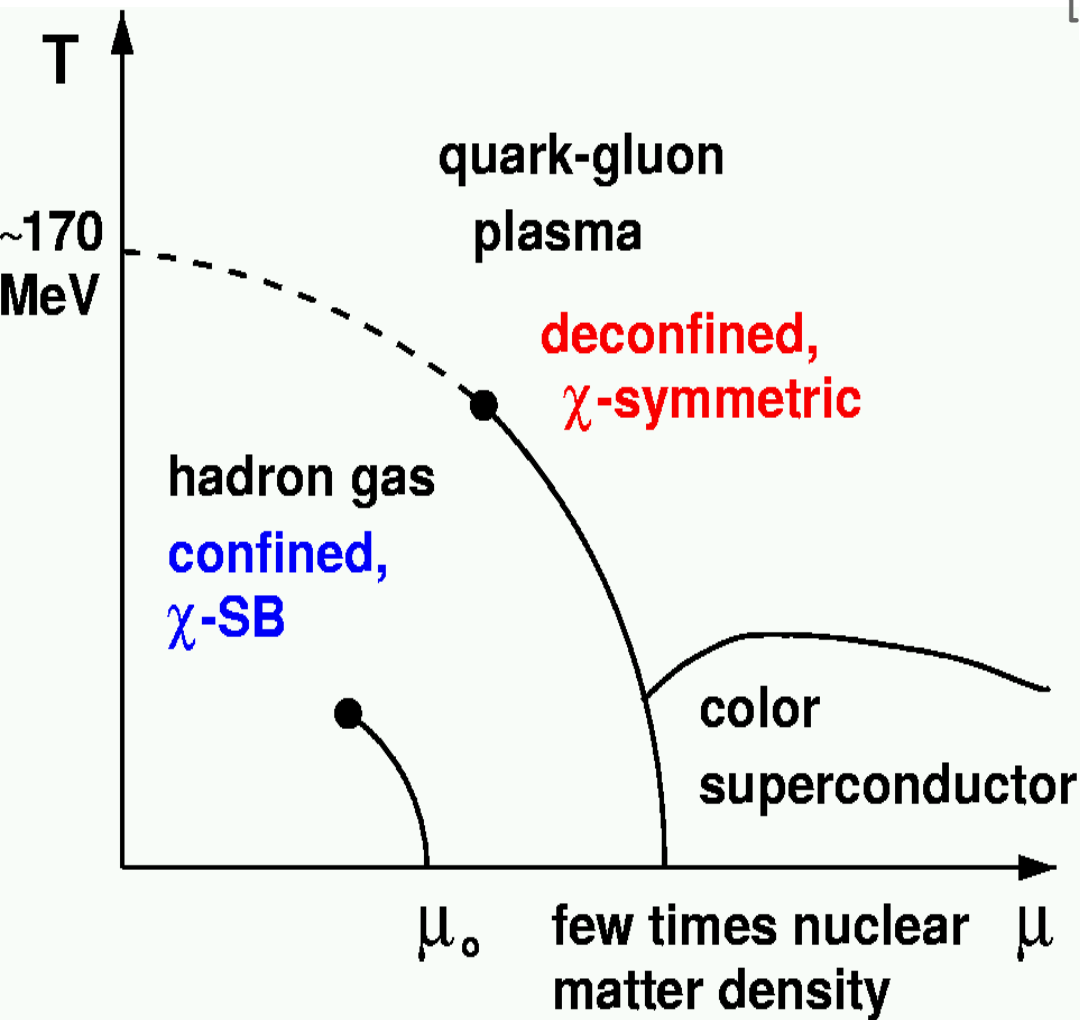
Overview

- **Confinement**, screening, and all that
 - Confinement of gluons at **zero temperature**
- Observations at **non-zero temperature**
 - Lattice
 - DSEs
- A **possible** interpretation
- Summary

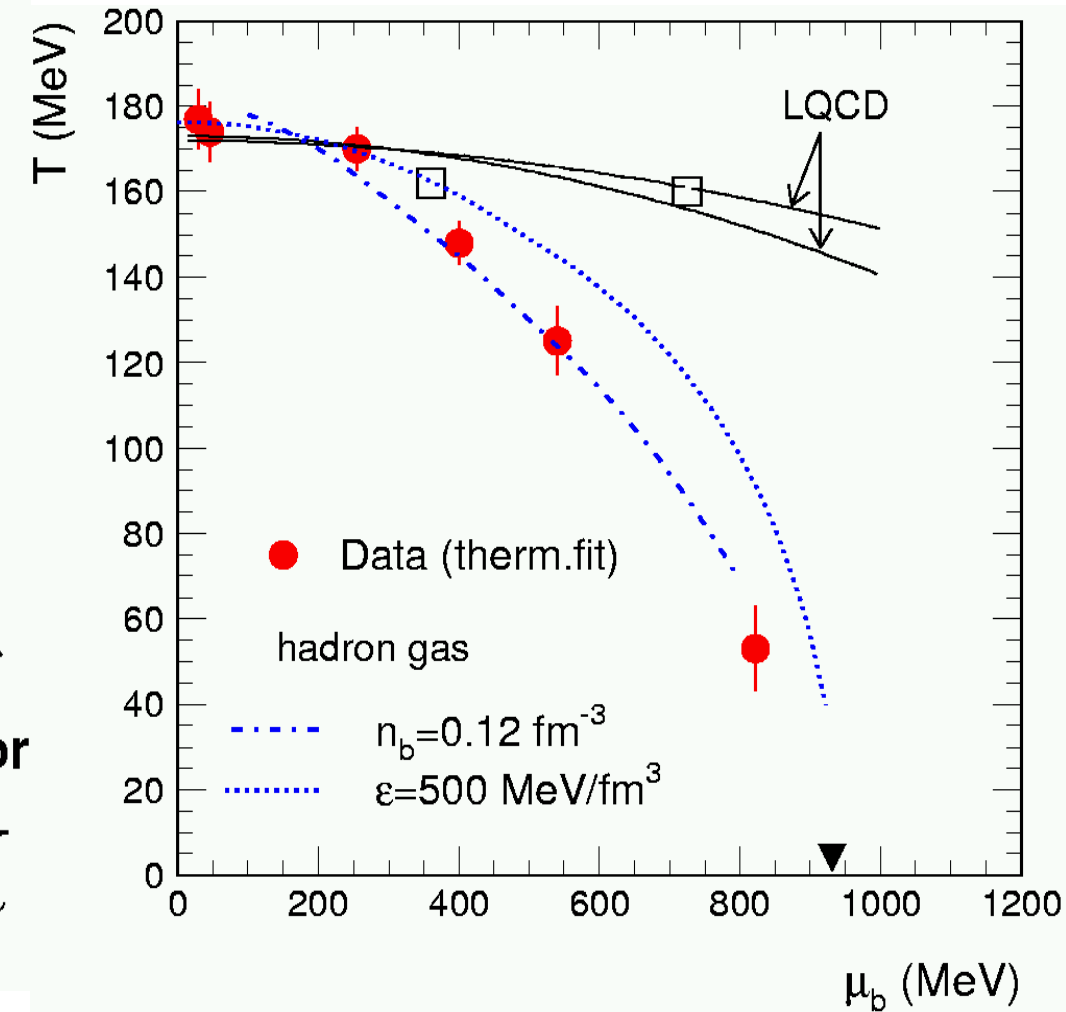
All lattice results for $SU(2)$

[First look: Maas et al., hep-lat/0610006]

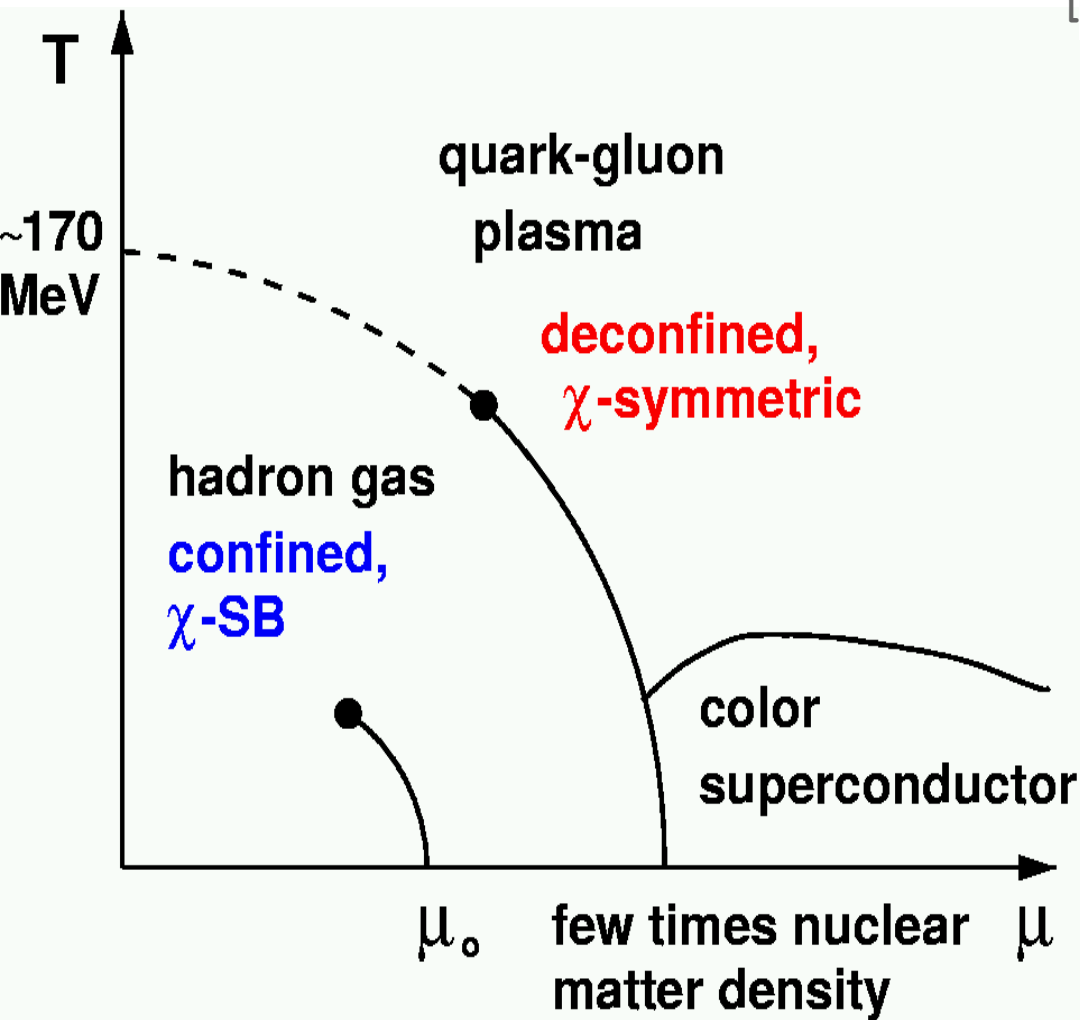
Finite Temperature QCD



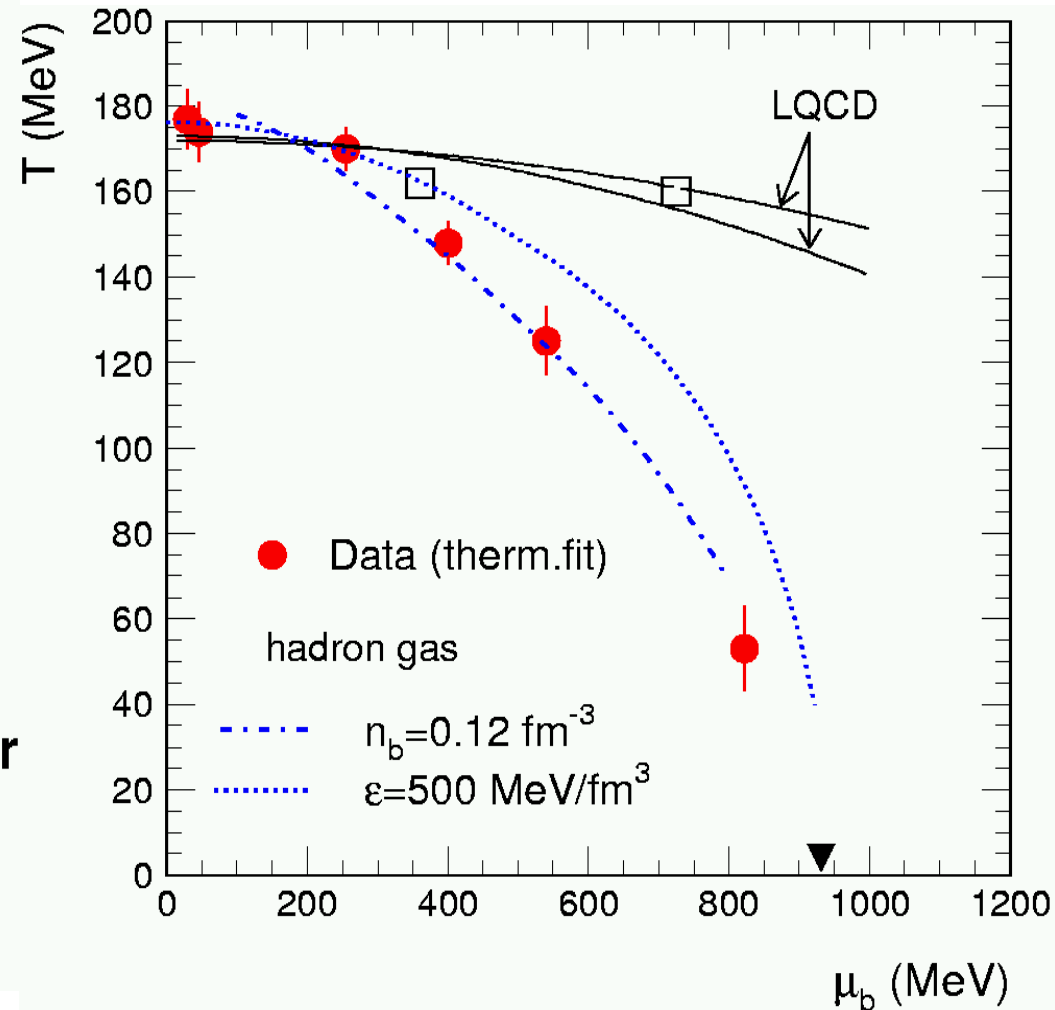
[Figures from Karsch et al. 2003 (l), Andronic et al., 2004 (r)]



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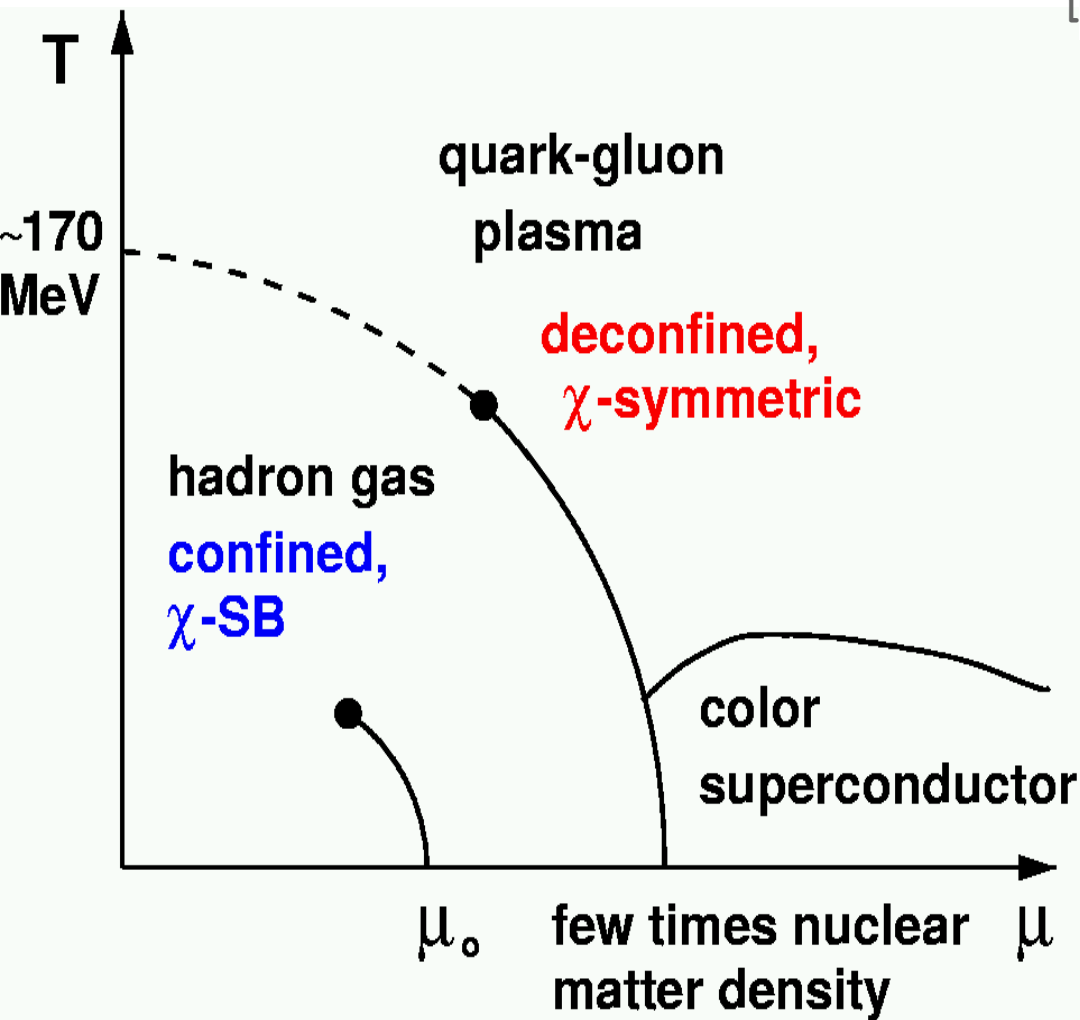


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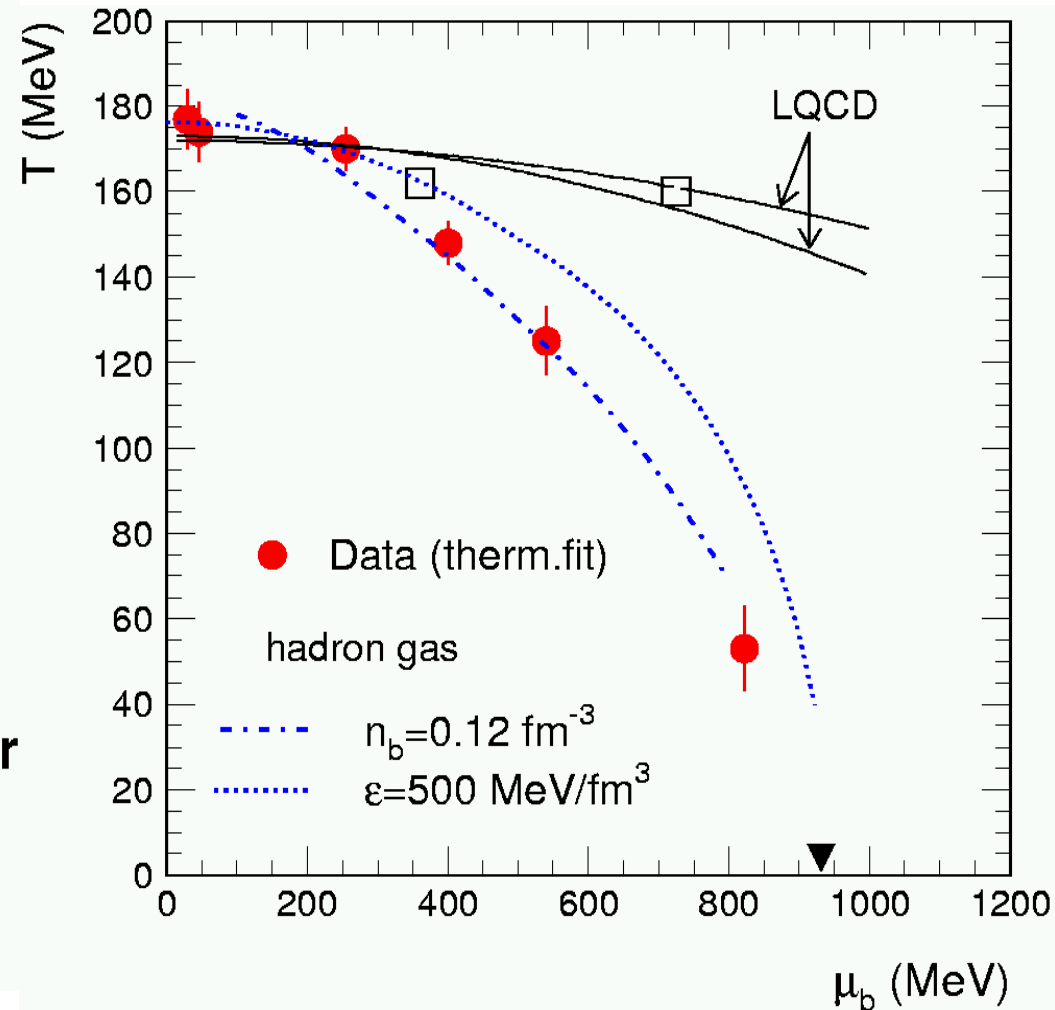


- Aim: From microscopic dynamics to experimental observables

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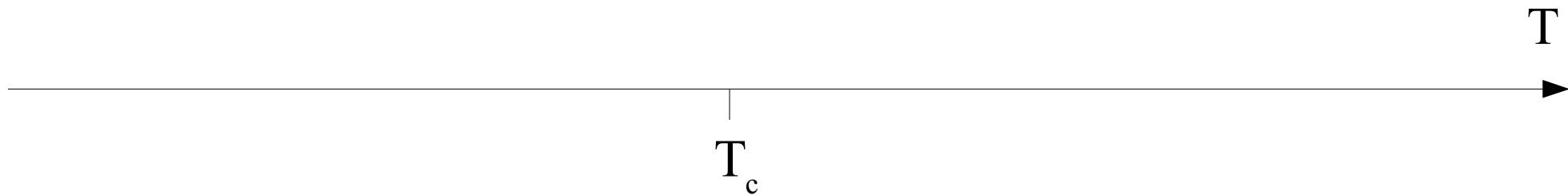
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- More modest: Yang-Mills (QCD without quarks) phase diagram

Phase diagram of Yang-Mills theory

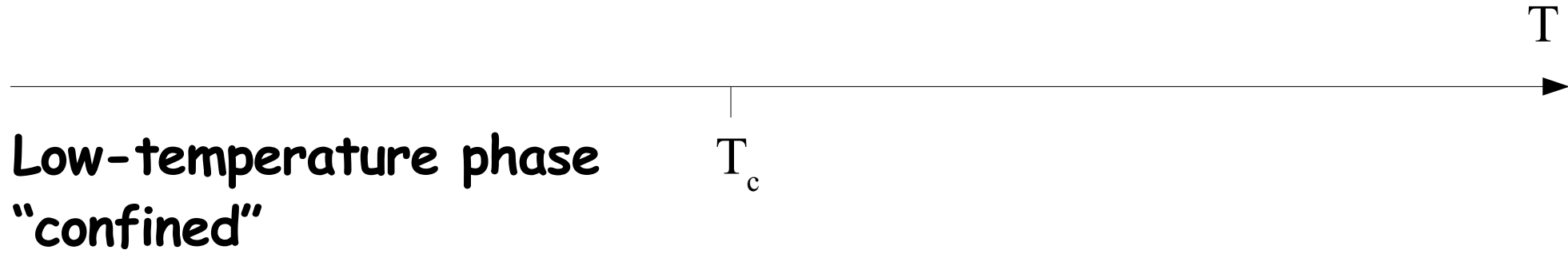
T



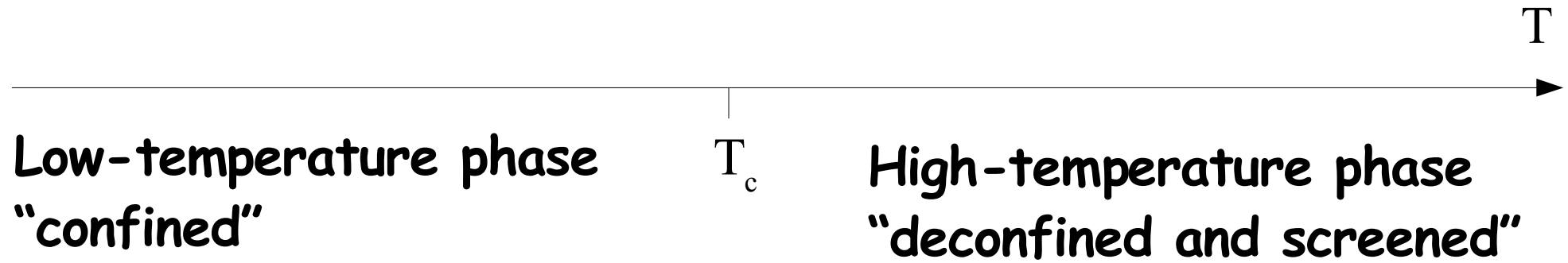
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Order of transition depends on the gauge group

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"confined"

T_c

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"deconfined and screened"

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- **Why??**

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- **Non-perturbative dynamics for arbitrary small coupling constant in QFT**
 - Haag's theorem [Haag's book, 1992]
- (Perturbative) **Tree-level** (stable) particles are **not suitable asymptotic states** at finite temperature
 - Narnhofer-Thirring theorem [Narnhofer et al., CMP 1983]

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 - Yang-Mills theory: What happens to confinement?
 - What is meant by 'confined' and 'deconfined', anyway?

Confined, screened, deconfined

- **Confinement**

What is confinement

What is confinement - Experiment

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Confinement

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 - No confinement in perturbation theory
 - **Non-perturbative effect**

Confined, screened, deconfined

- **Confinement**

- Colored particles are not physical states
- Colored states exist only in an unphysical part of the describing Hilbert space
- Only bound states are physical
- There has to be at least one stable bound state
- Interactions are non-perturbative, but may be weak

Confined, screened, deconfined

- **Confinement**
 - **Strong confinement**
 - Requires additionally linear rising potentials for the object in question (e.g. quarks in Yang-Mills theory)

Confined, screened, deconfined

- **Confinement**
- **Deconfined**
 - Colored particles are quasi-free and measurable in detectors
 - Requires phase transition to confinement
 - Bound states can decay into their constituents, when energetically possible
 - Interactions can be strong or weak
 - Colored states have to have a gauge-invariant representation – free constituent gluons

Confined, screened, deconfined

- **Confinement**
- **Deconfined**
- **Screened**
 - Colored particles are screened and can travel only a finite distance – not directly observable
 - No phase transition to confinement necessary (e.g. Adjoint Higgs-Yang-Mills)
 - Requires a gauge-invariant description only of asymptotically detectable states
 - Interactions non-perturbative, but may be weak

Confined, screened, deconfined

- **Confinement**
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- **How to observe confinement?**

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$$\text{Propagator} = \text{One particle part} + \int dq^2 \frac{\text{spectral function}(q^2)}{p^2 + q^2}$$

- Sum rule for gluons

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

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

How to observe confinement

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 - Necessary and sufficient
- One option for individual particles
 - **No positive definite-spectral function/no Källén-Lehmann representation**
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- **Confining potentials**, e.g. linear rising
 - Works only for non-dynamic objects – useless for gluons

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 - Geometry of field configuration space: Gribov-Zwanziger
 - Yield non-positive definite spectral functions

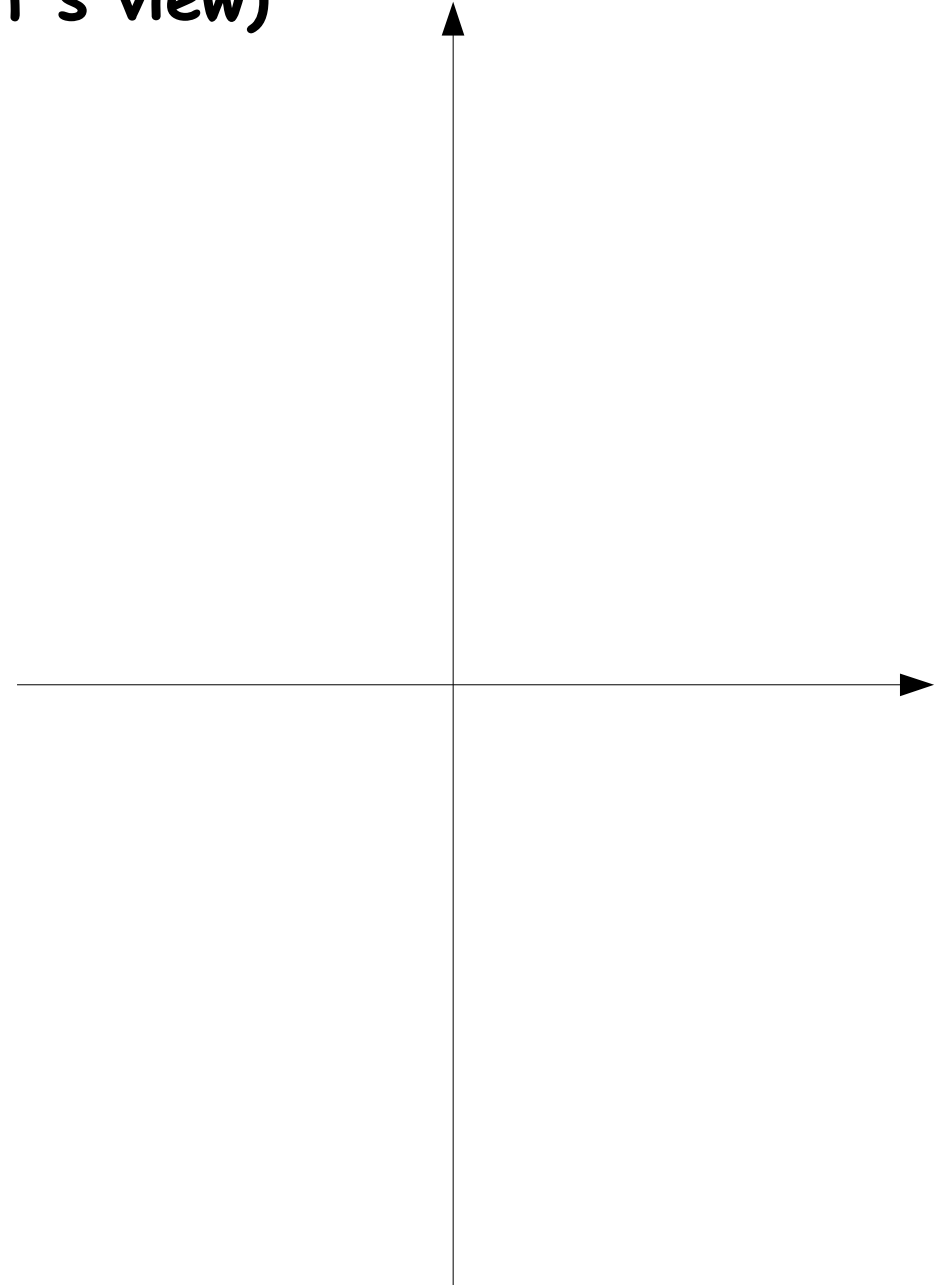
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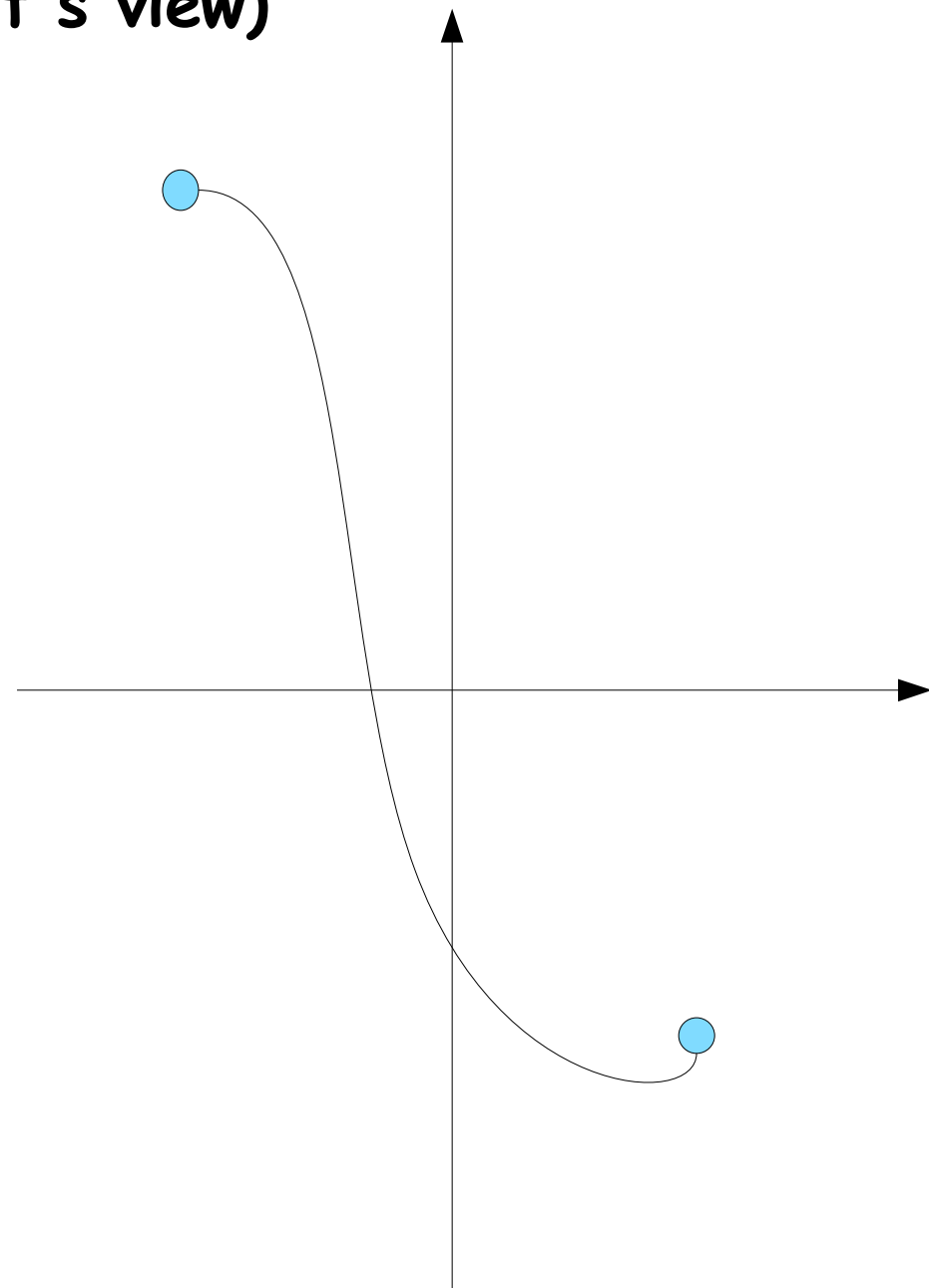
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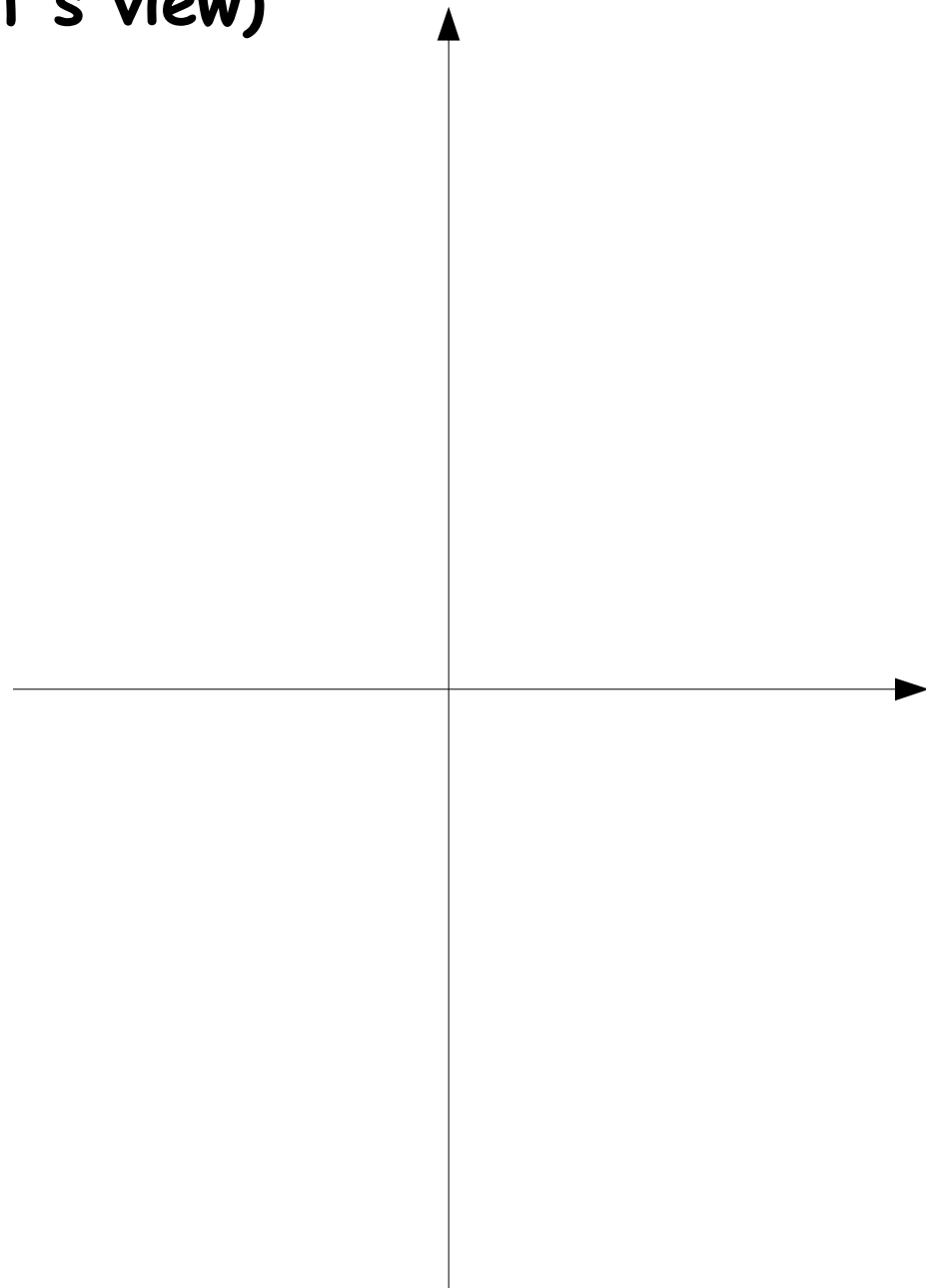
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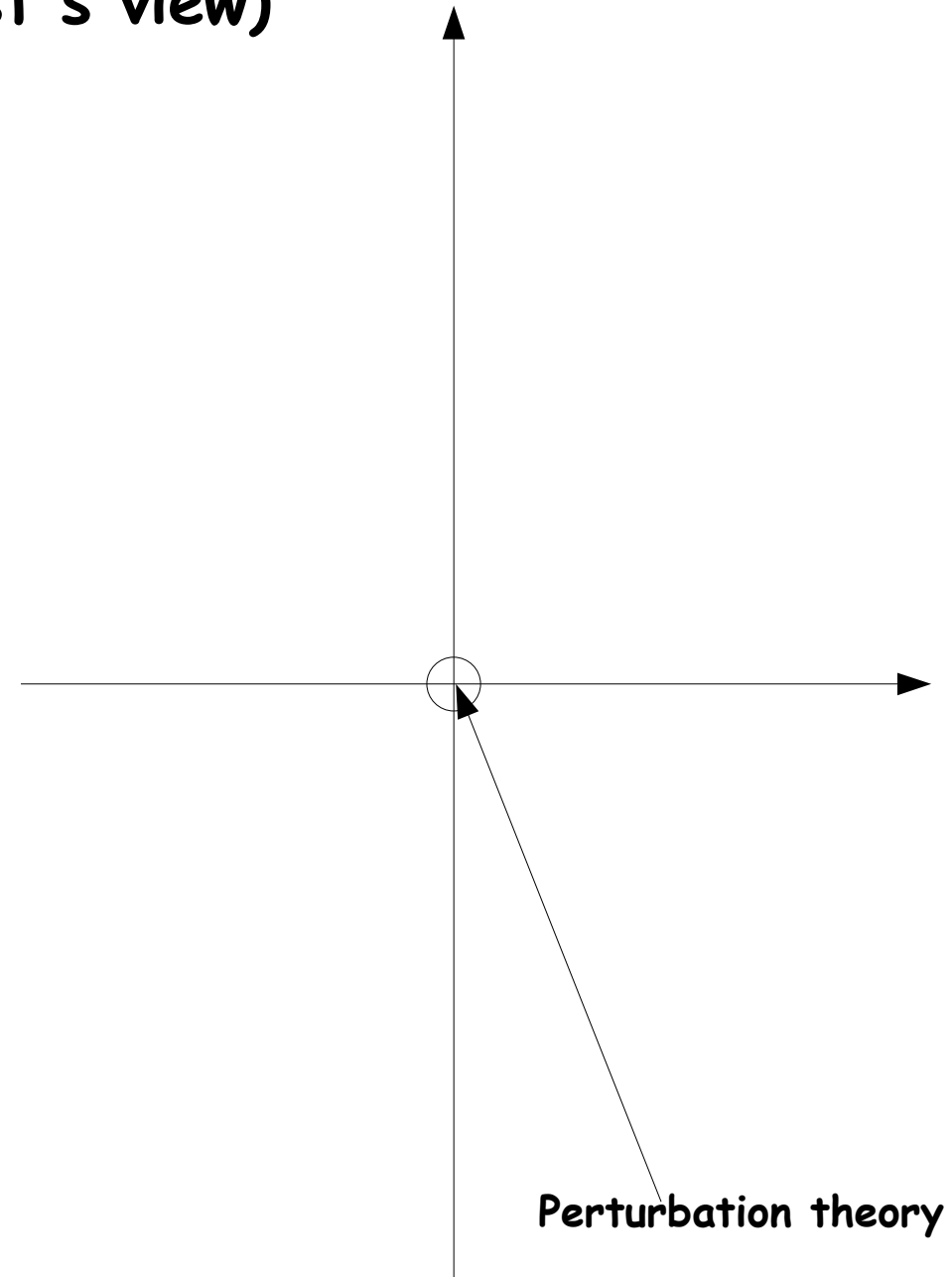
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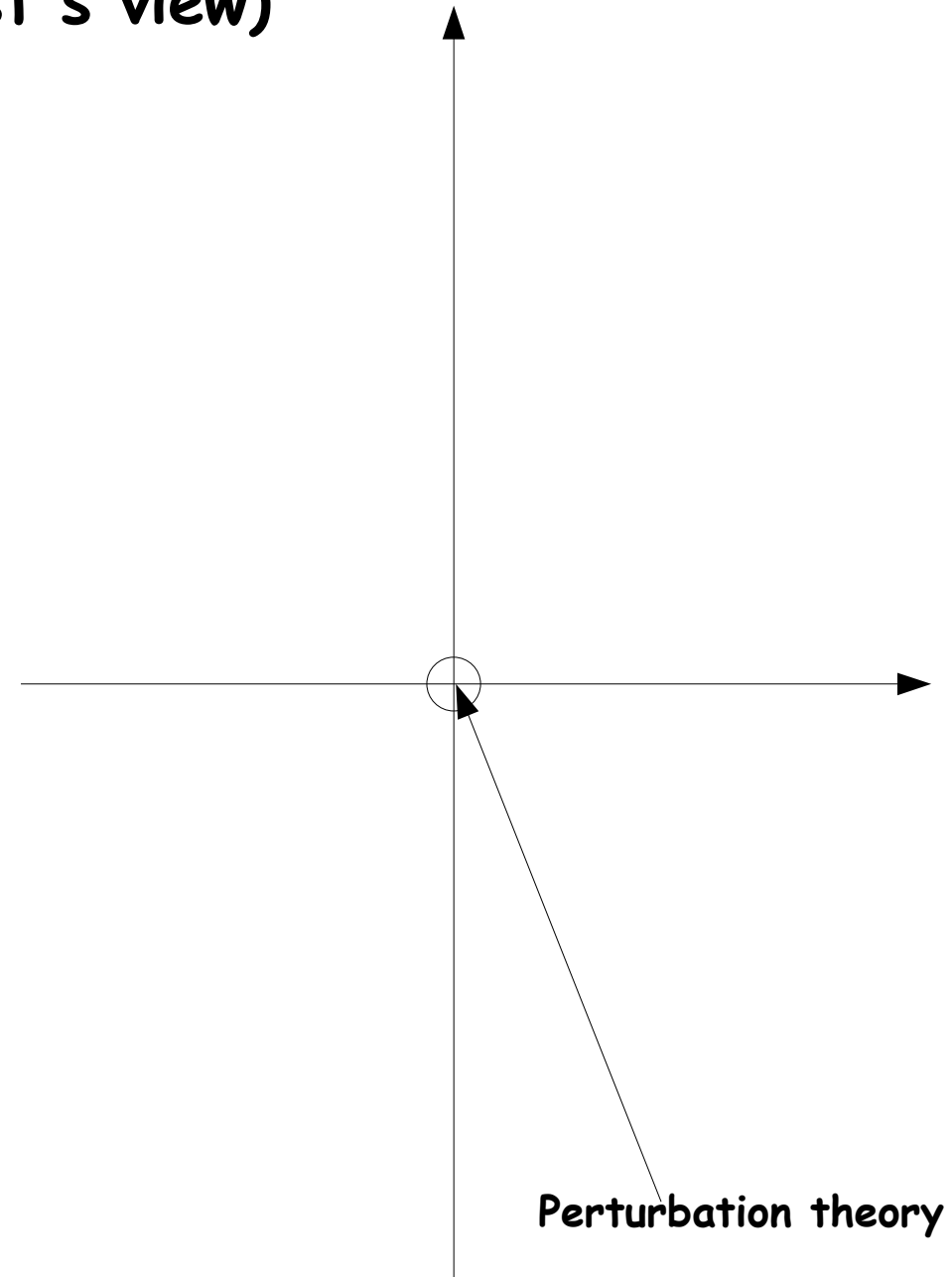
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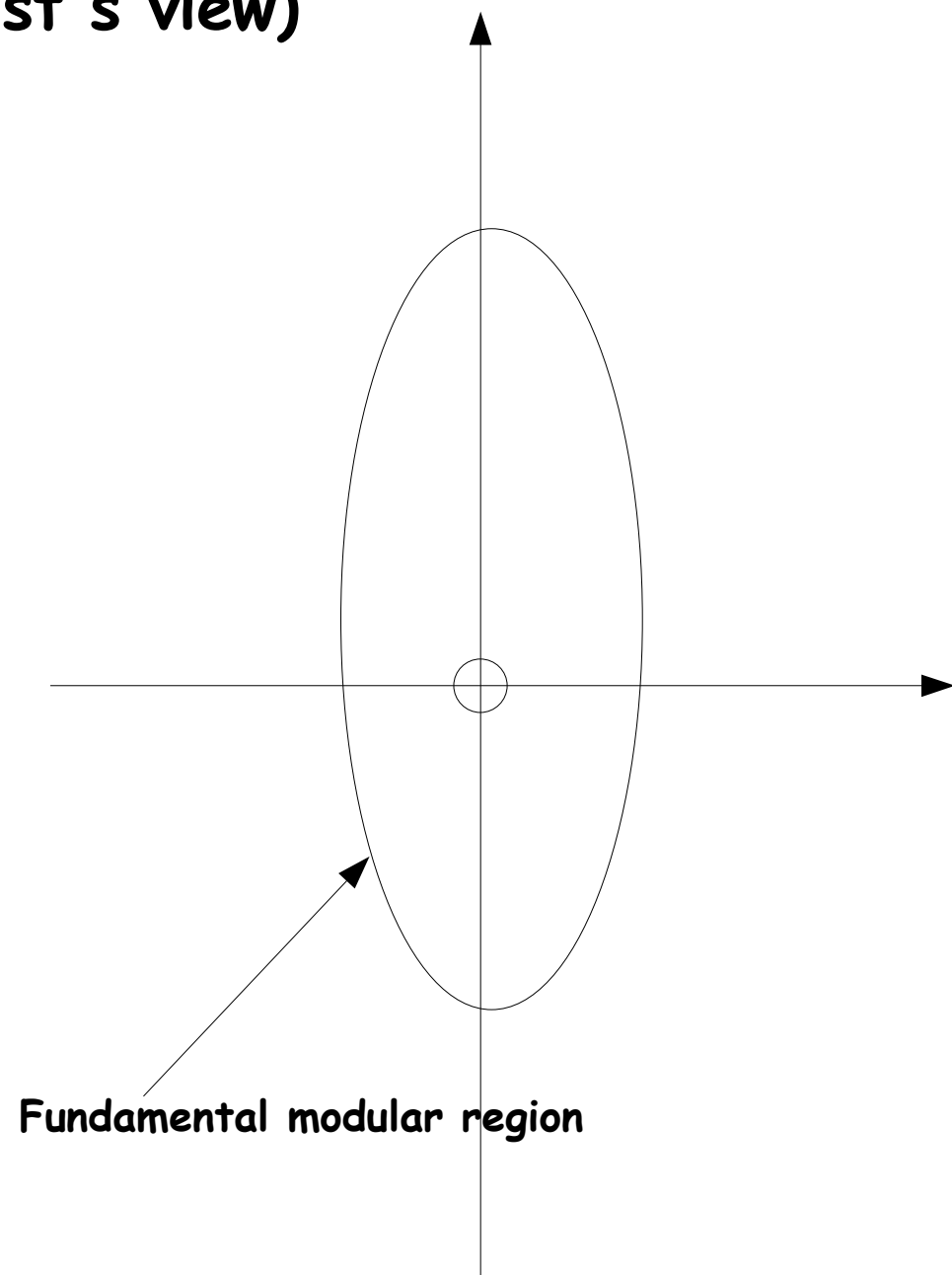
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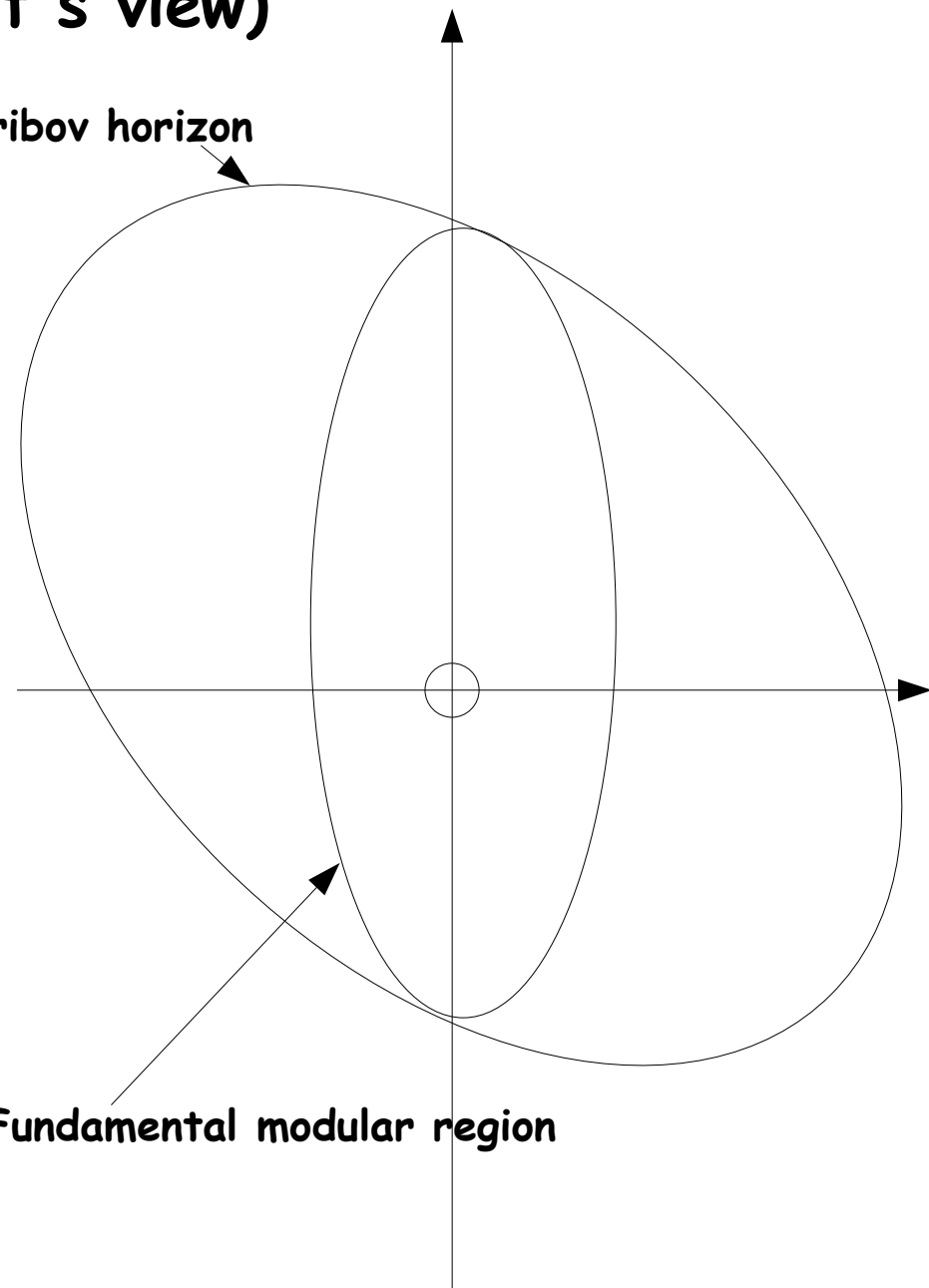
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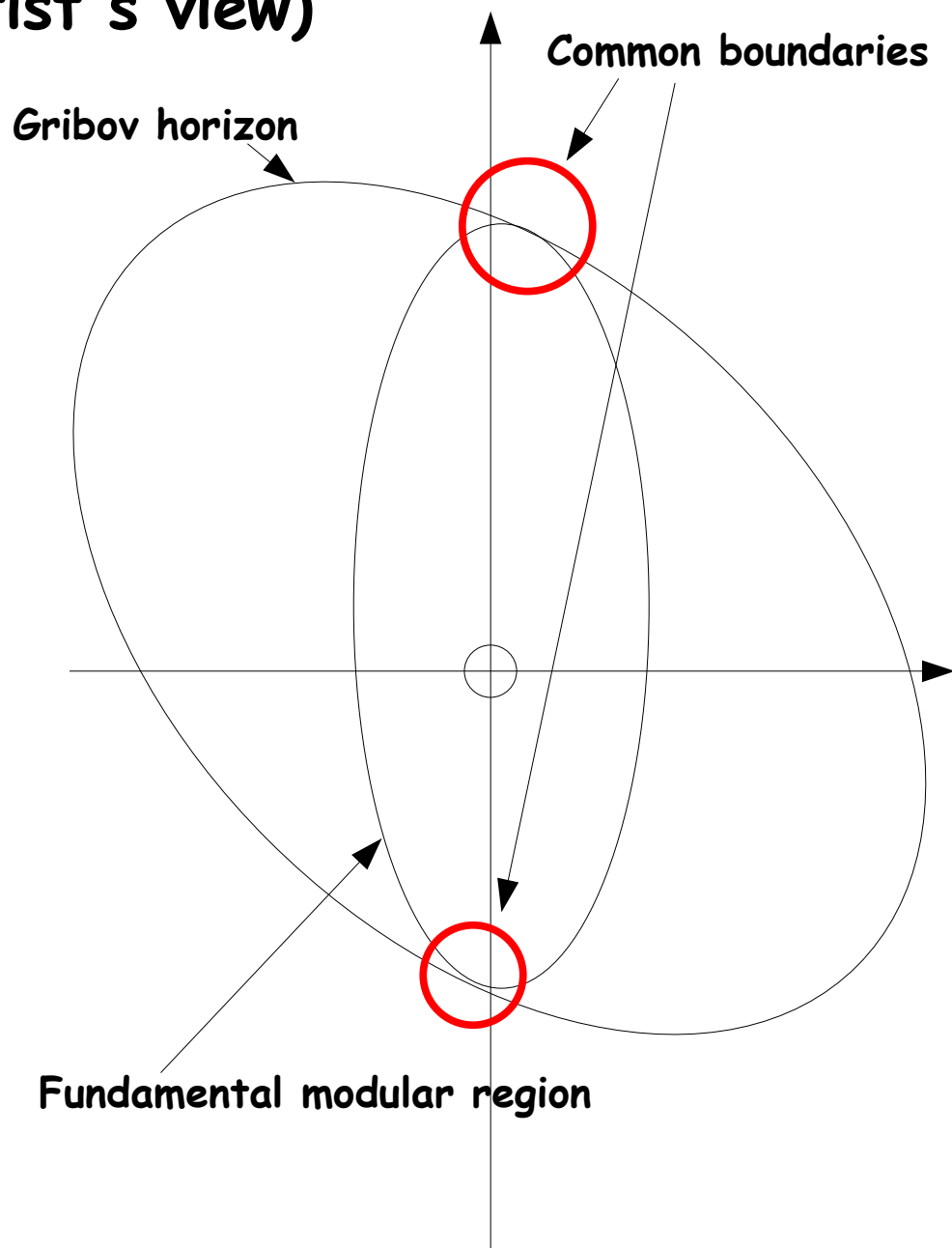
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Gribov horizon



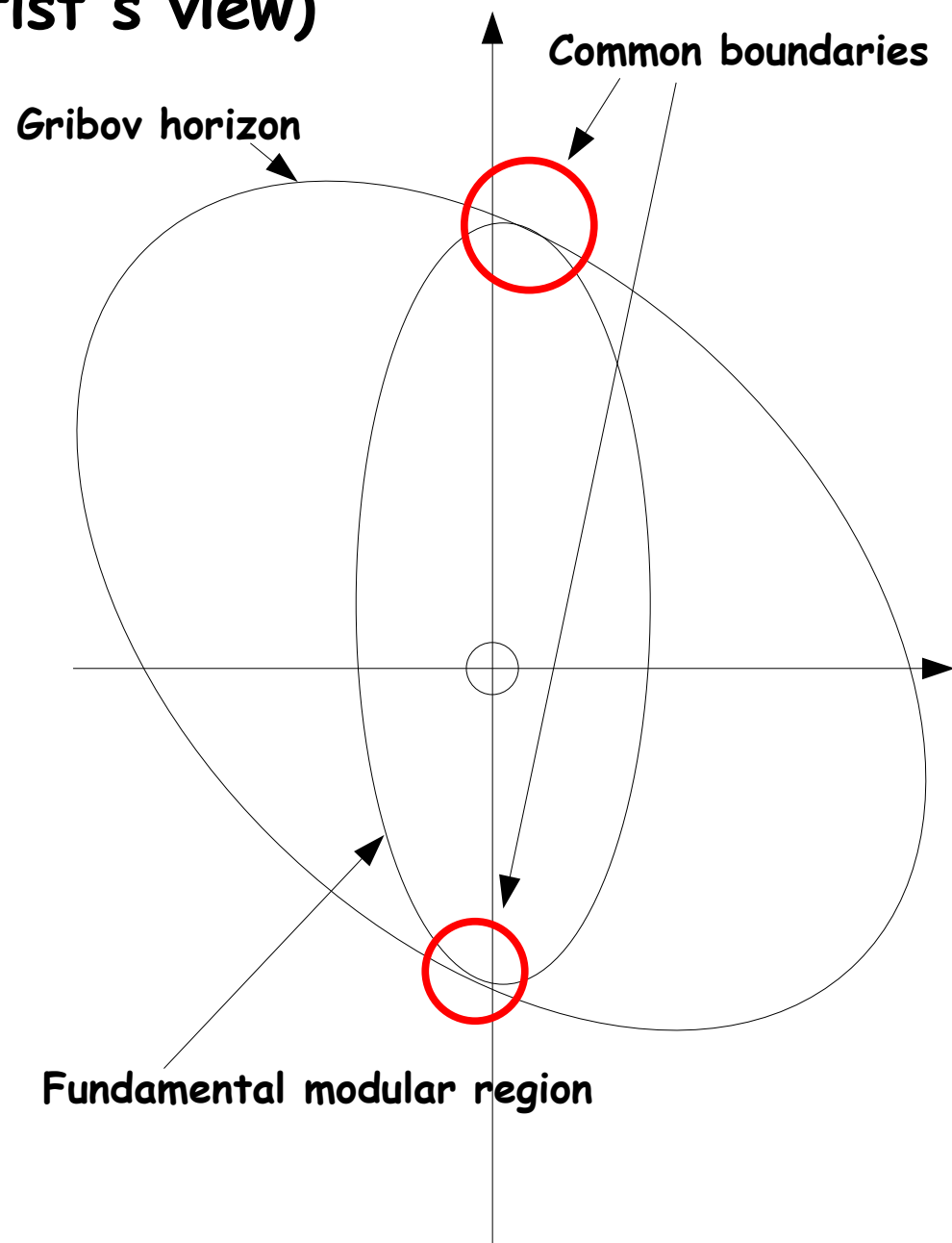
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- Both have a common boundary



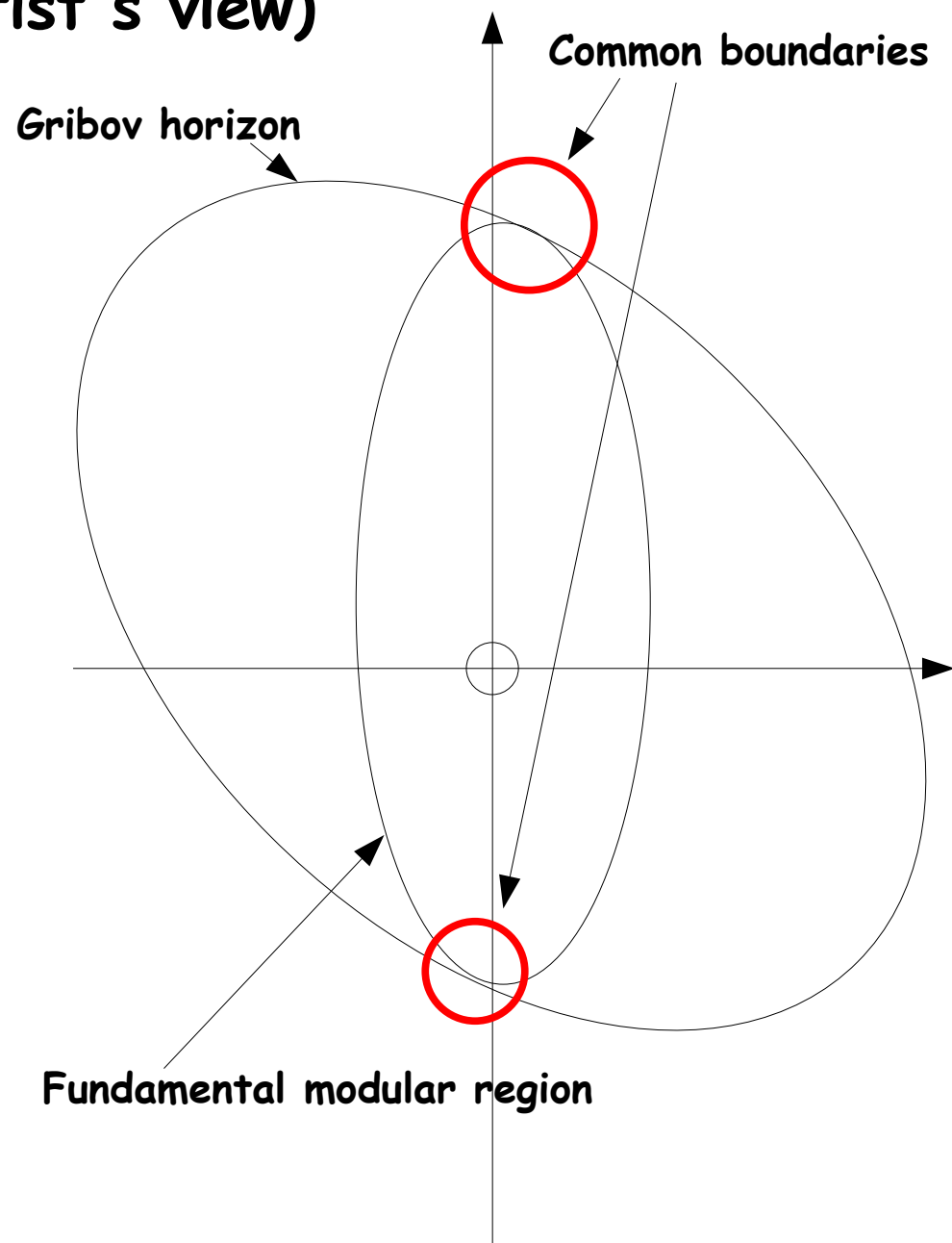
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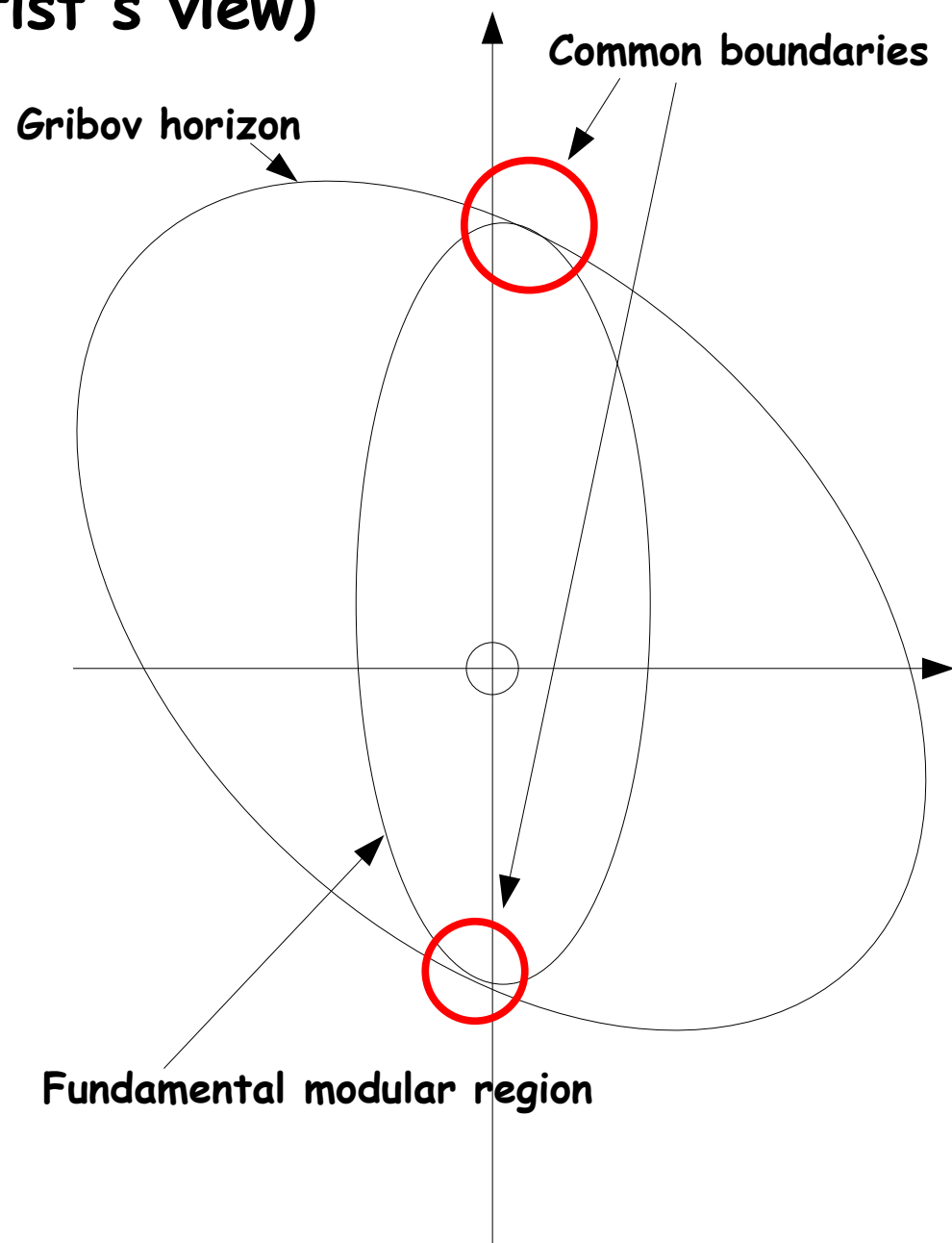
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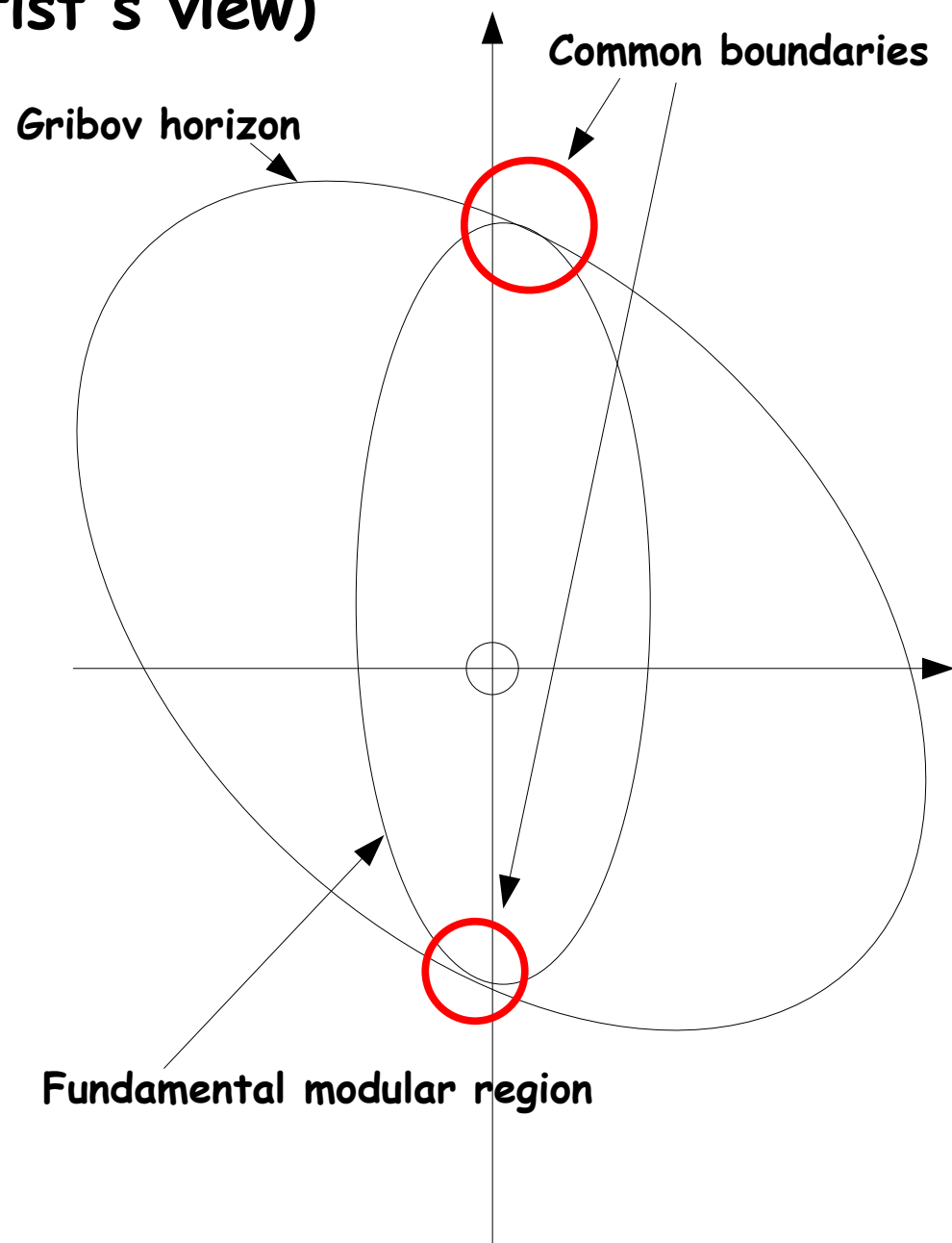
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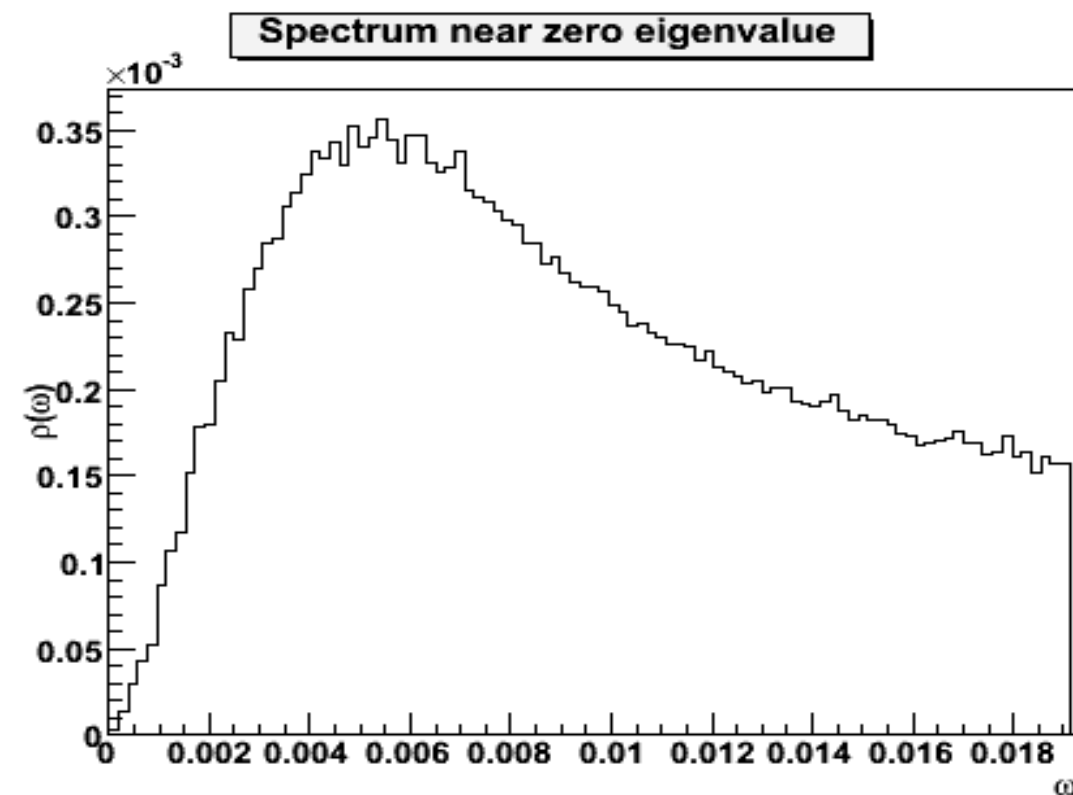


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- **Faddeev-Popov determinant vanishes there**
- **Leads to positivity violating spectral functions**



Landau-gauge Faddeev-Popov operator eigenspectrum

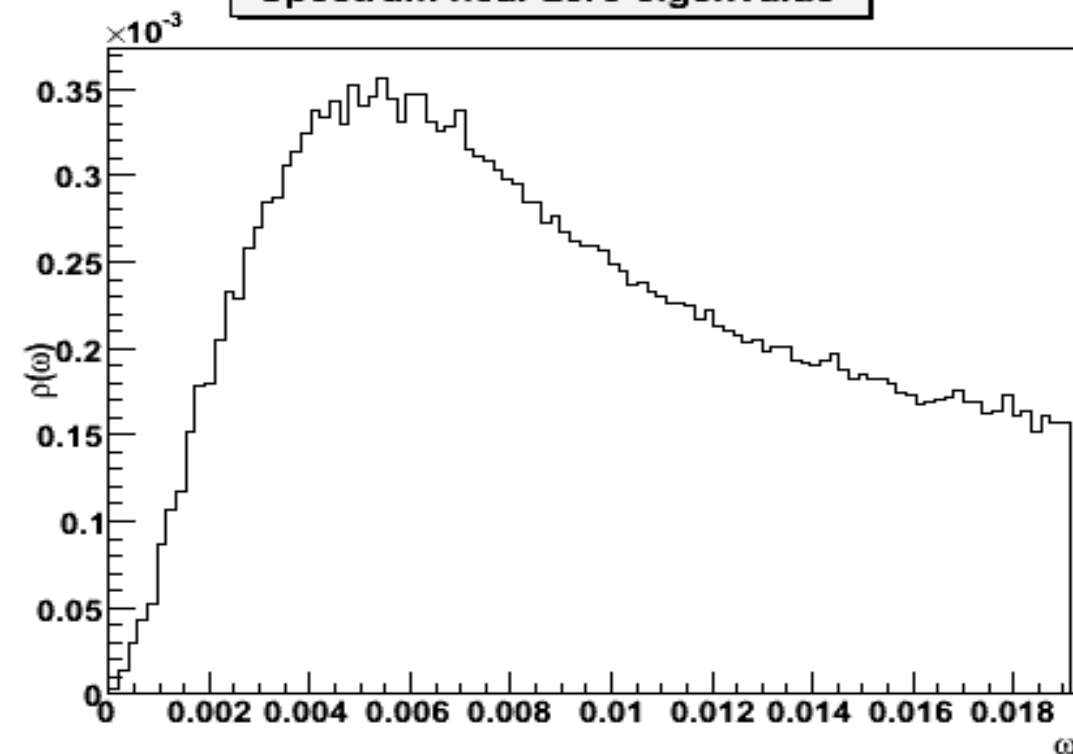


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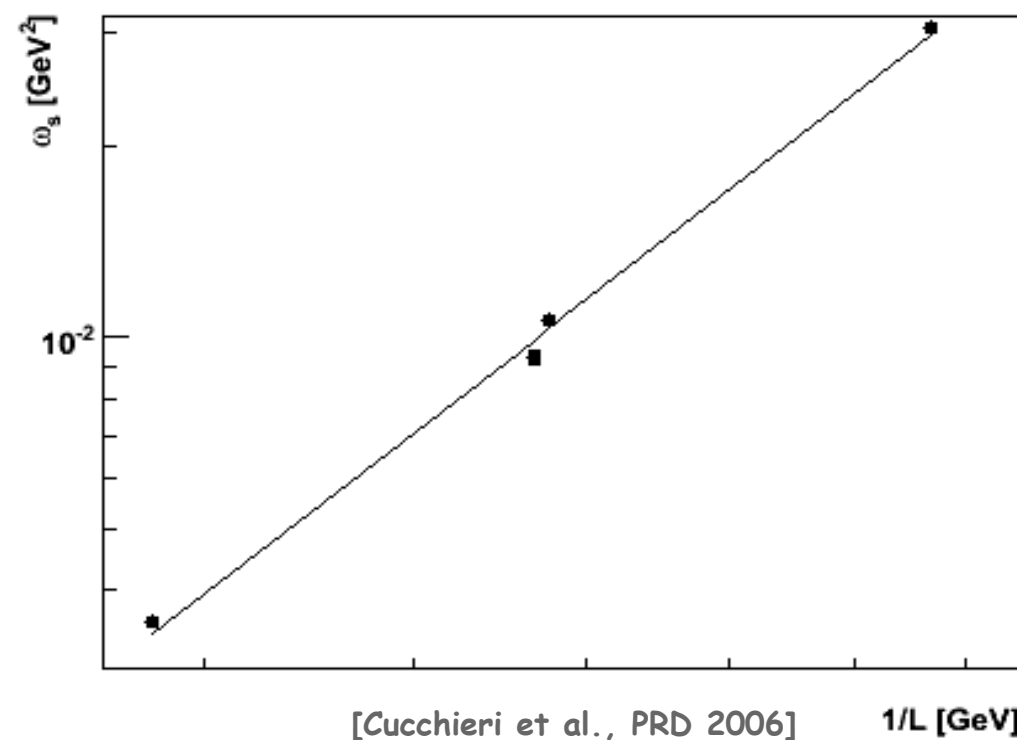
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Landau-gauge Faddeev-Popov operator eigenspectrum

Spectrum near zero eigenvalue



Smallest eigenvalue of the Faddeev-Popov operator



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

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- **Gribov-Zwanziger supported for other gauges**
 - Linear lambda gauge class (includes Landau gauge)
[Cucchieri et al., 2006, unpublished]
 - Coulomb gauge i[Cucchieri 2006, Cucchieri et al. PRD 2002]

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

(Intermediate states - not observable)

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[Introduction: Alkofer & von Smekal, 2001]

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- **Ghost linked to the Faddeev-Popov operator**

$$D_G^{ab}(x-y) \sim \langle (\partial_\mu D_\mu^{ab})^{-1} \rangle = \langle (\partial_\mu (\delta^{ab} \partial_\mu - g f^{abc} A_\mu^c))^{-1} \rangle$$

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 - Relation to the **Faddeev-Popov operator**

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Green's functions - The predictions

- Confinement scenarios give predictions
 - Gribov-Zwanziger:
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 - Infrared enhancement - **mediates long-range forces**

Methods

- **Lattice**
 - Finite volume, discrete - minimal and maximal momenta
 - Full non-perturbative dynamics correctly implemented

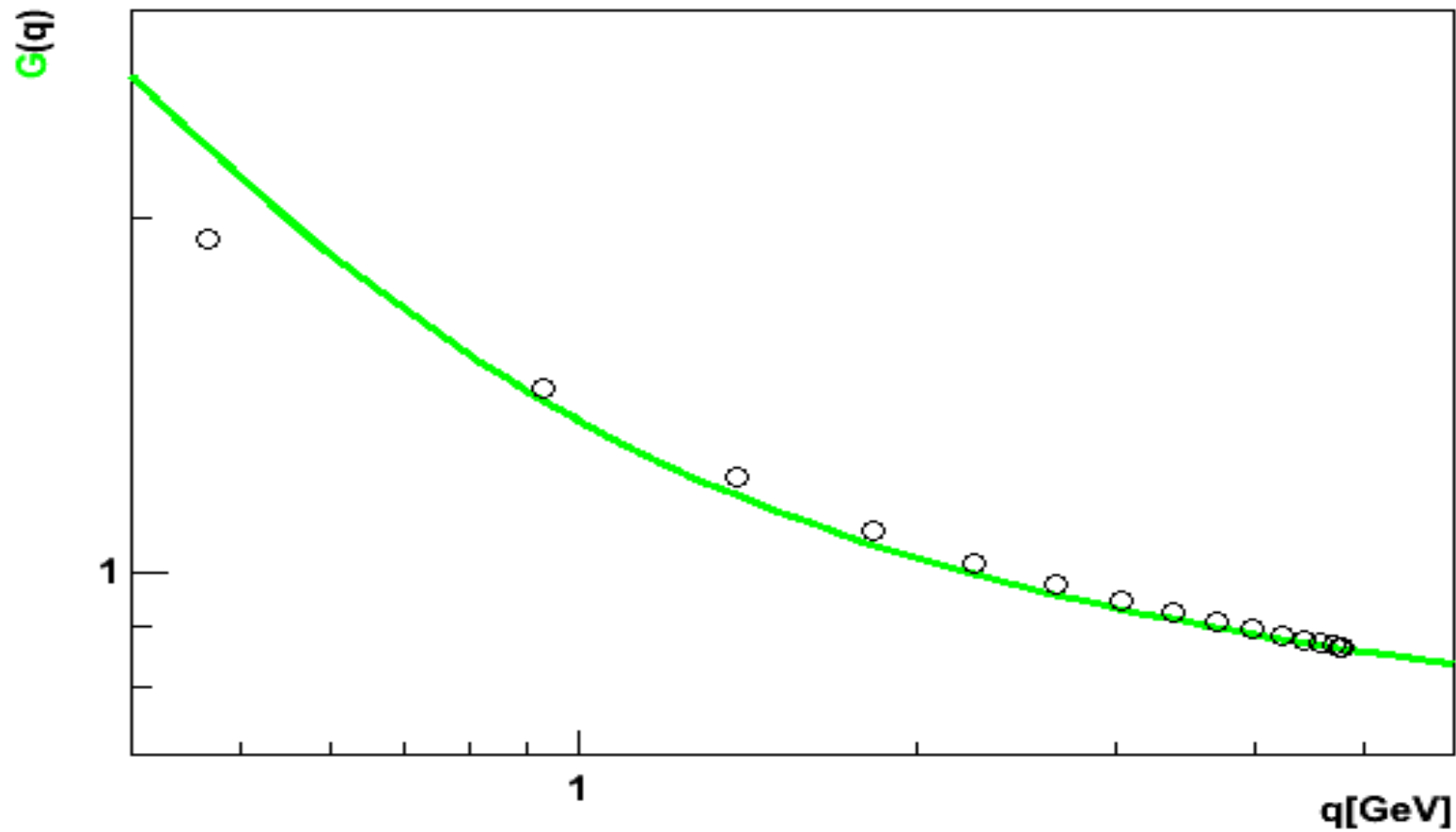
Methods

- **Lattice**
 - Finite volume, discrete - minimal and maximal momenta
 - Full non-perturbative dynamics correctly implemented
- **Dyson-Schwinger equations** (Quantum equations of motion)
 - Requires (partly uncontrolled) approximations
 - Continuum, partly analytical

Ghost

[DSE: Fischer et al., PLB 2002,
Lattice 32⁴: Cucchieri et al., unpublished]

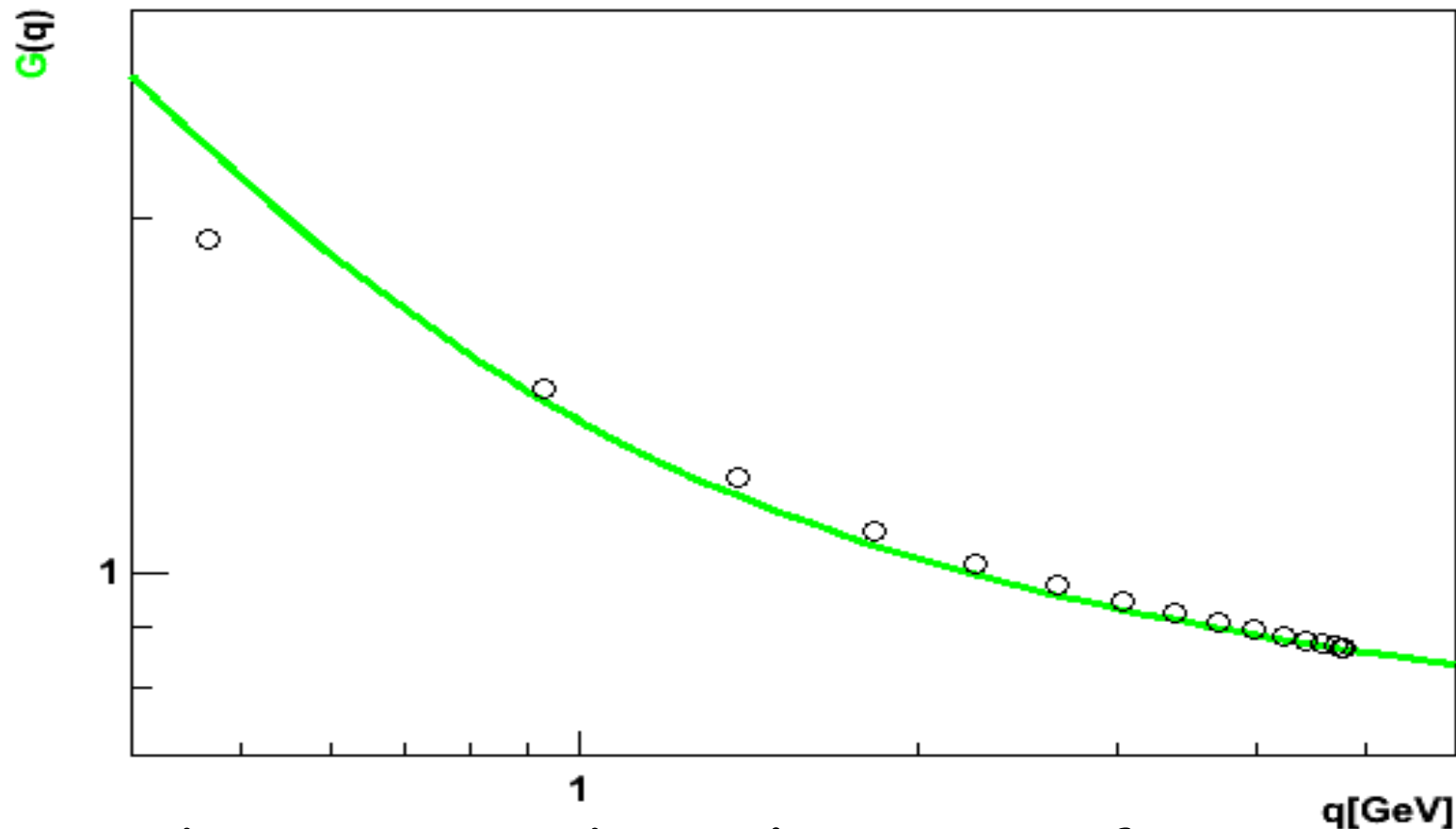
Ghost Dressing Function



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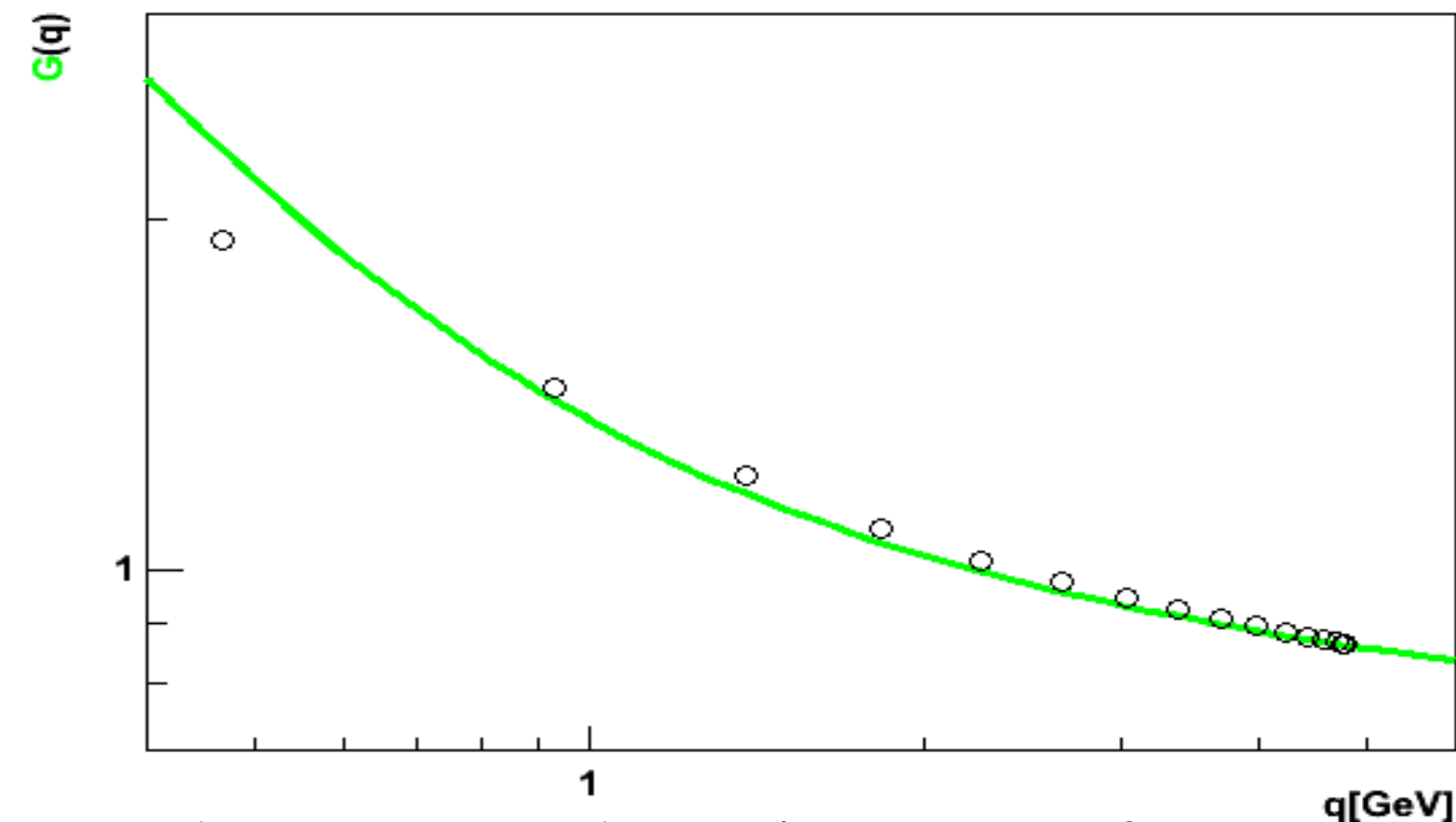


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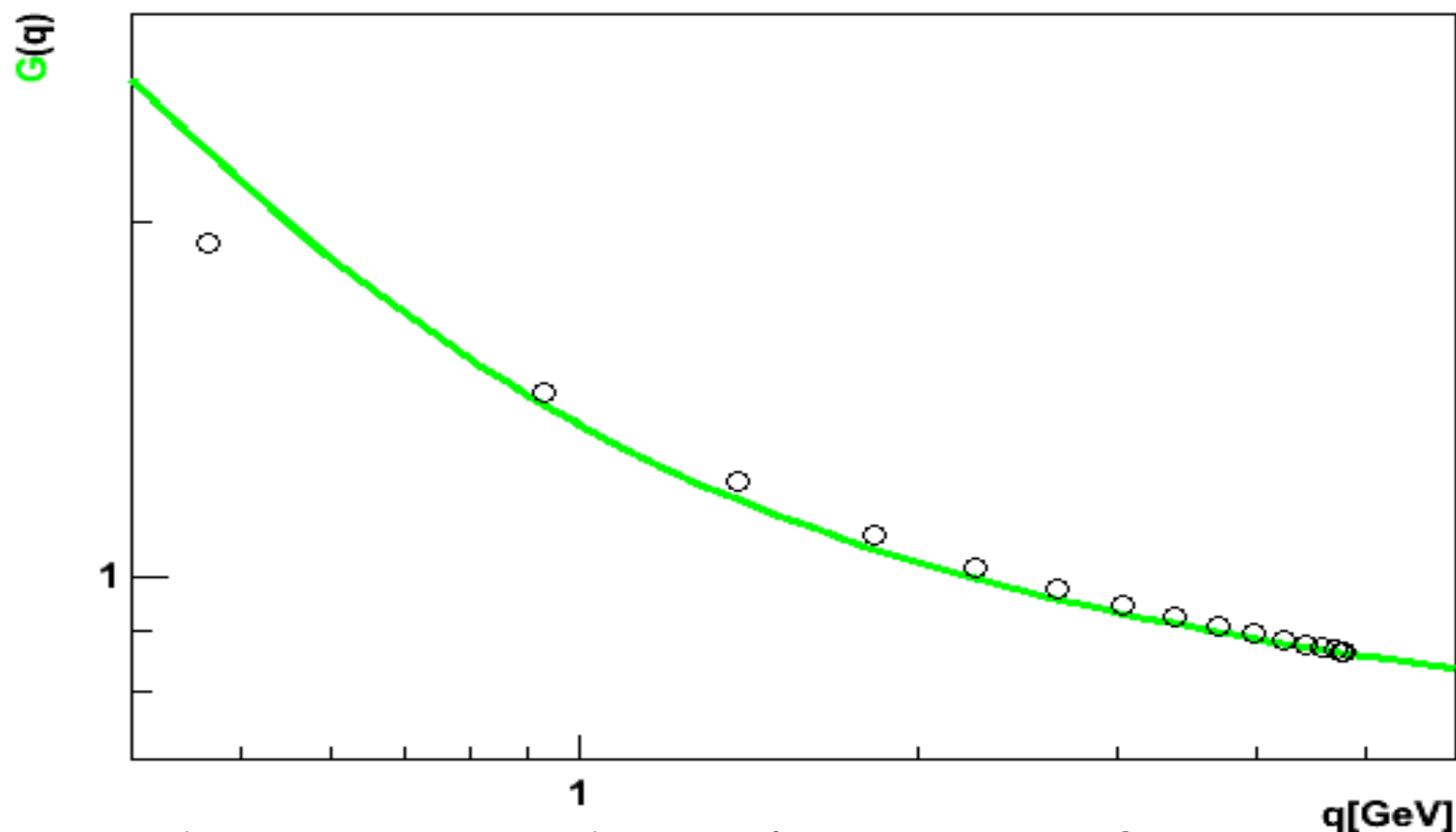


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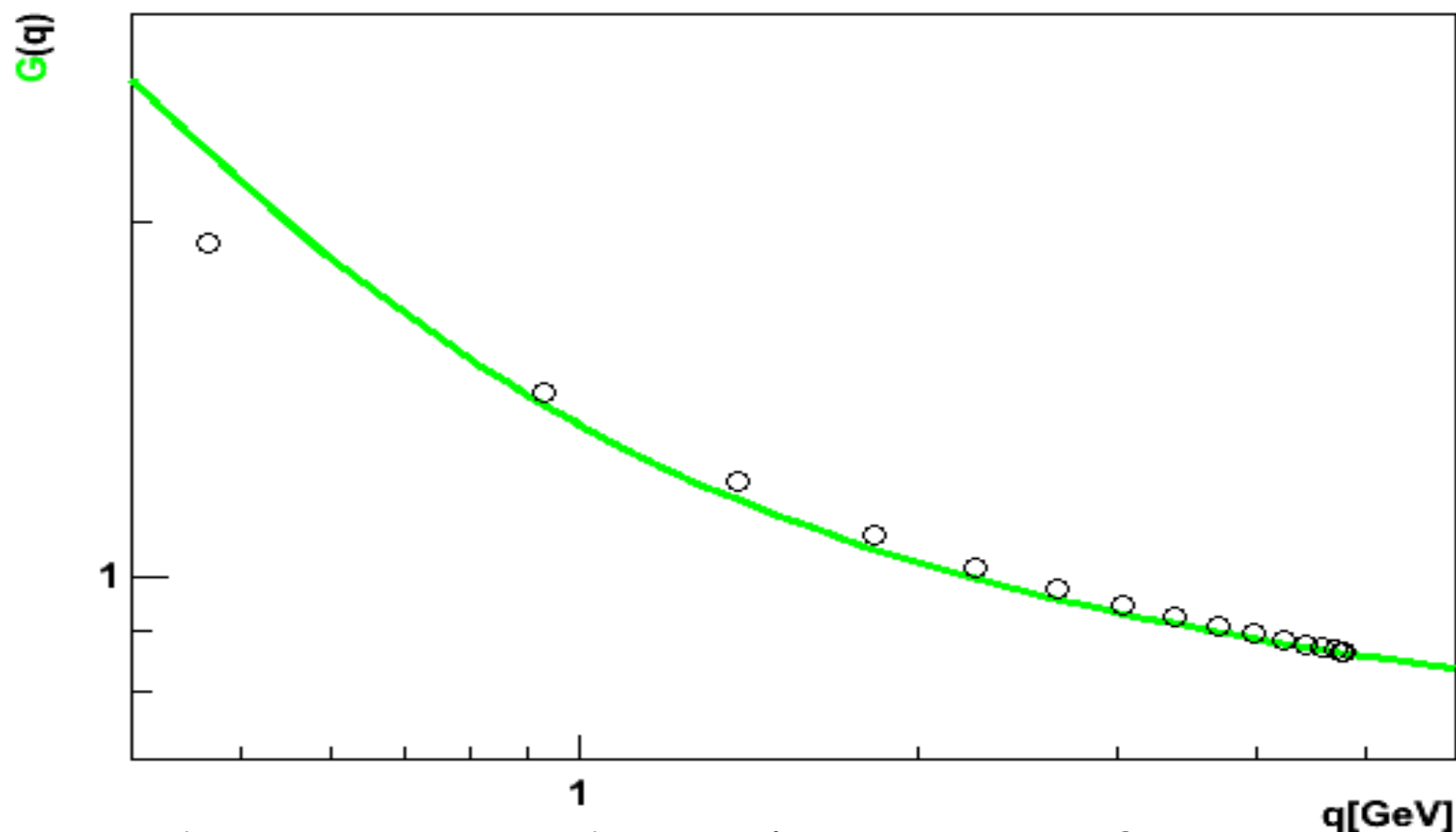


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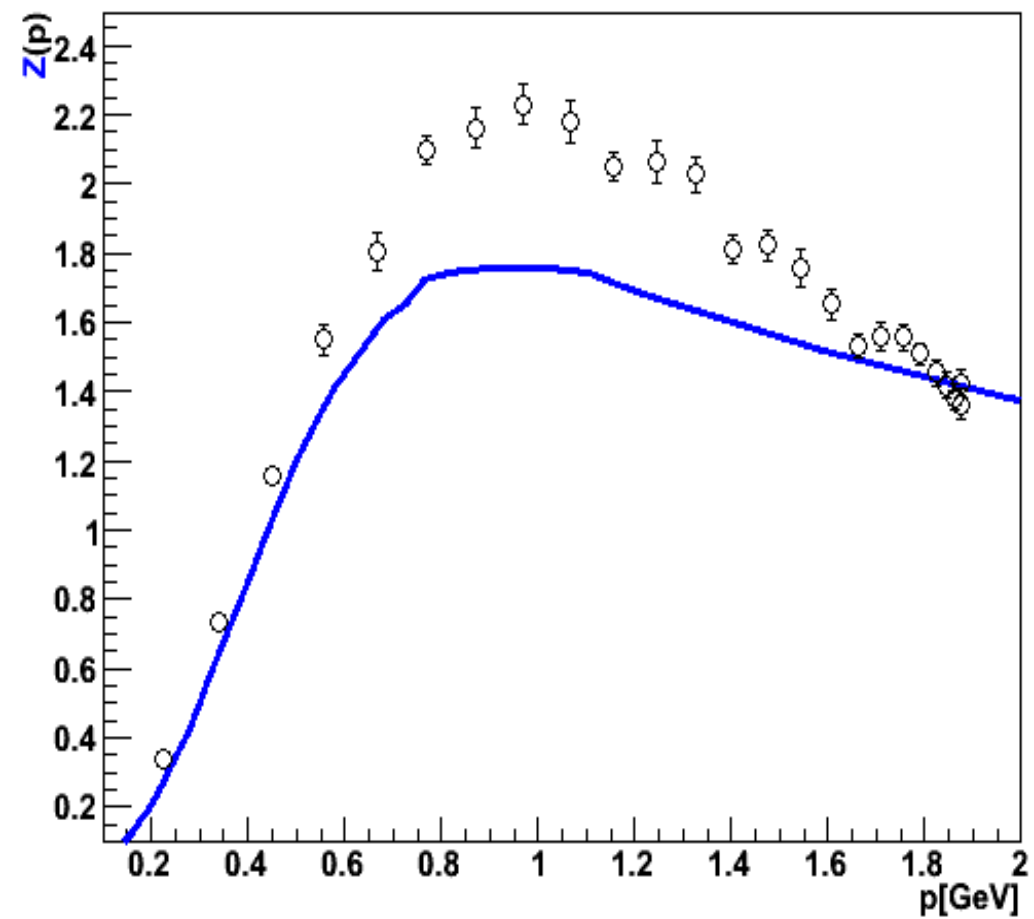
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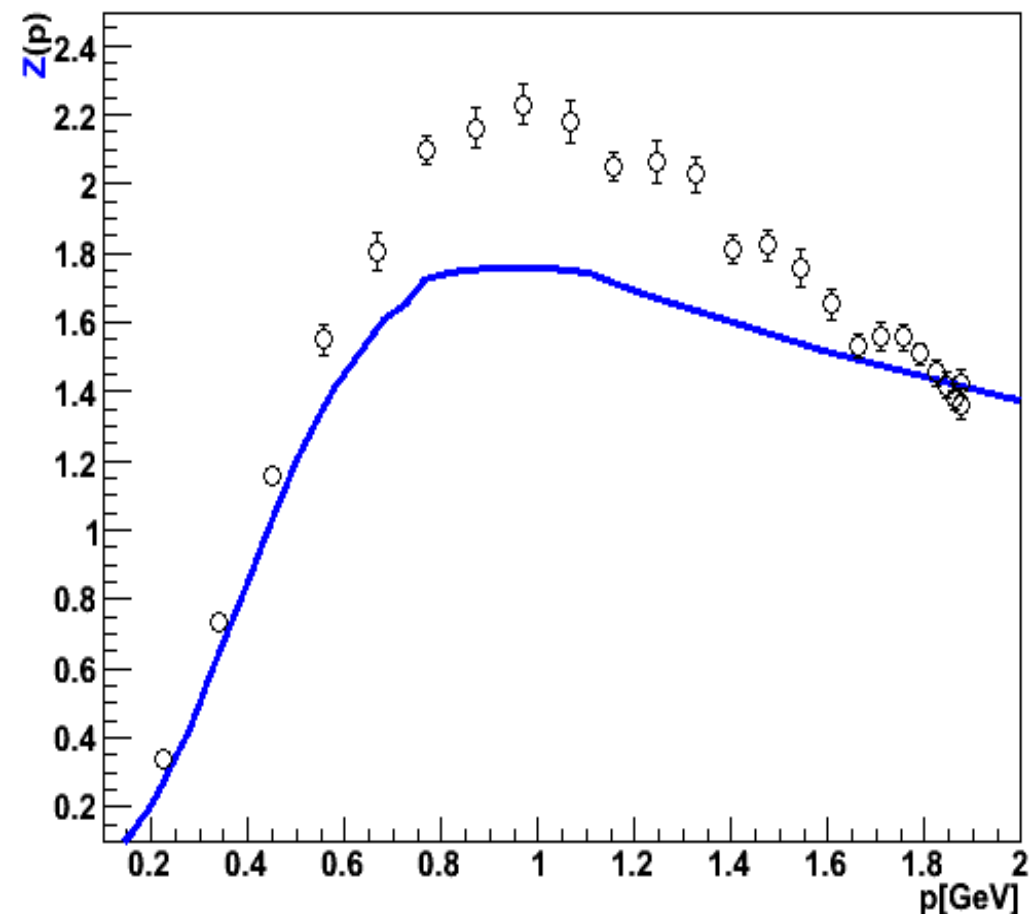
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- Due to topological configurations? [Gattnar et al., 2004, Greensite et al., 2004, Maas, 2006]

Gluon

[DSE: Fischer et al., PLB 2002, Lattice 52⁴: Cucchieri et al., 2006]

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- Infrared vanishing - confined

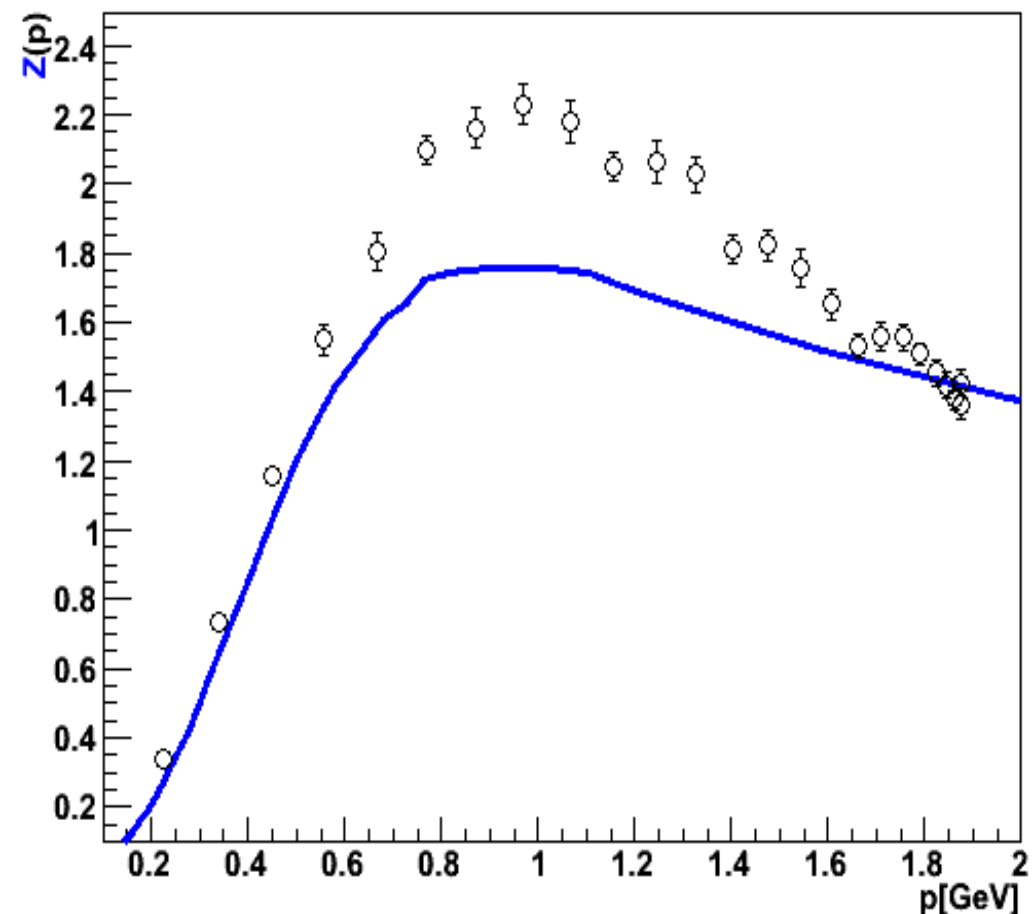
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[Pawlowski et al., PRL 2004]

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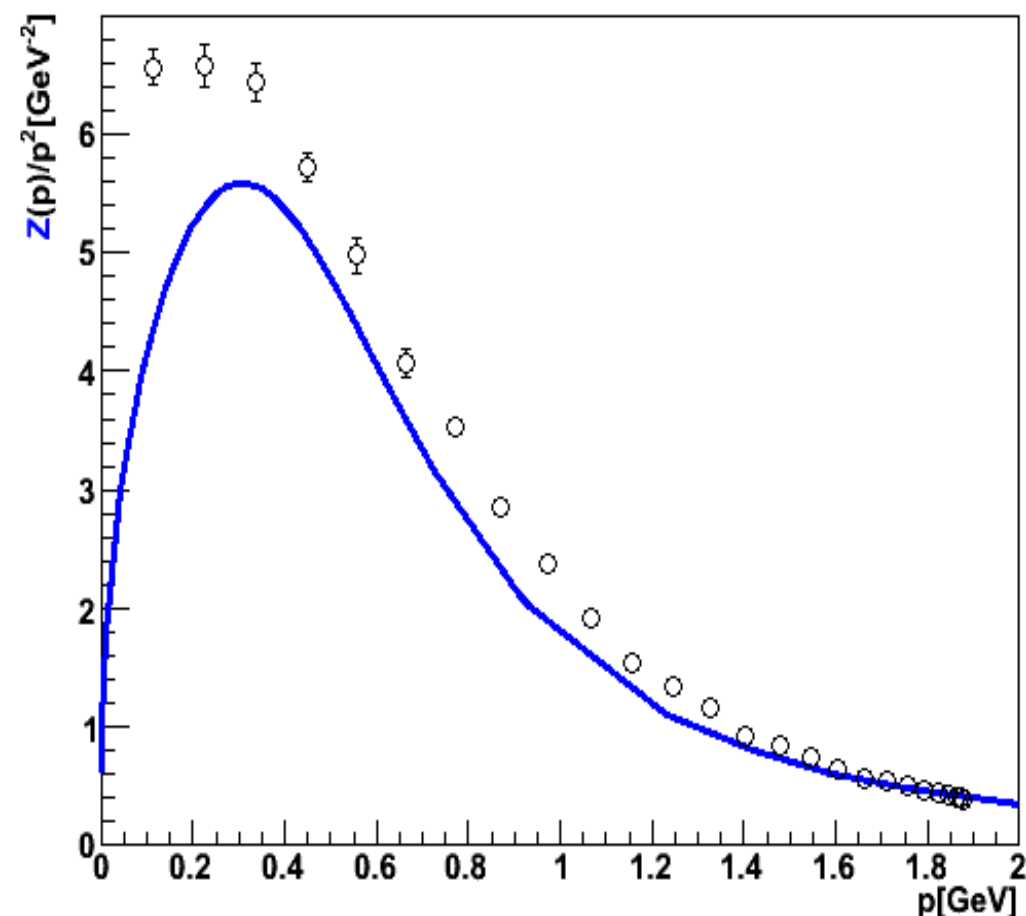
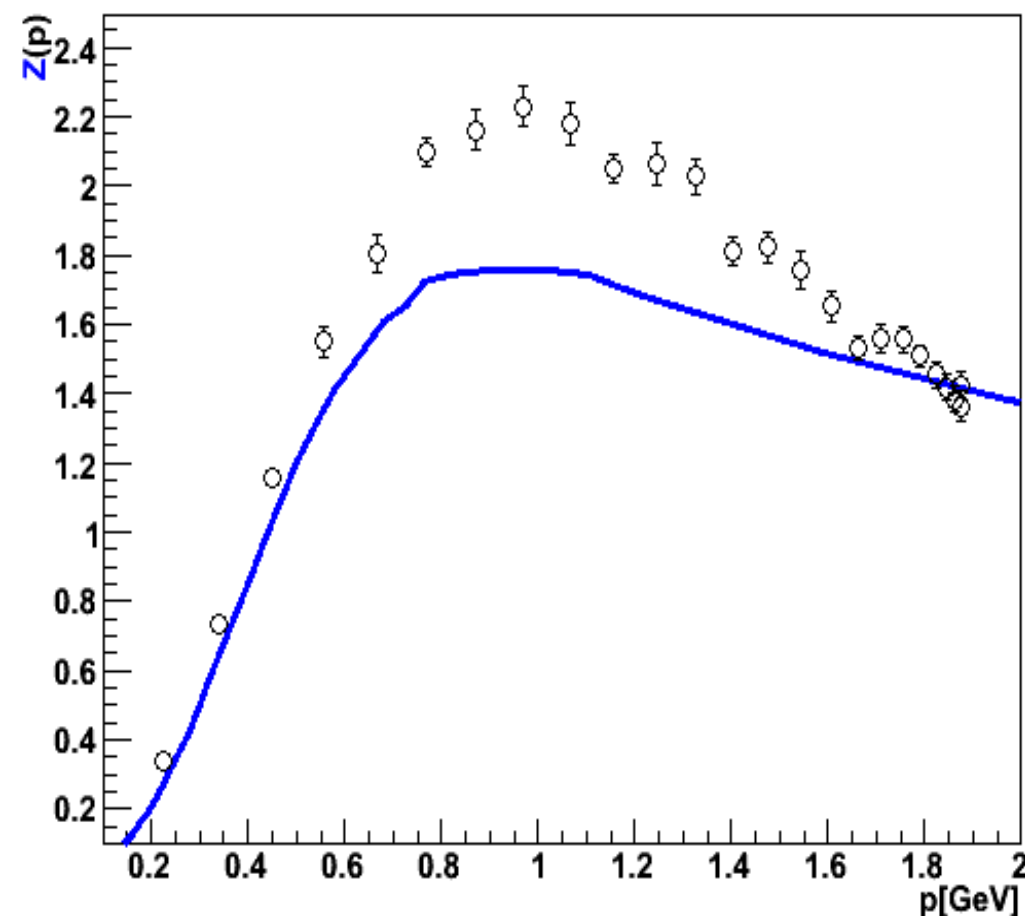
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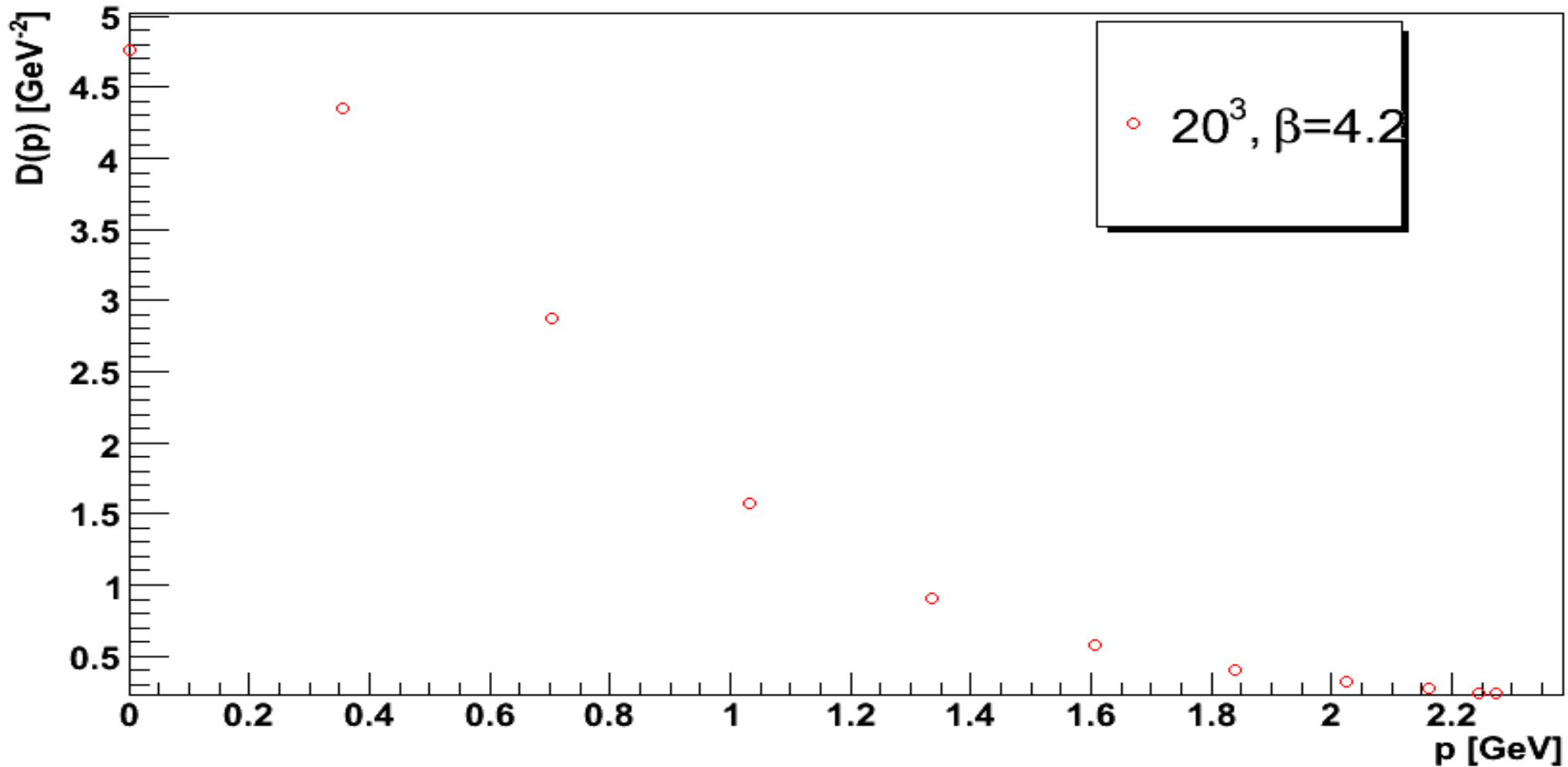


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Gluon - large lattice volumes needed

[20³: Cucchieri et al., 2006]

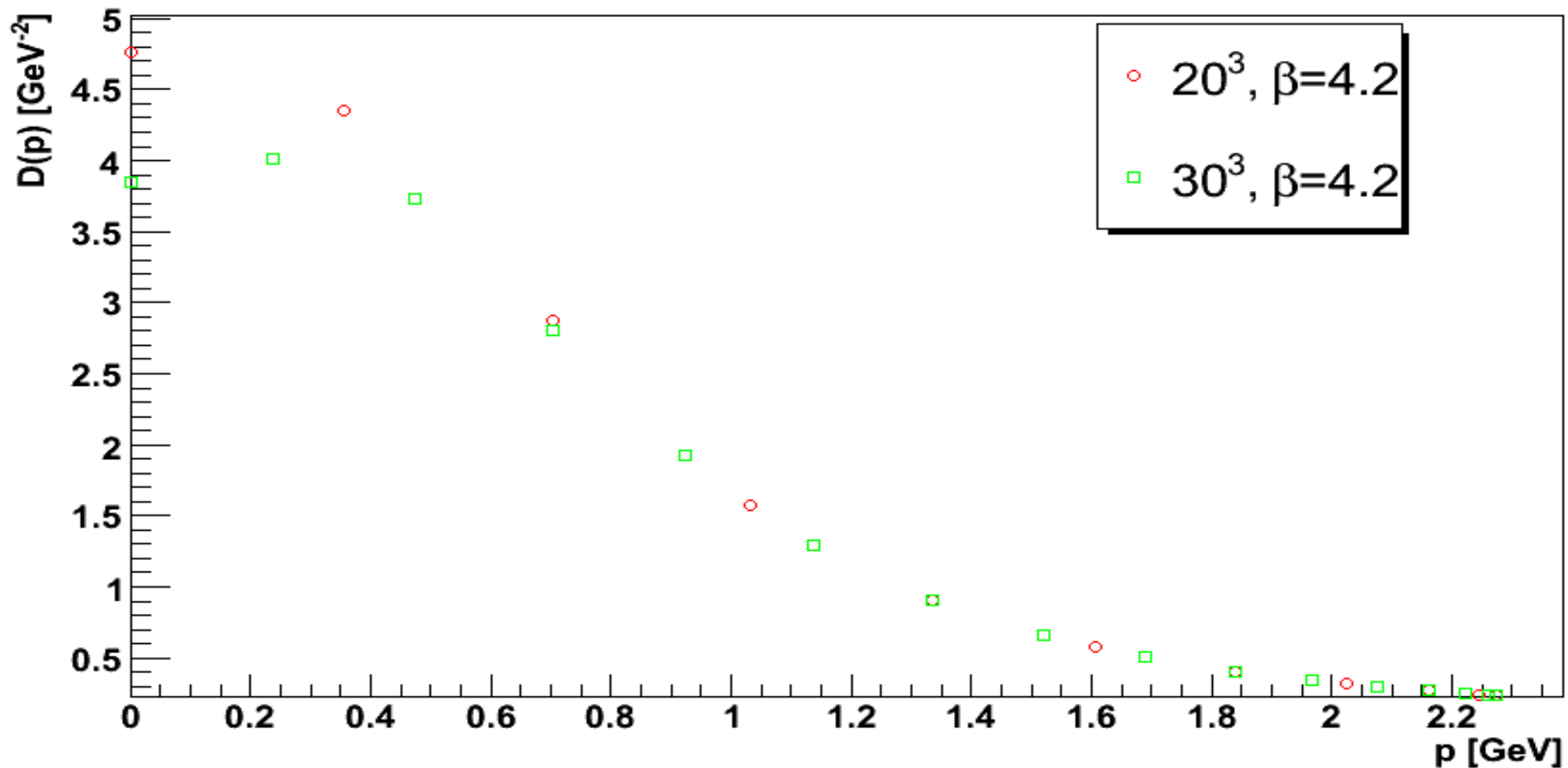
Gluon propagator



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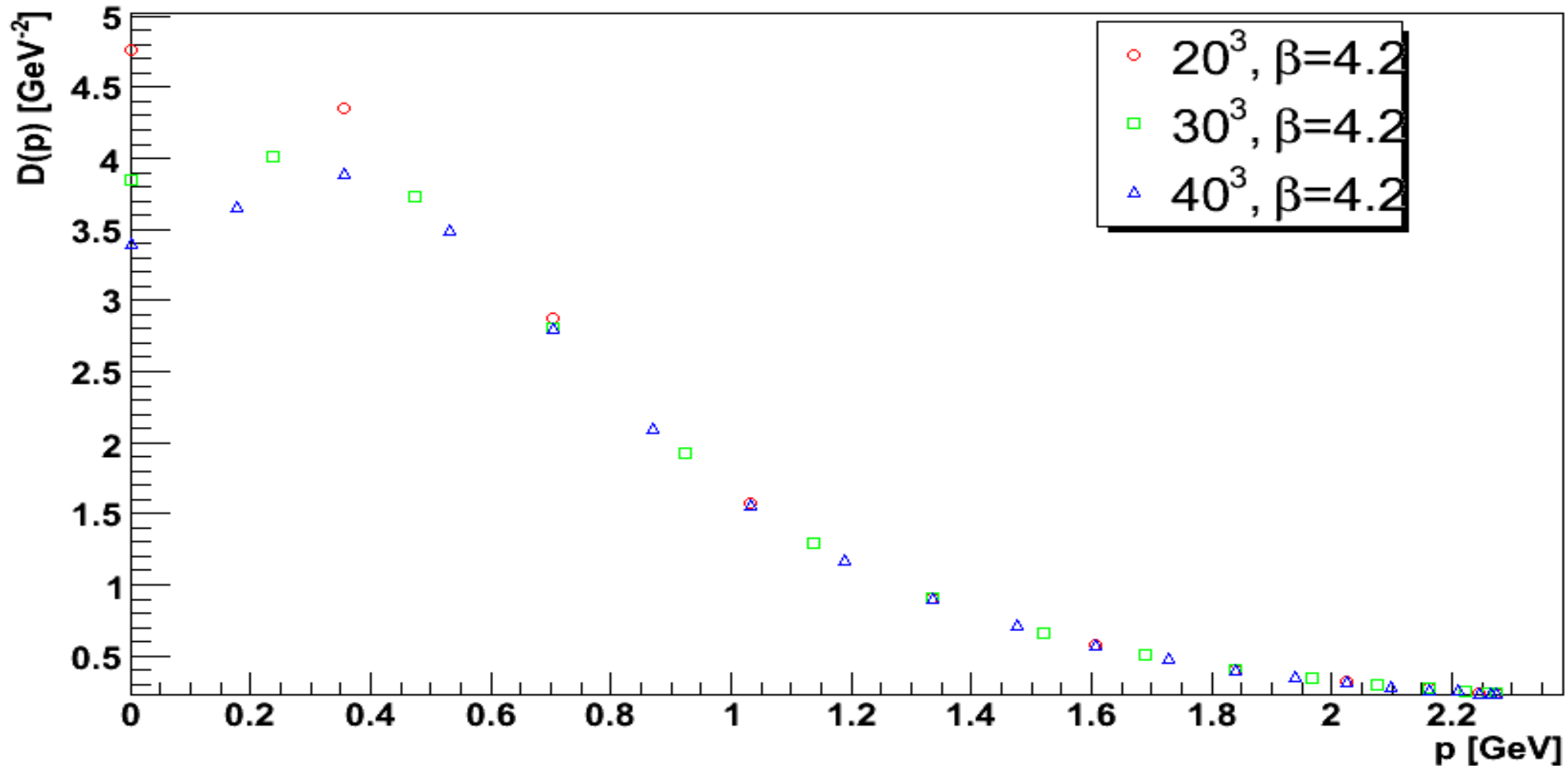


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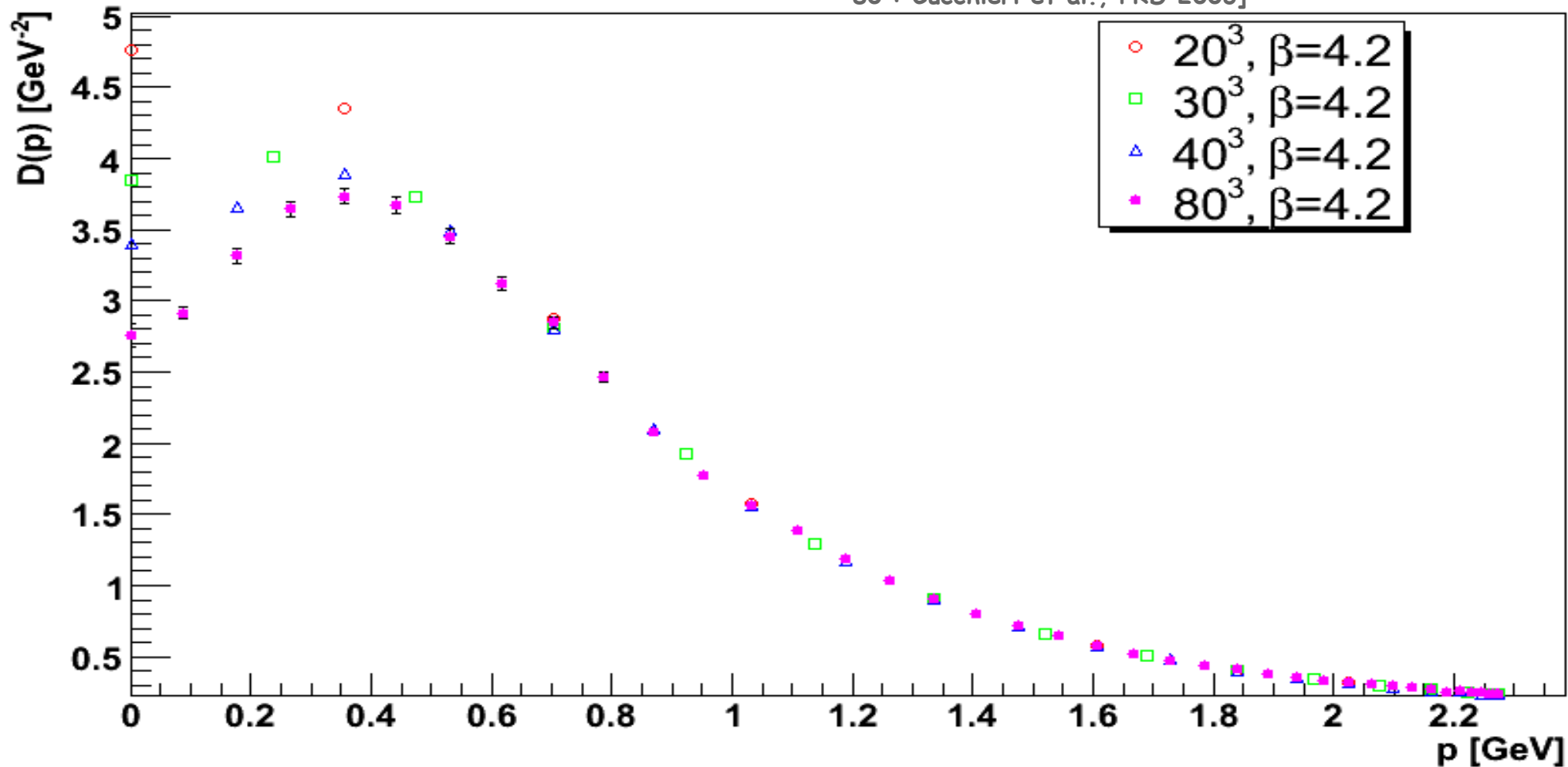
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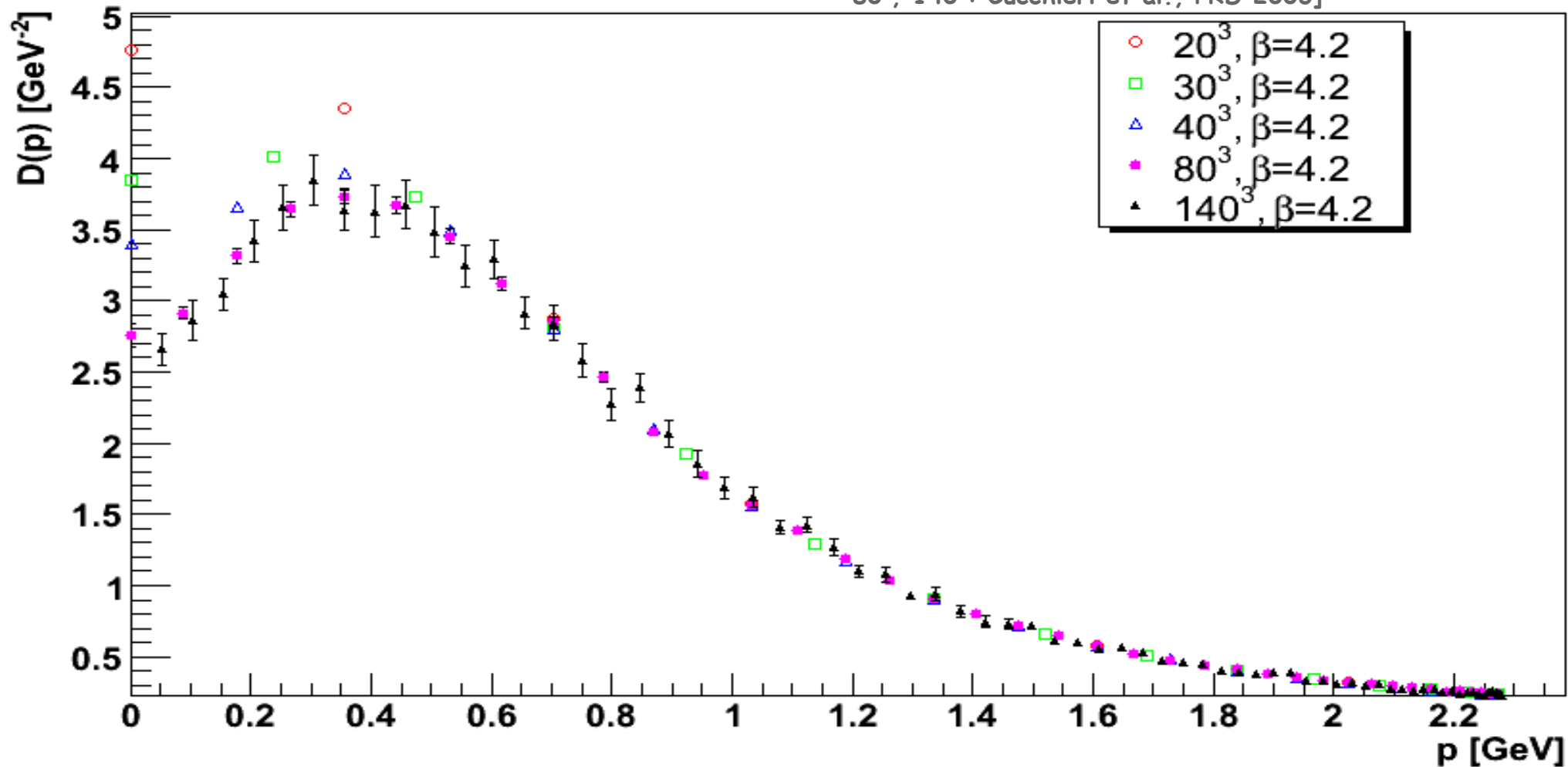
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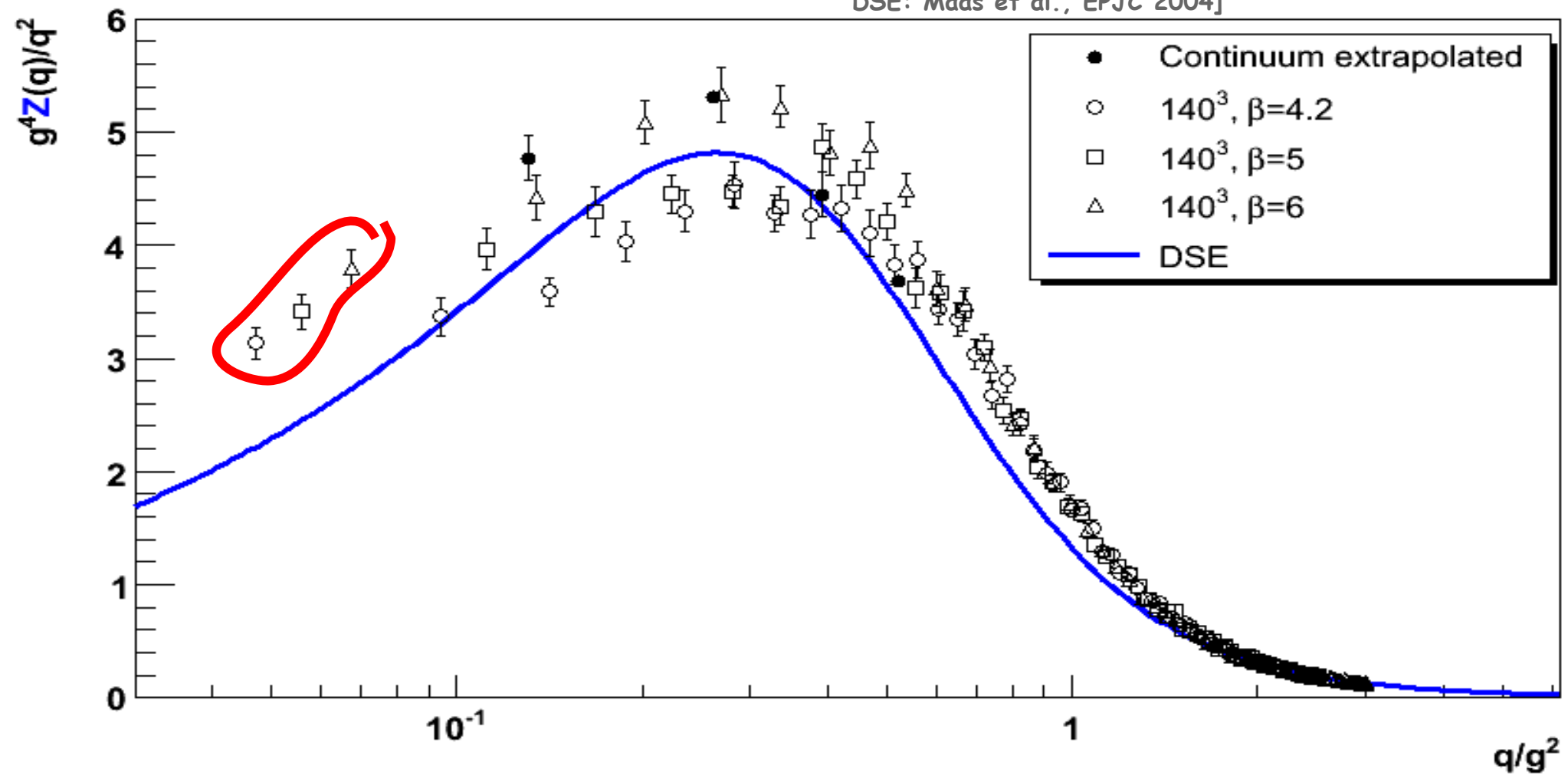
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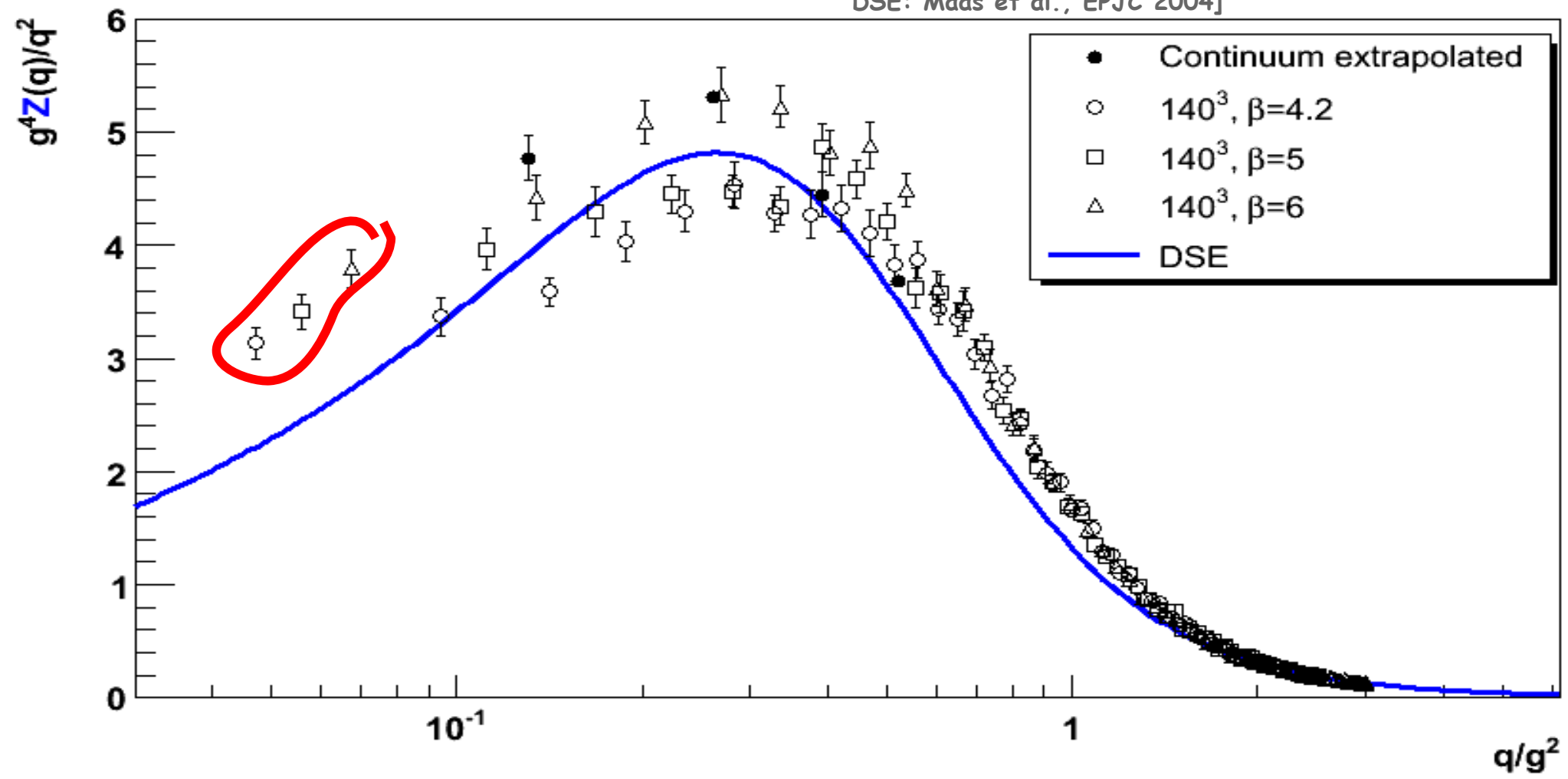


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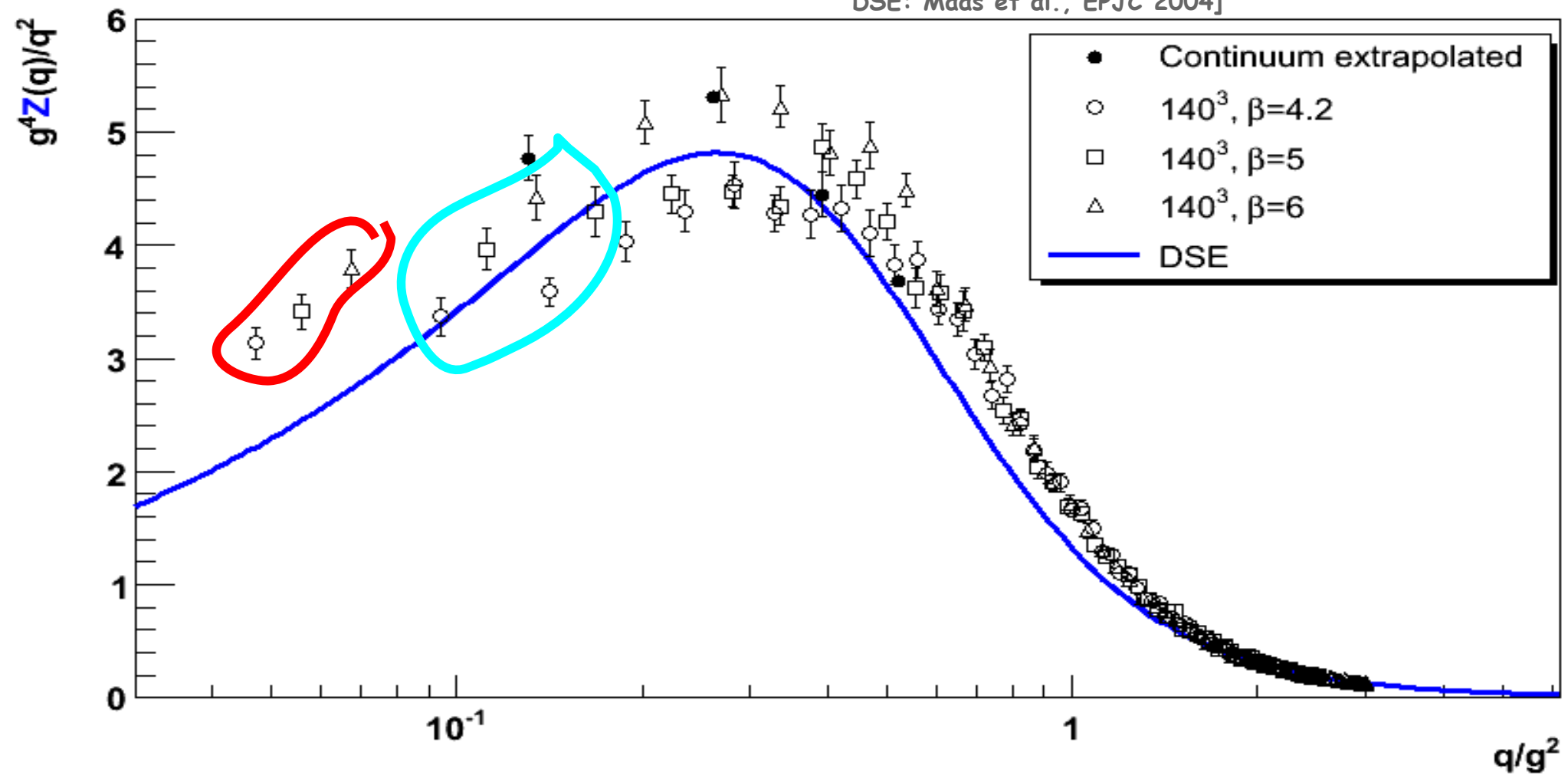


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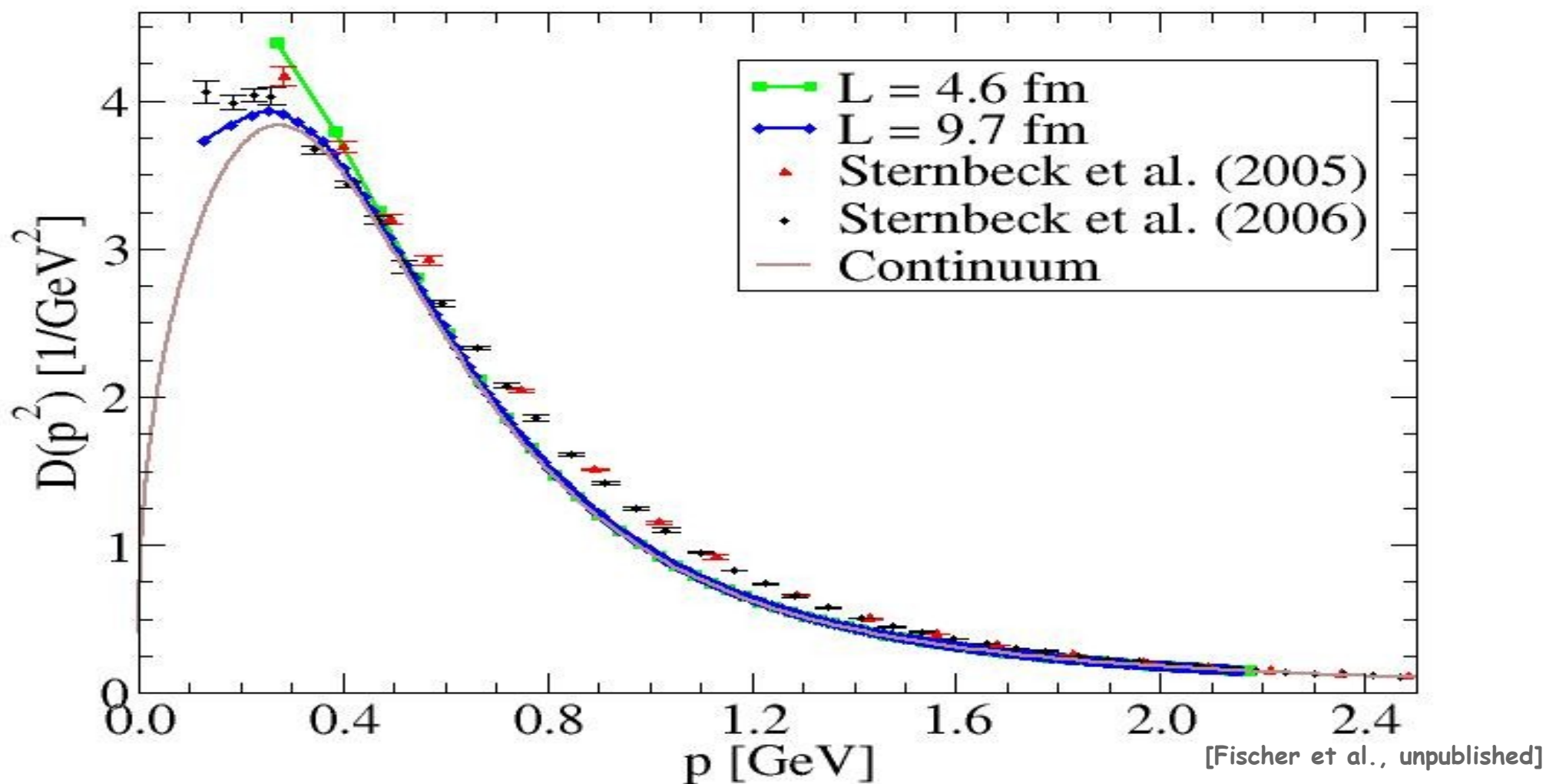
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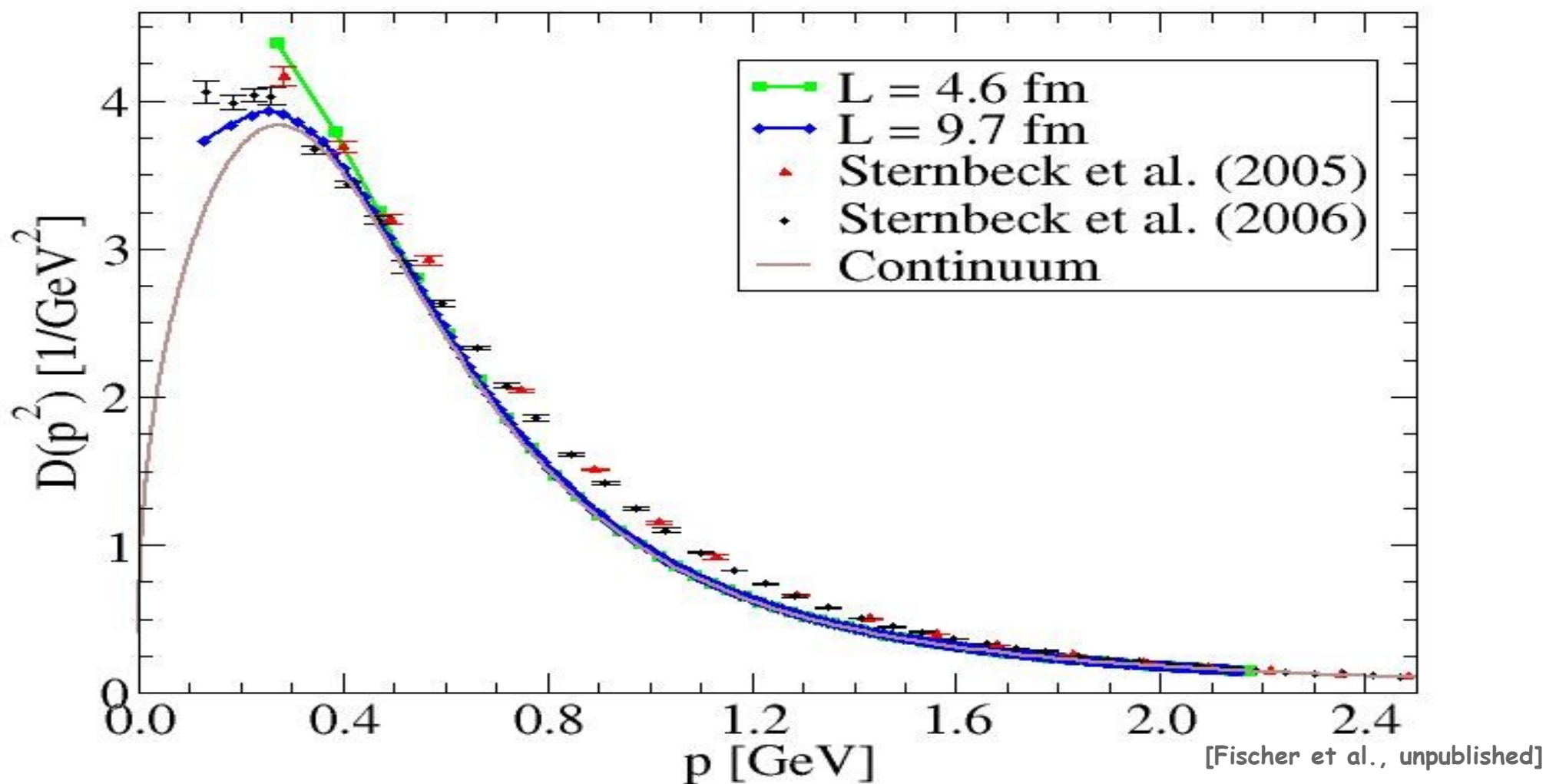
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Lattice vs. DSE in a finite volume



- Qualitative similar behavior

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[Fischer et al., unpublished]

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

Finite-Temperature Propagators

- **Equilibrium Physics: Matsubara formalism**

Finite-Temperature Propagators

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- Ghost

$$D_G(p_0^2, \vec{p}^2) = \frac{-G(p_0^2, \vec{p}^2)}{p^2}$$

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- **p_0 discrete, $p_0=0$: soft, $p_0 \neq 0$: hard**

Finite-Temperature propagators

- **Explicit dependencies on the fields**

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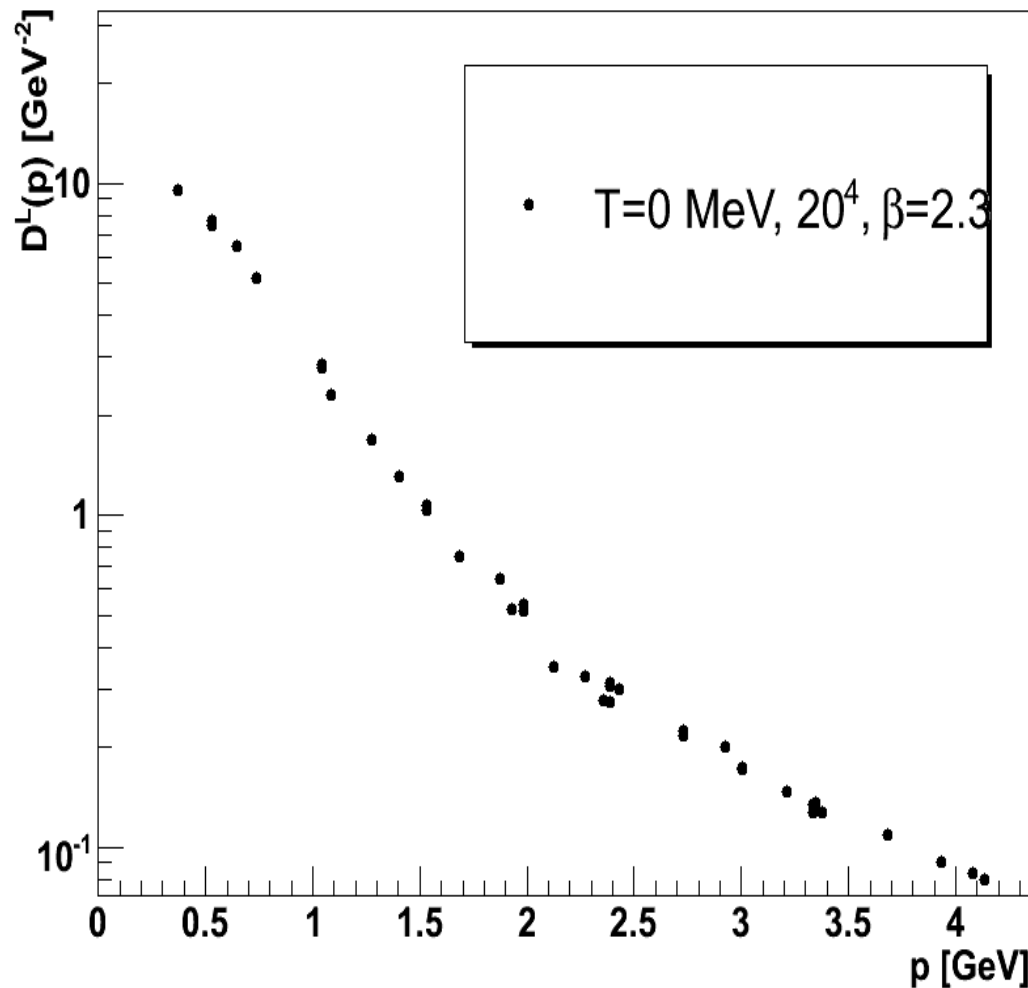
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- **Only valid in Landau gauge**

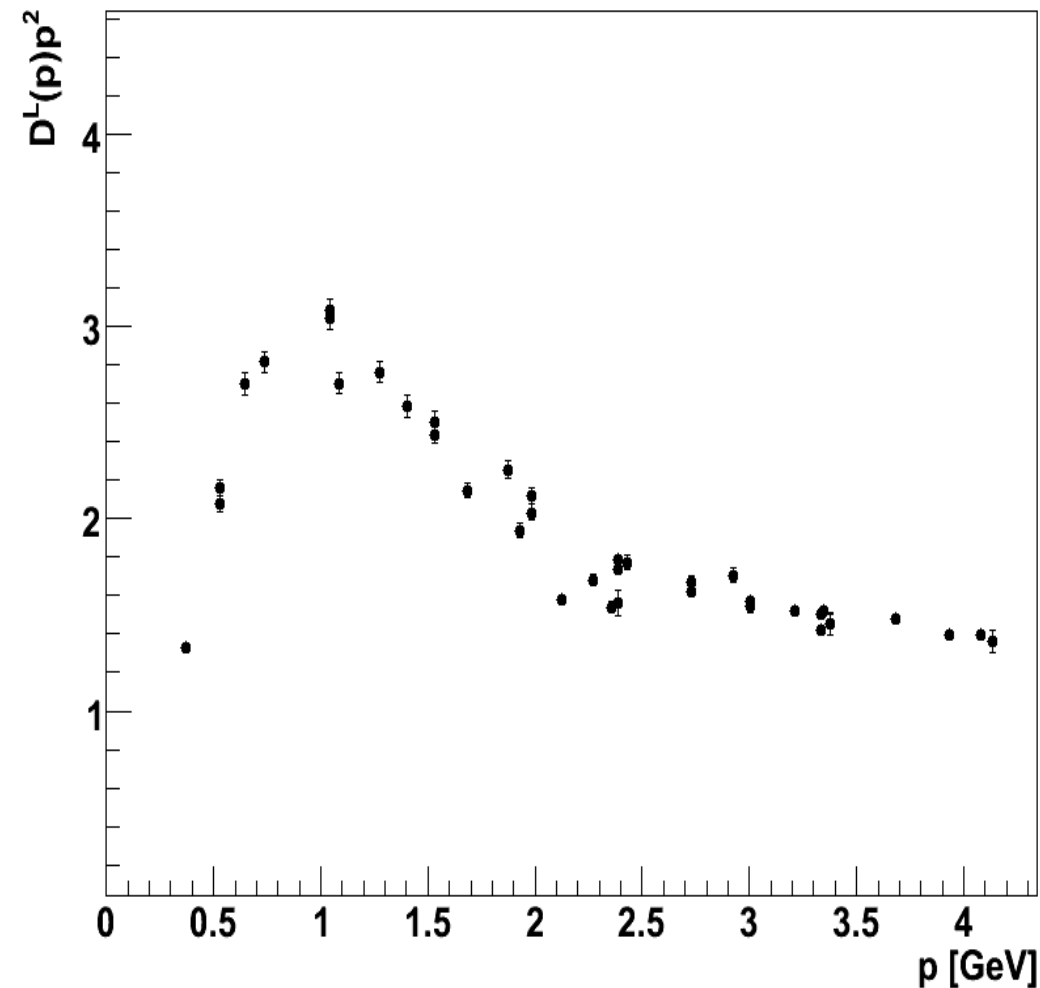
Gluon at finite temperature

[Cucchieri et al., 2006, unpublished]

Longitudinal gluon propagator



Longitudinal gluon dressing function

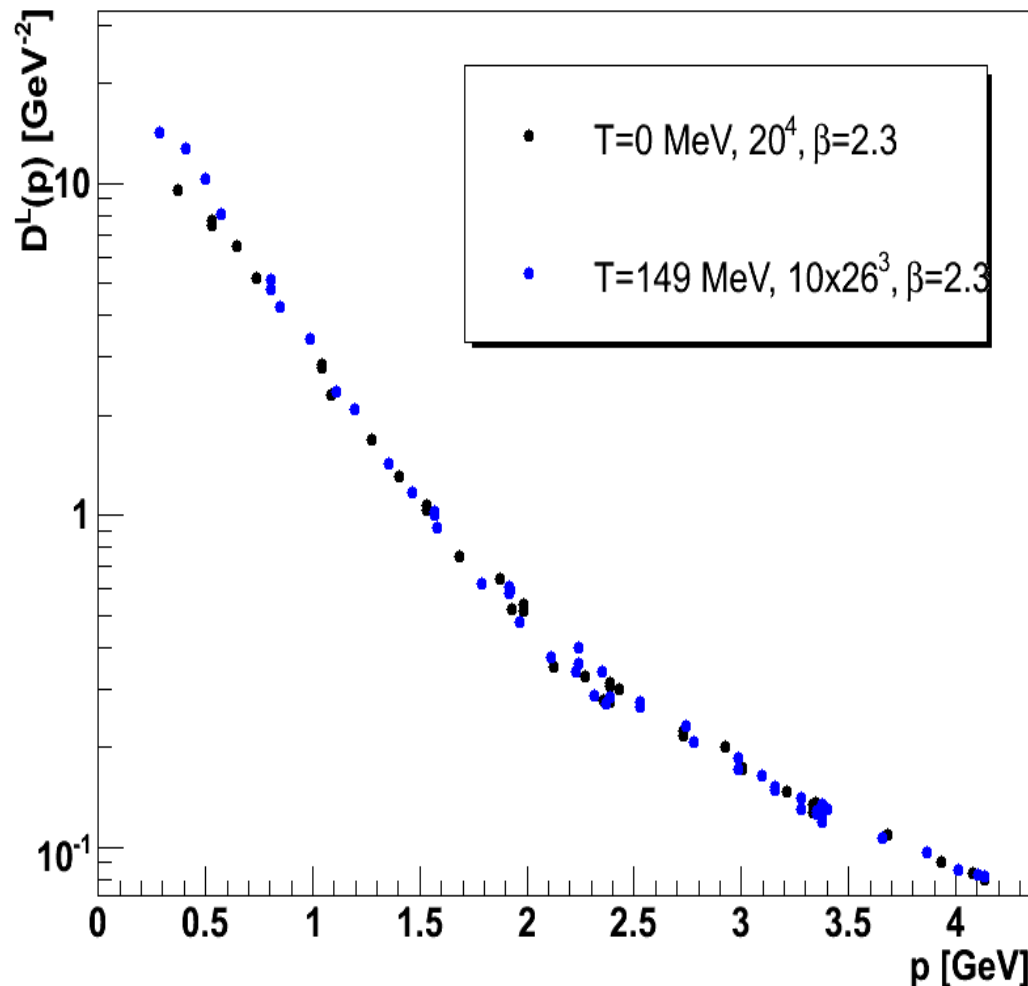


- Infrared suppression not visible - too small volume
- Identical to the transverse propagator

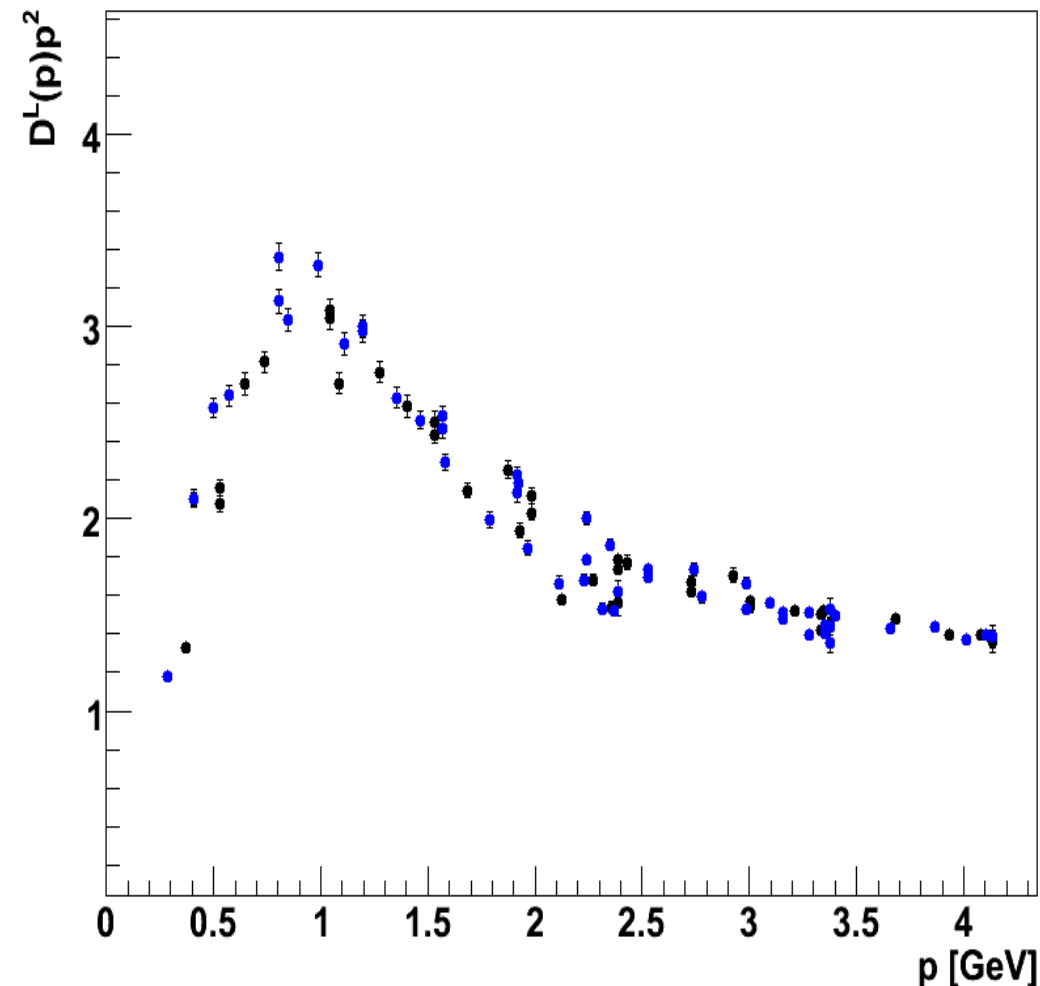
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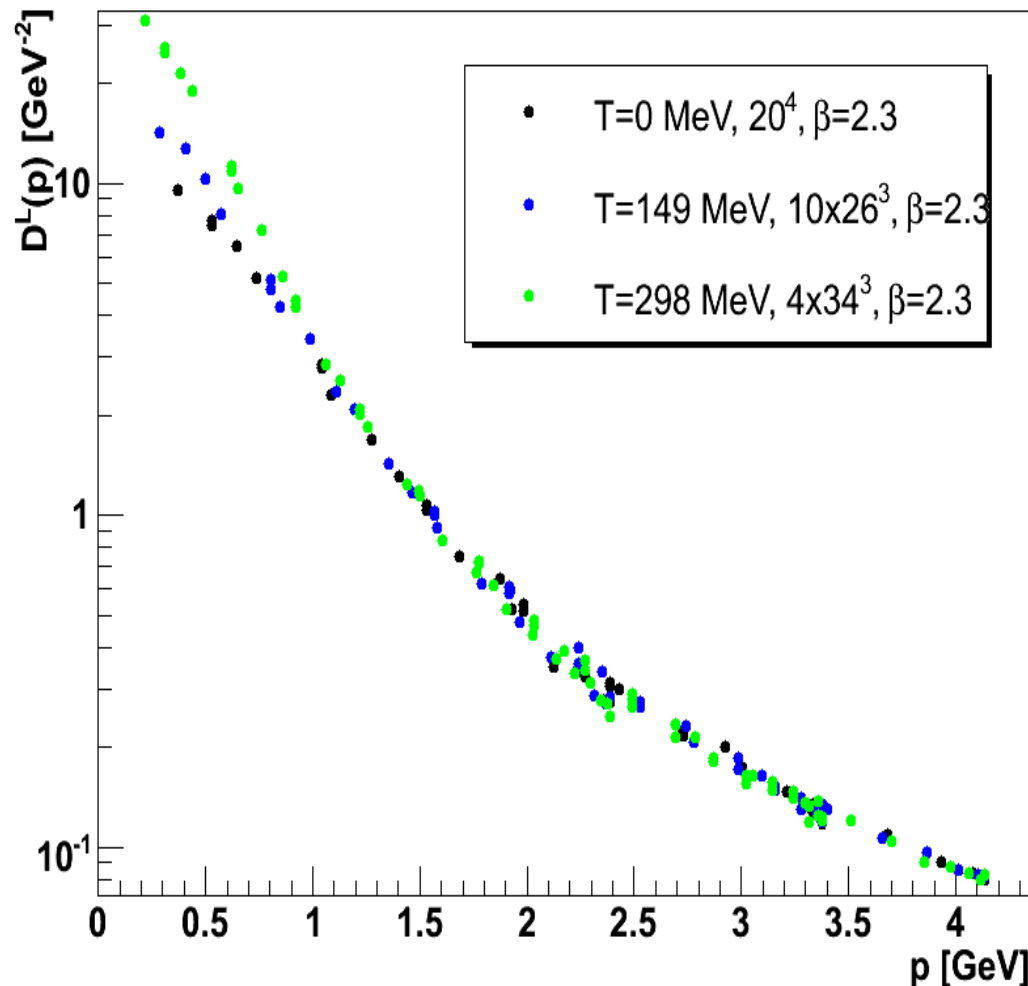


- (Weak) enhancement at small momenta
- Behavior now more similar to a screened object

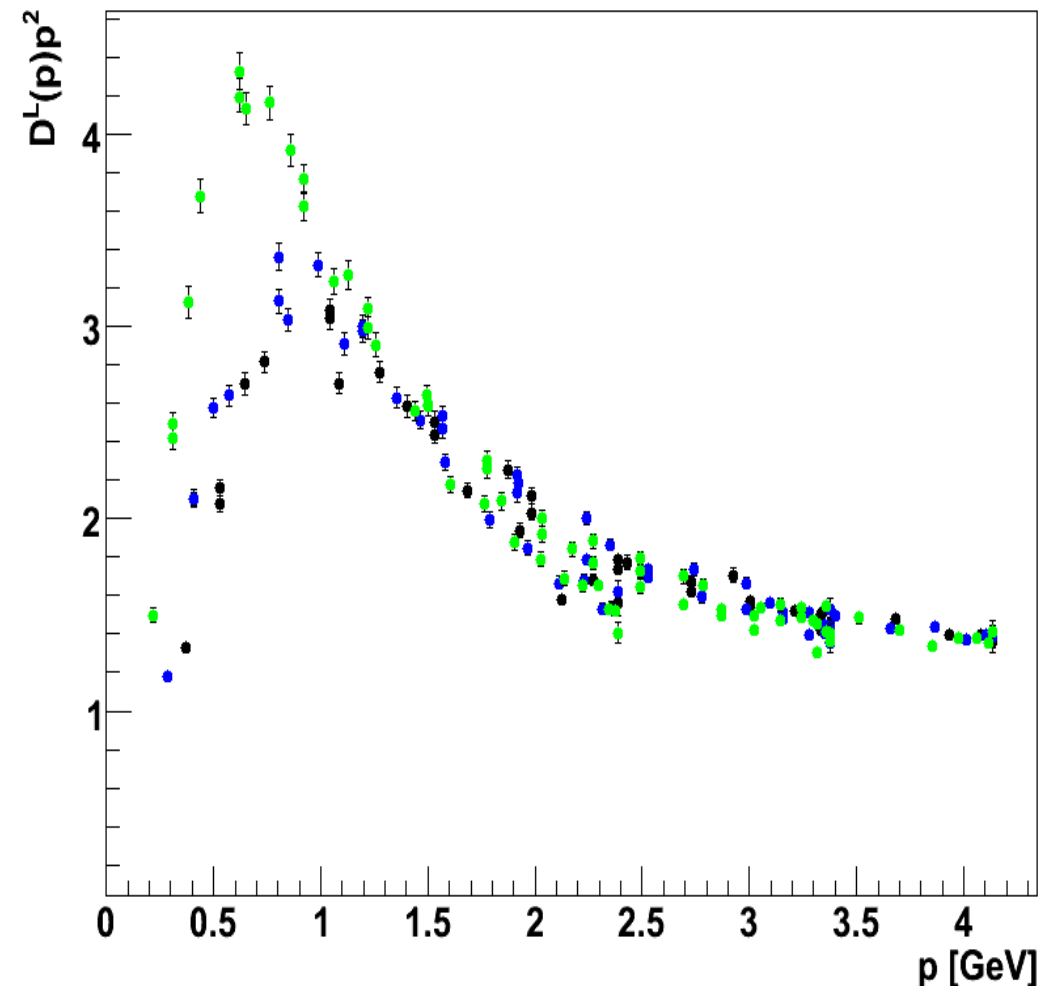
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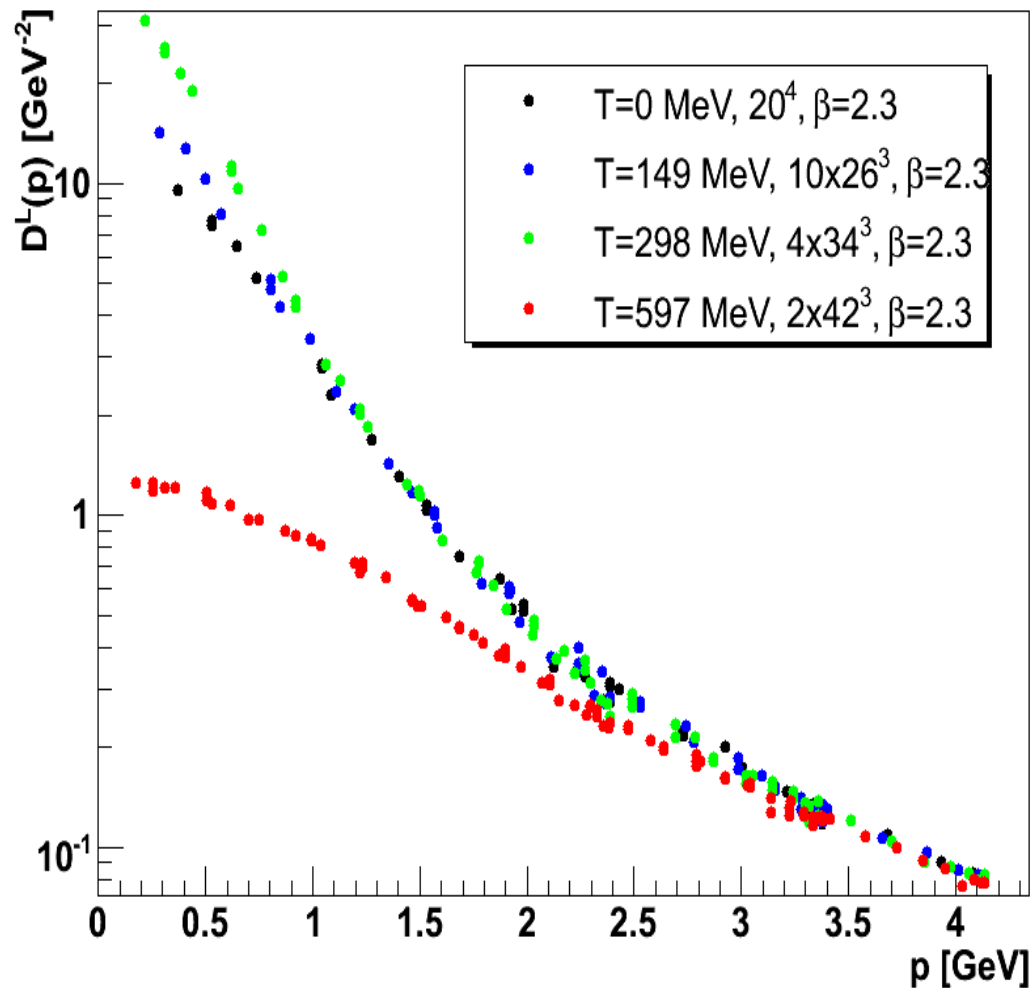


- Strong enhancement just above critical temperature (295 MeV)
- Not a massless like behavior – but strong lattice artifacts

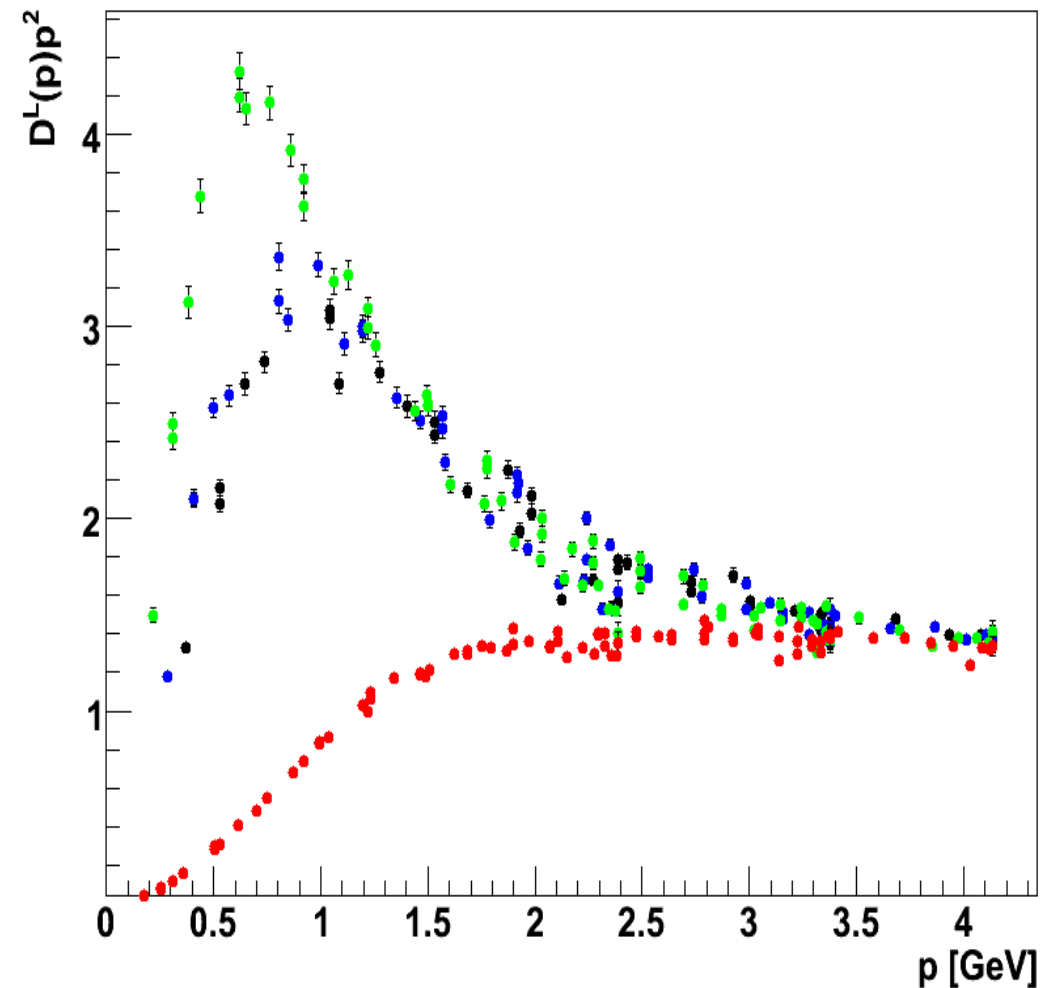
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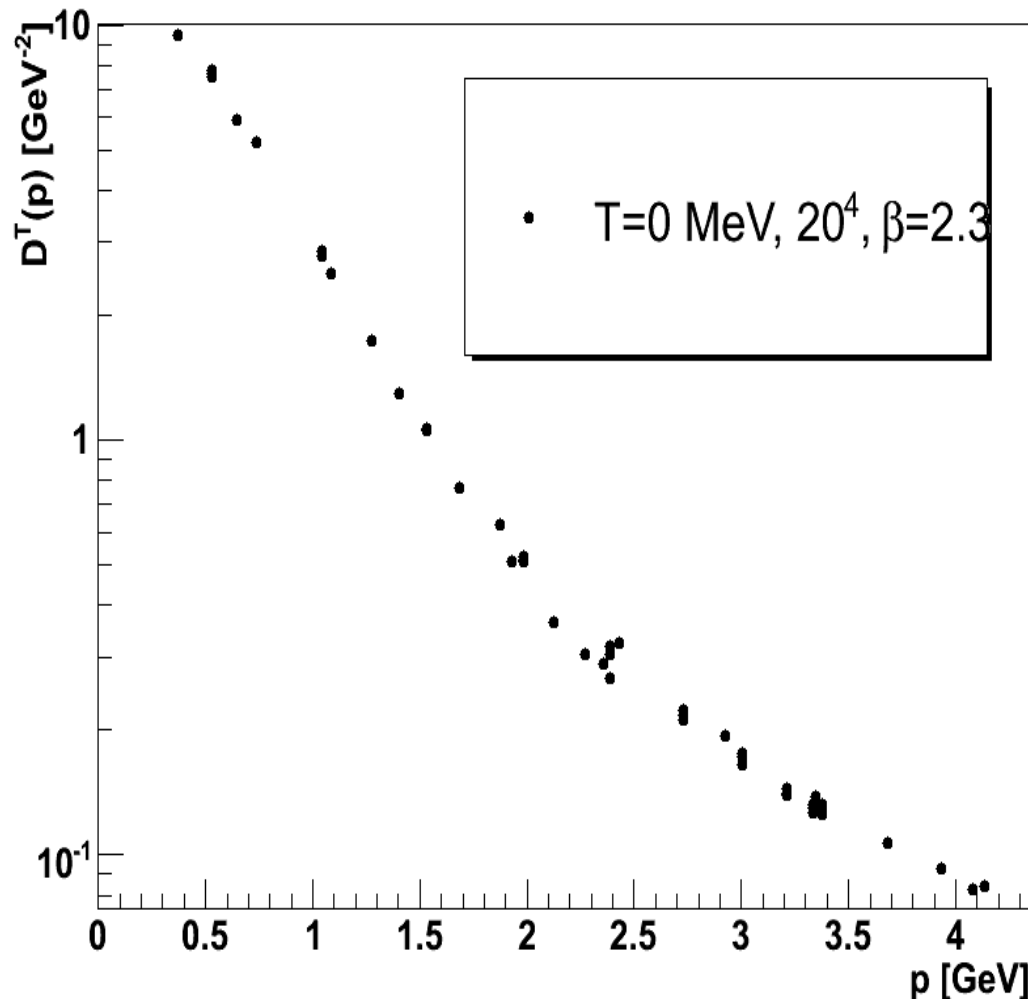


- Infrared suppressed, massive at high (and higher) temperatures
- Possibly strongest infrared enhancement at transition

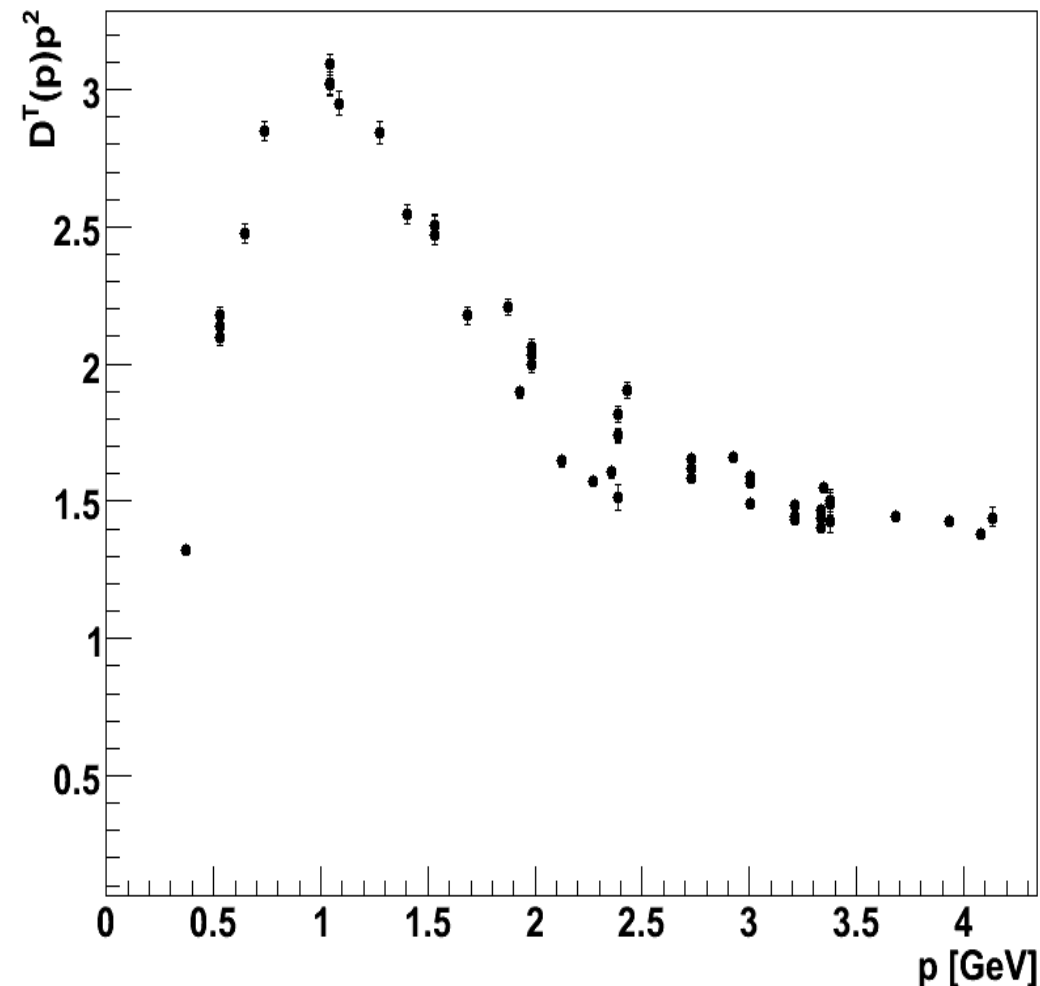
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Transverse gluon propagator



Transverse gluon dressing function

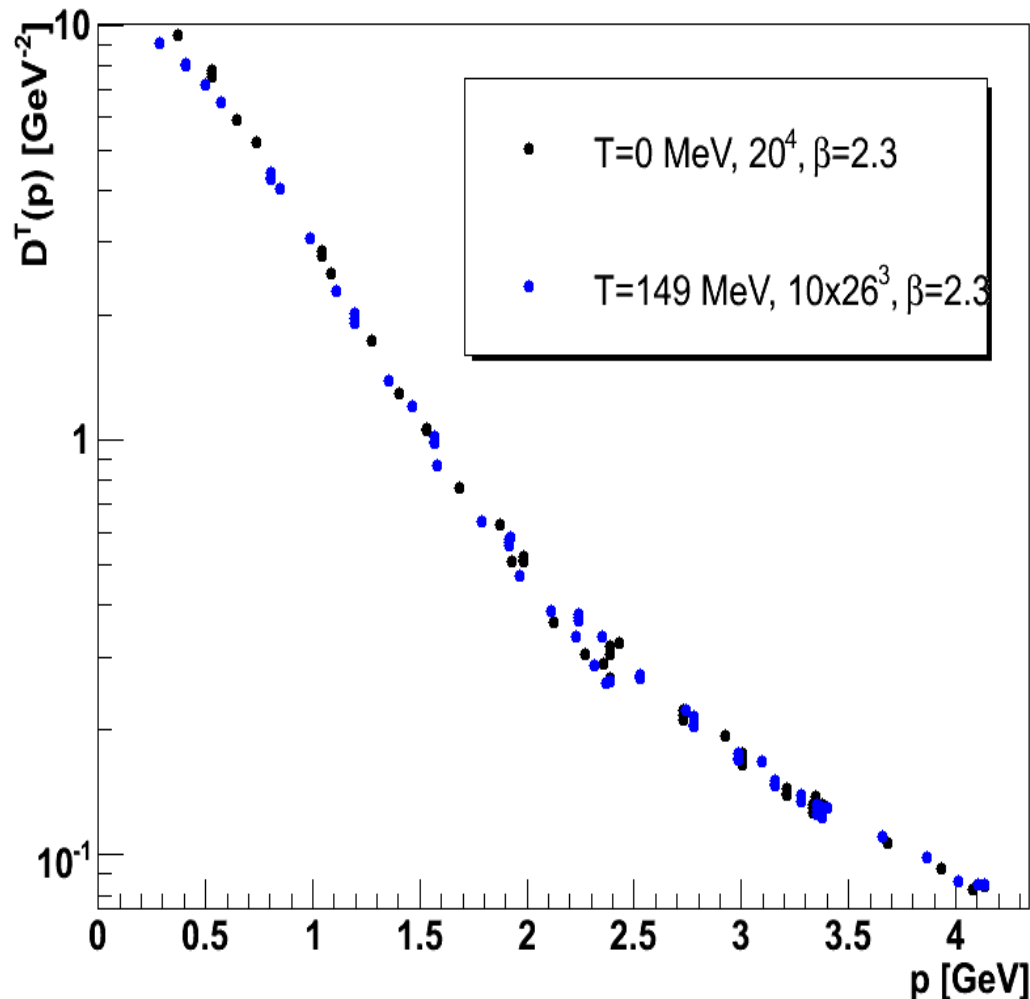


- Identical to 3d-longitudinal one at zero temperature
- Strongly finite volume affected

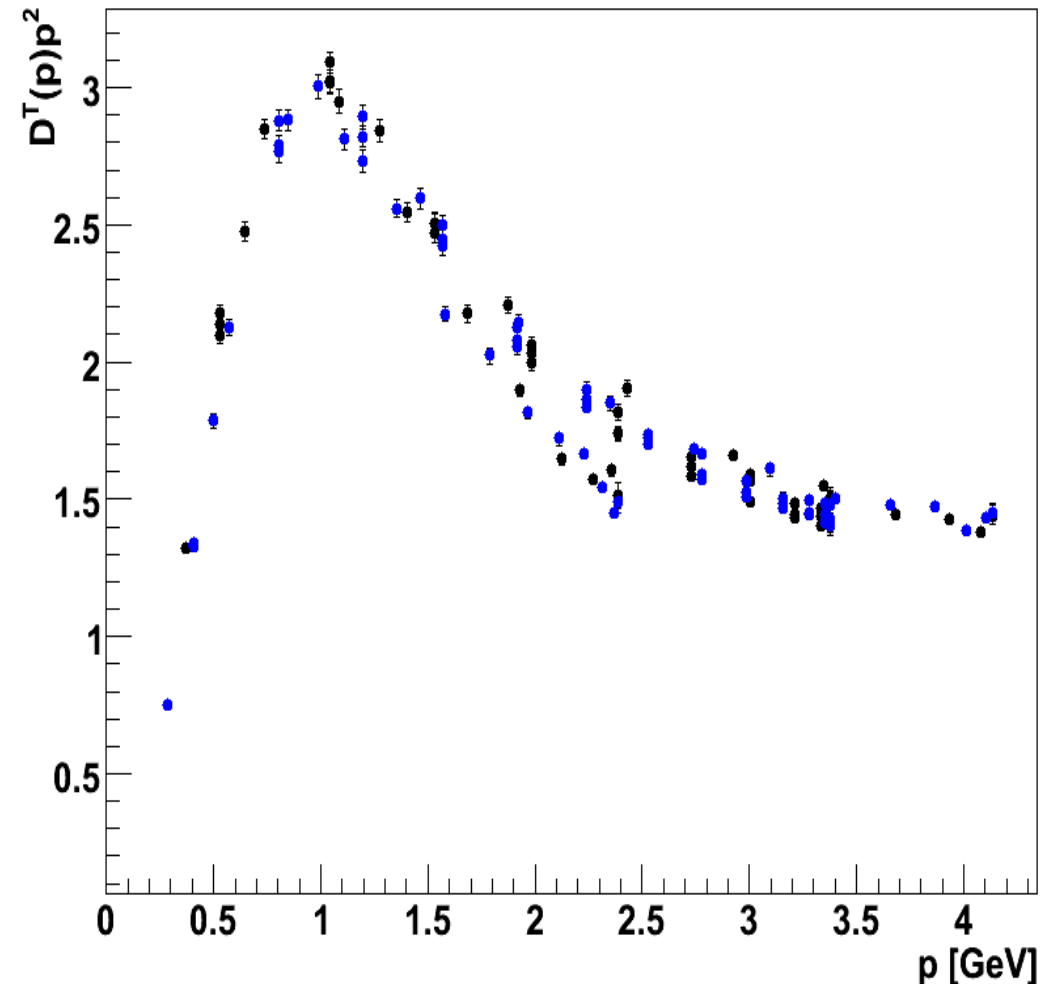
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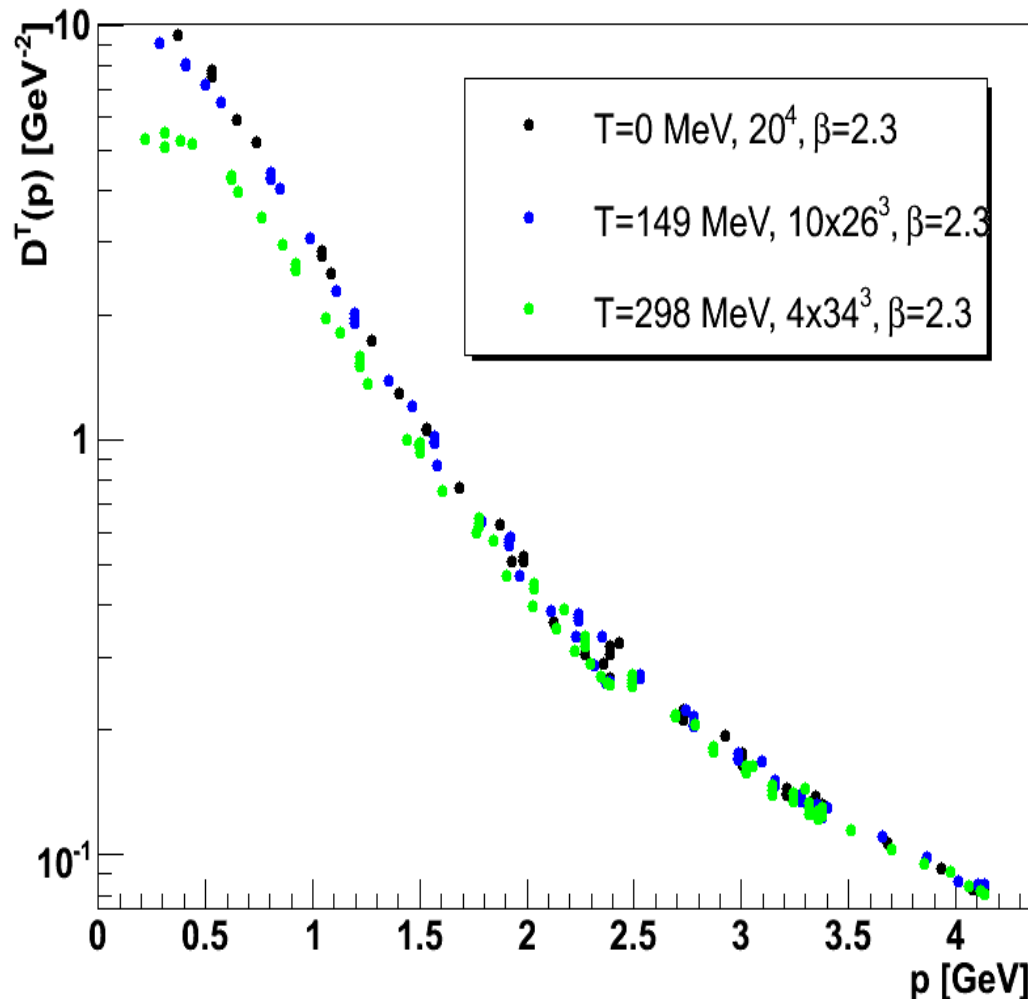


- Stronger infrared suppressed
- Opposite effect as for the 3d-longitudinal part

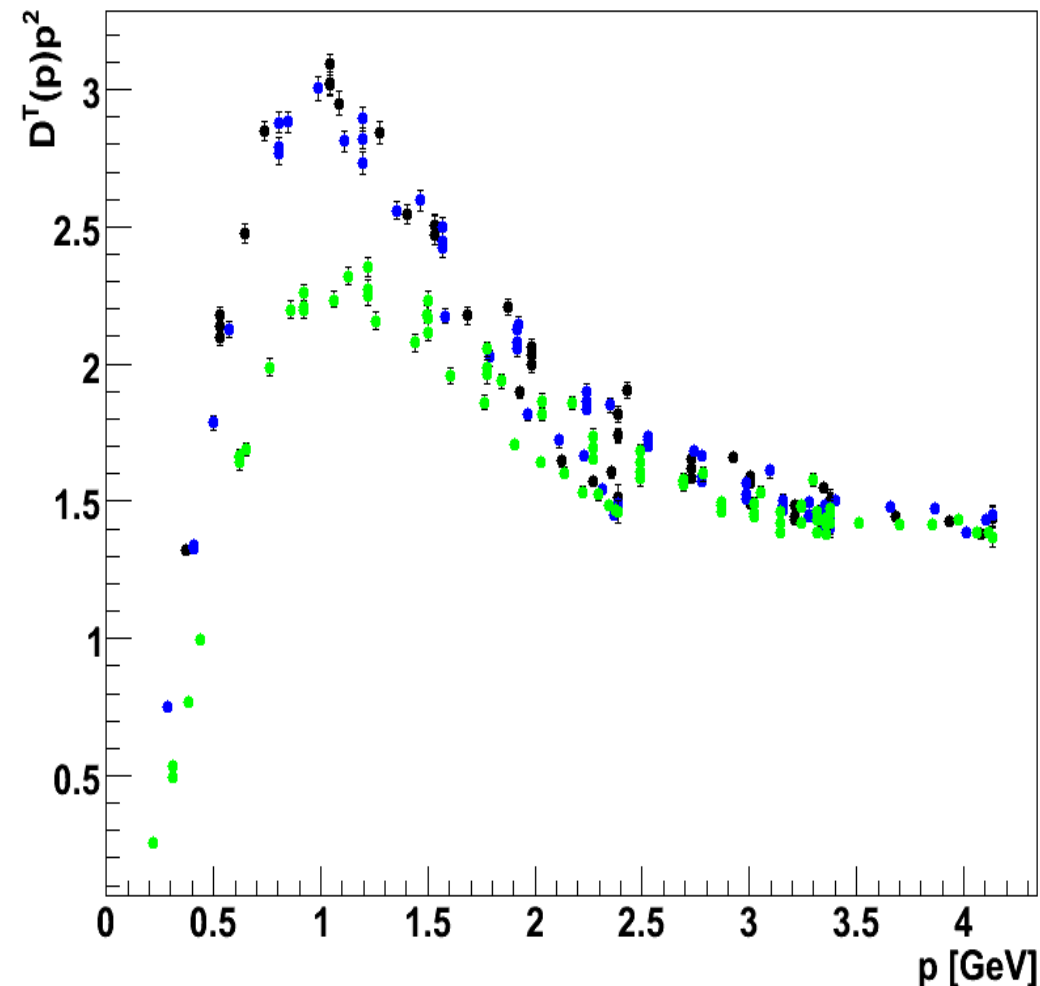
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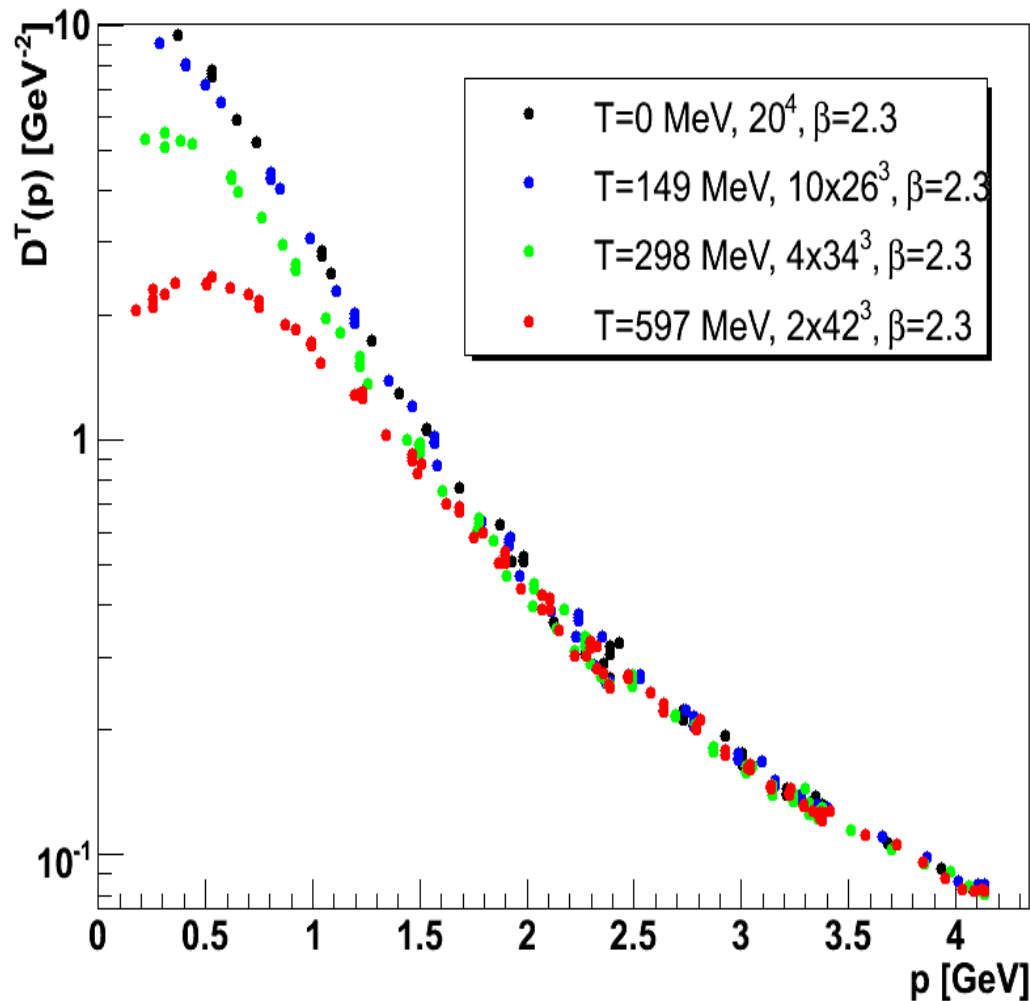


- Continuously stronger infrared suppressed
- No influence of the phase transition visible

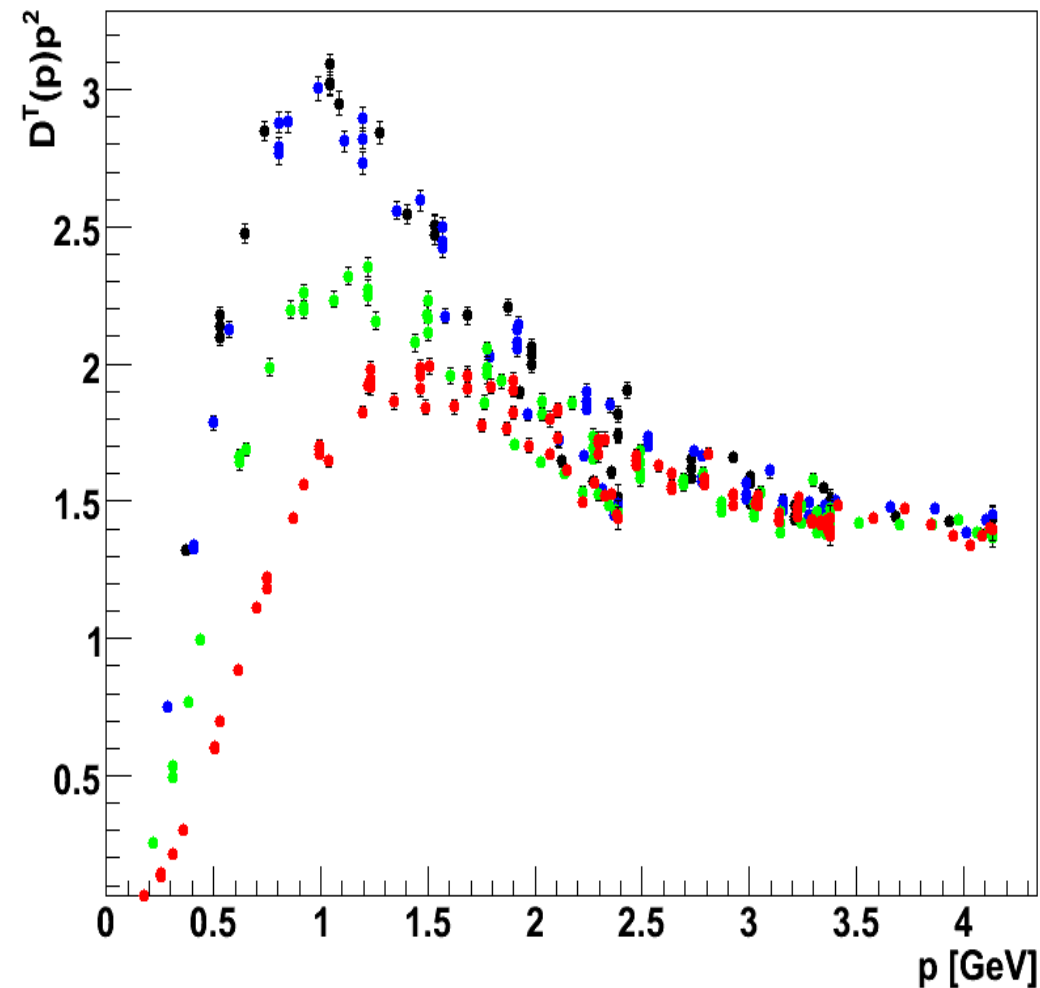
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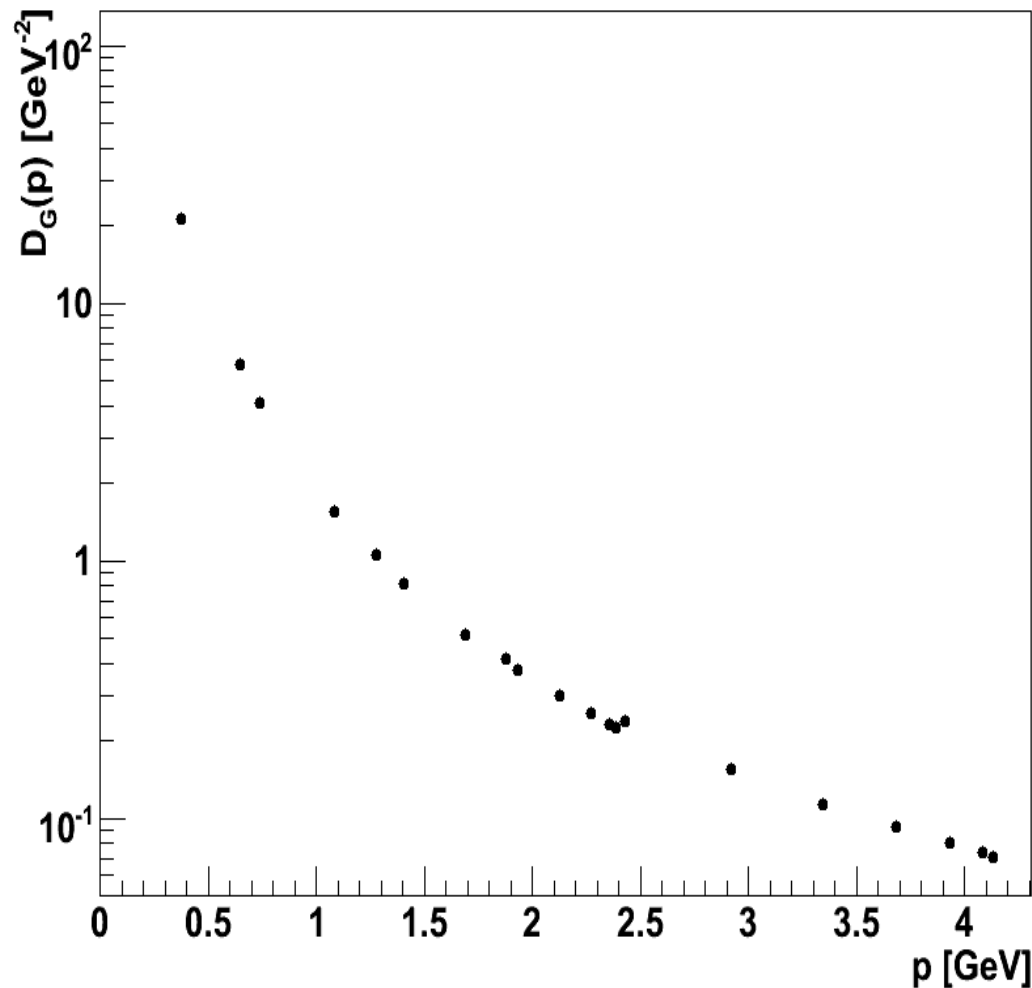


- Clear maximum - stronger infrared suppressed than at zero T !
- Solves the "infrared problem" - invalidates HTL in the infrared

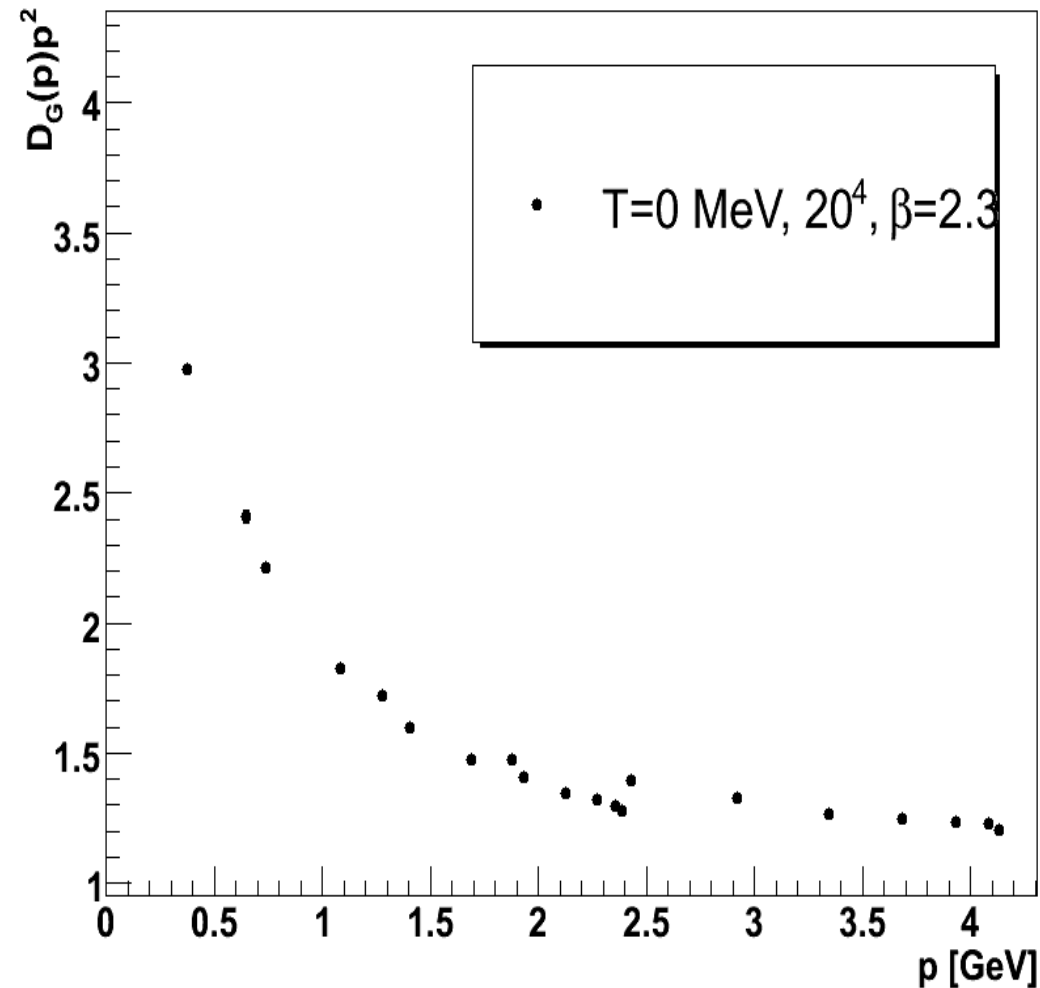
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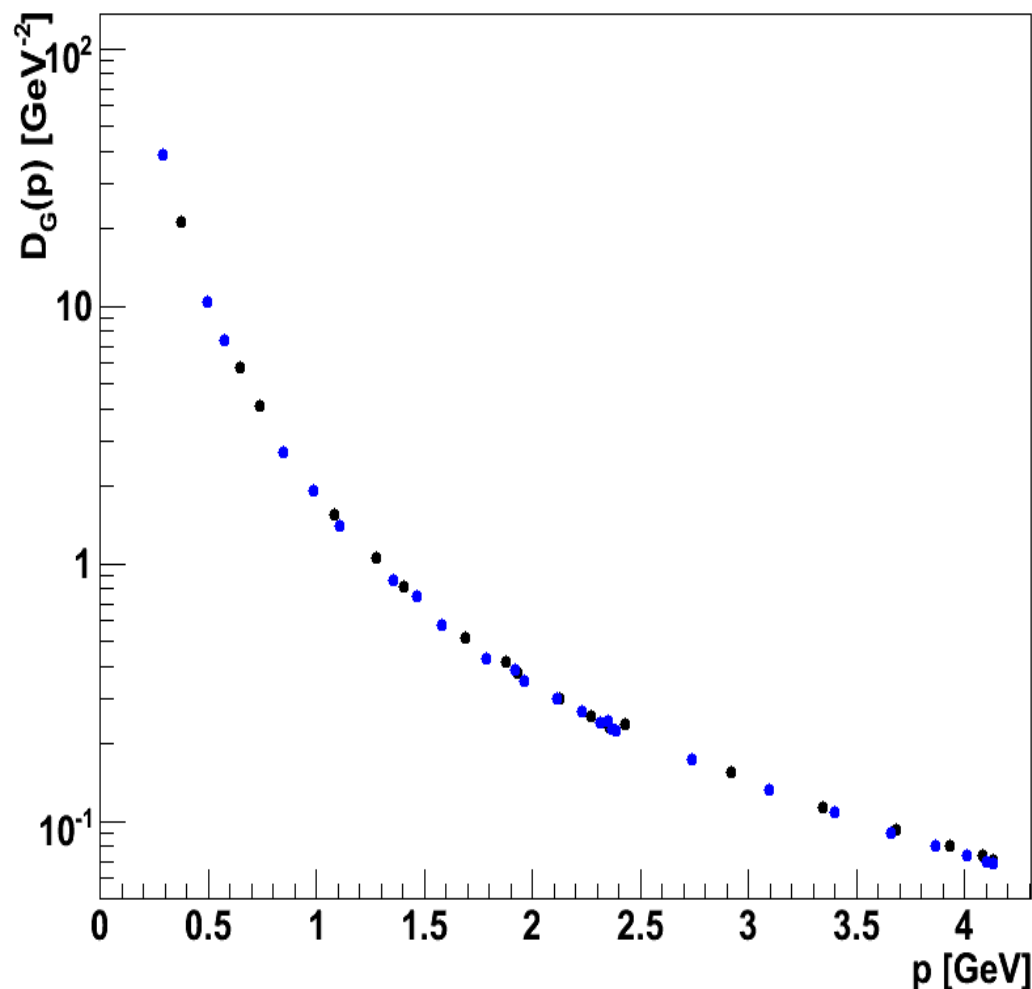


- Infrared enhanced

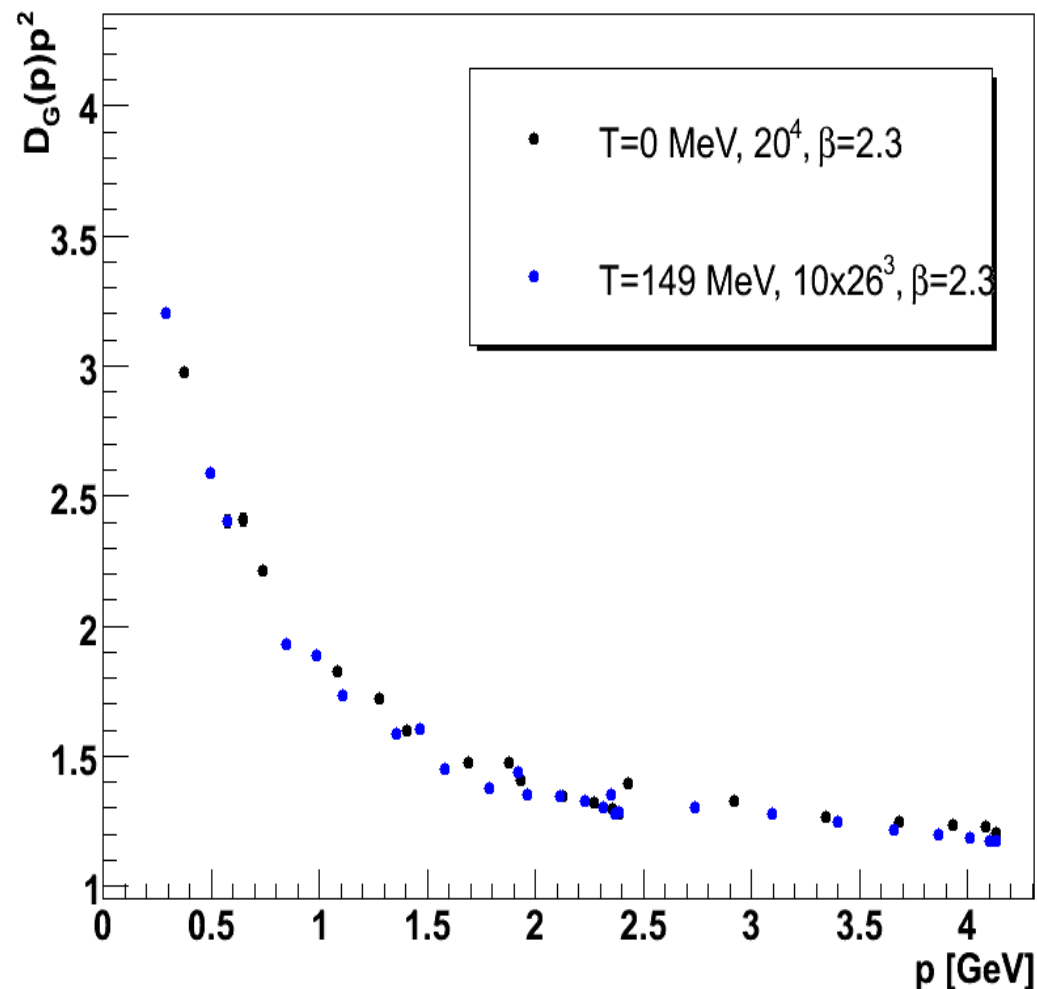
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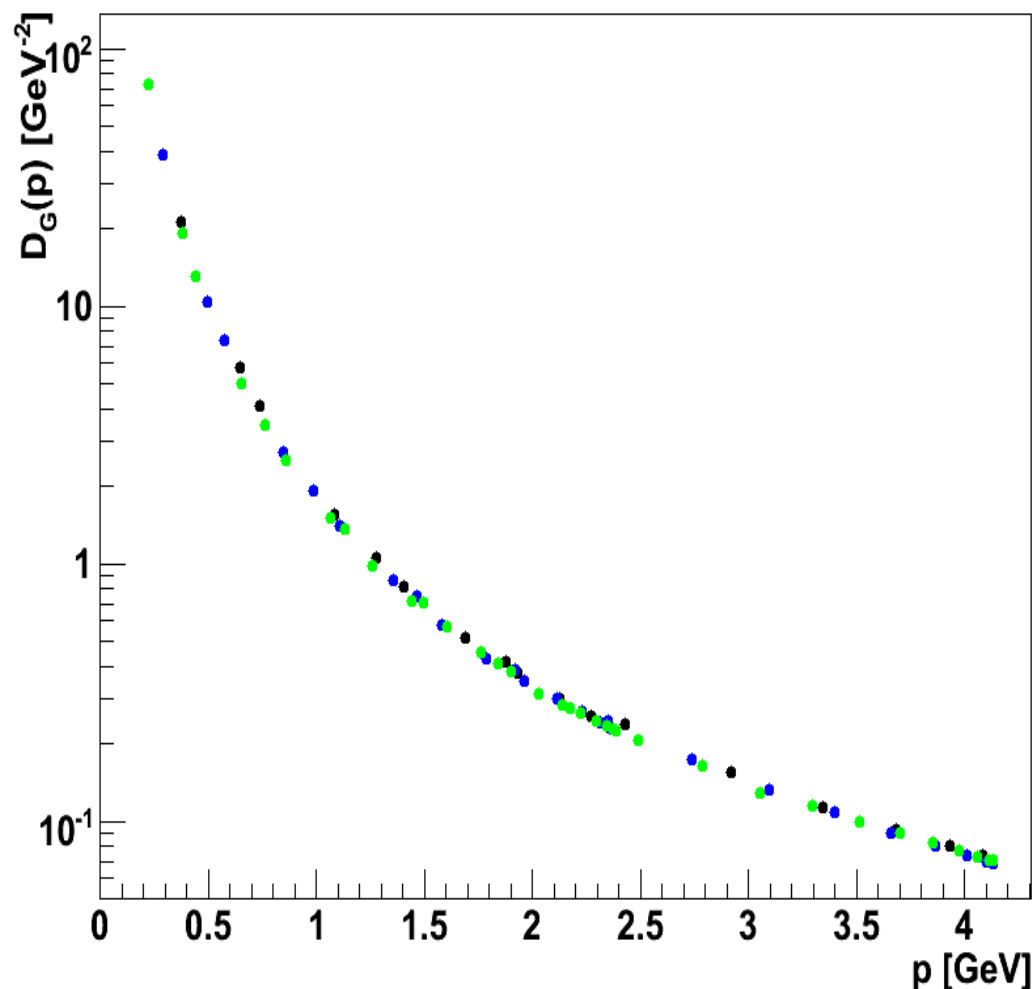


- Essentially unaffected by temperature

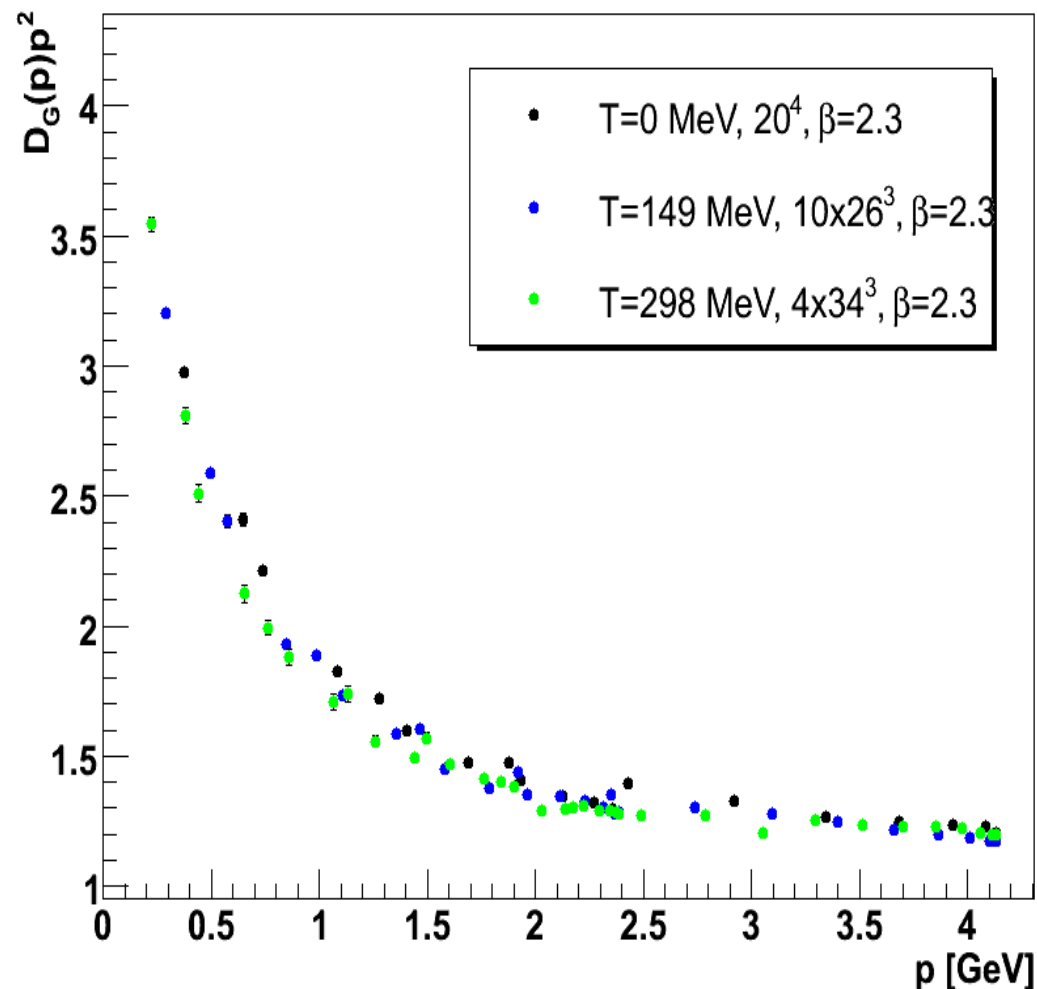
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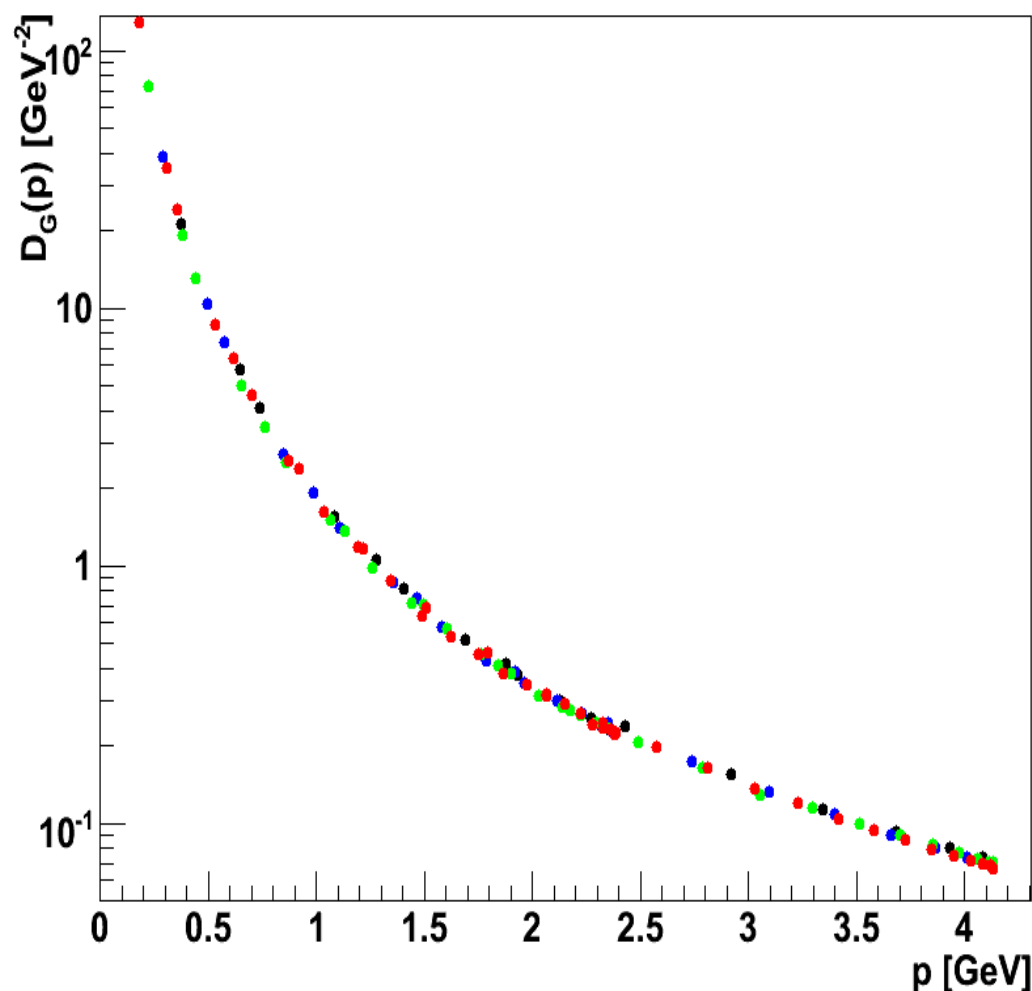


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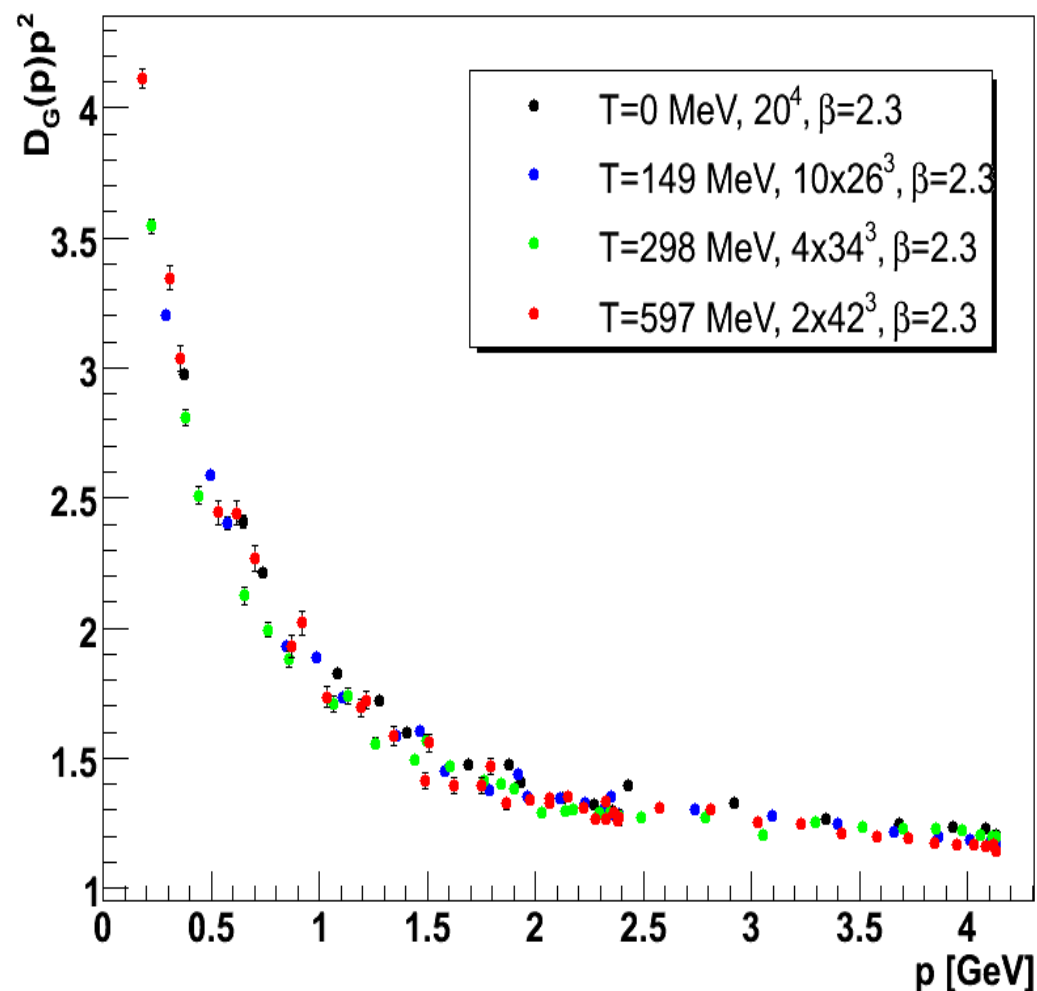
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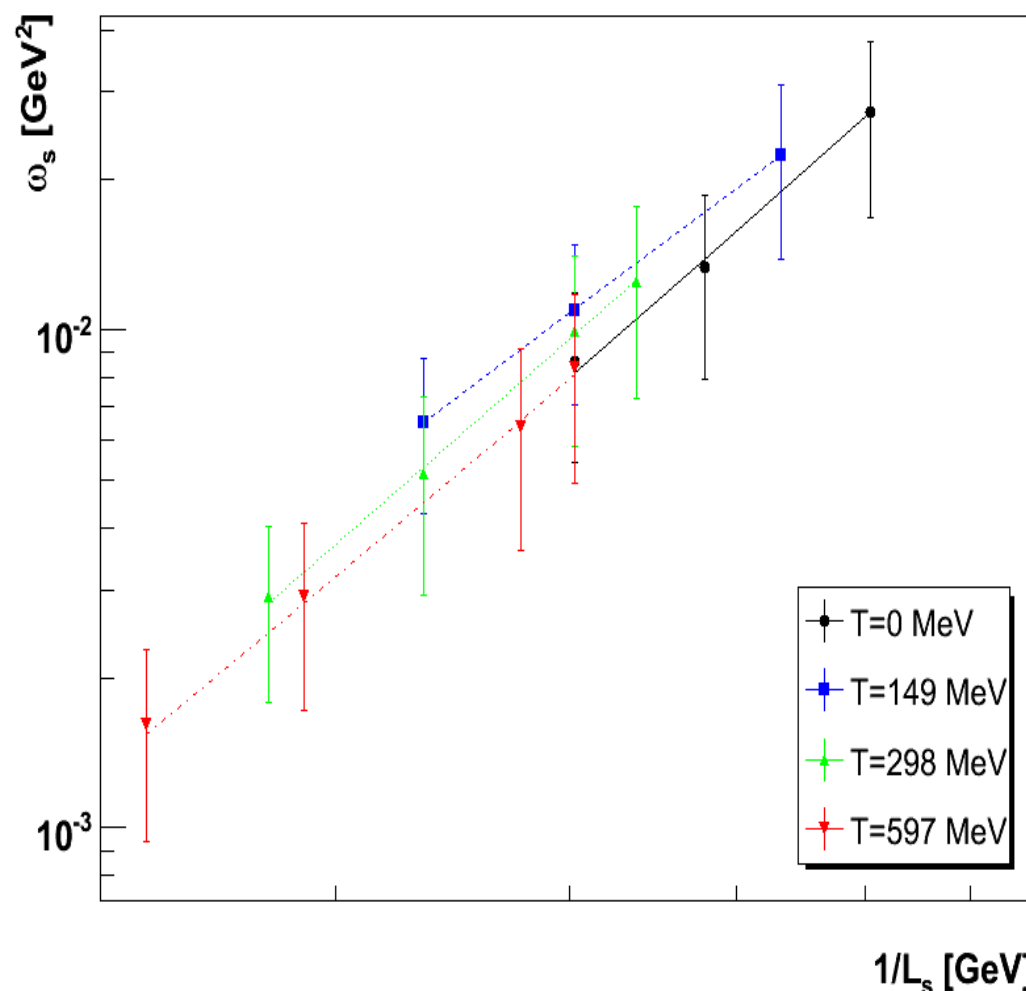
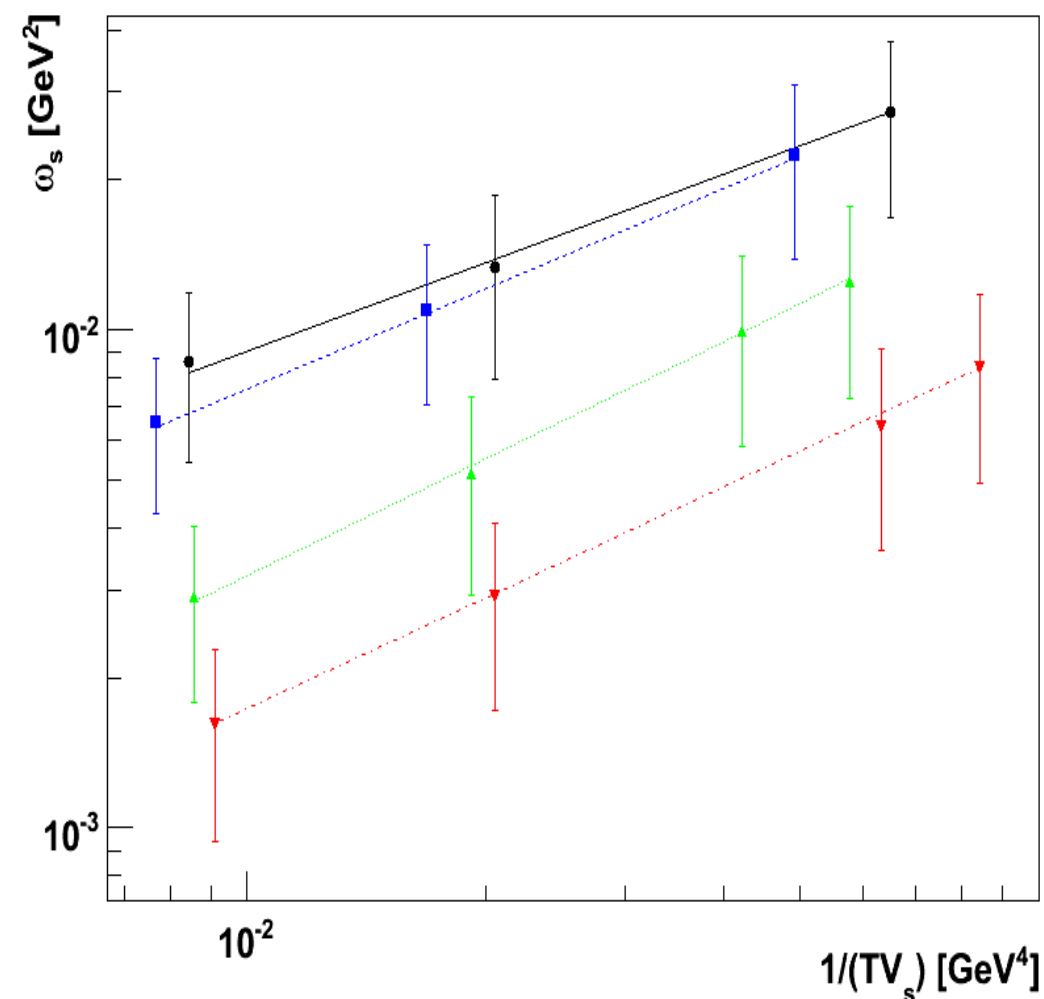
Ghost dressing function



- No change resolvable on current lattices
- No temperature effect at large momenta

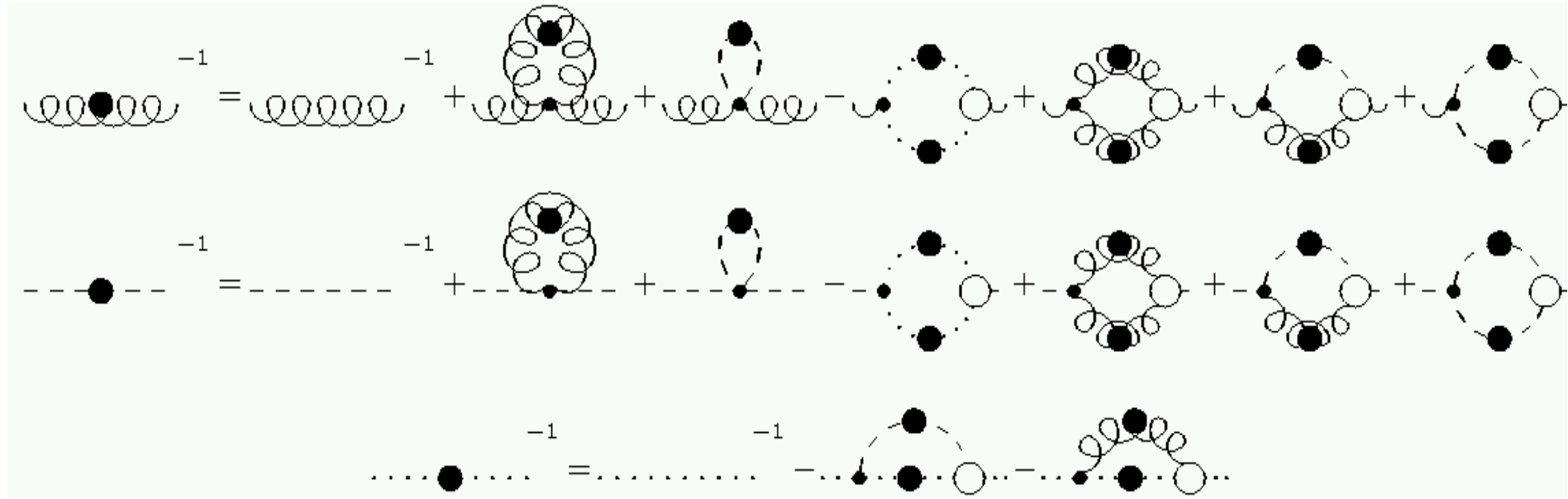
The lowest FPO-eigenvalue

[Cucchieri et al., unpublished]

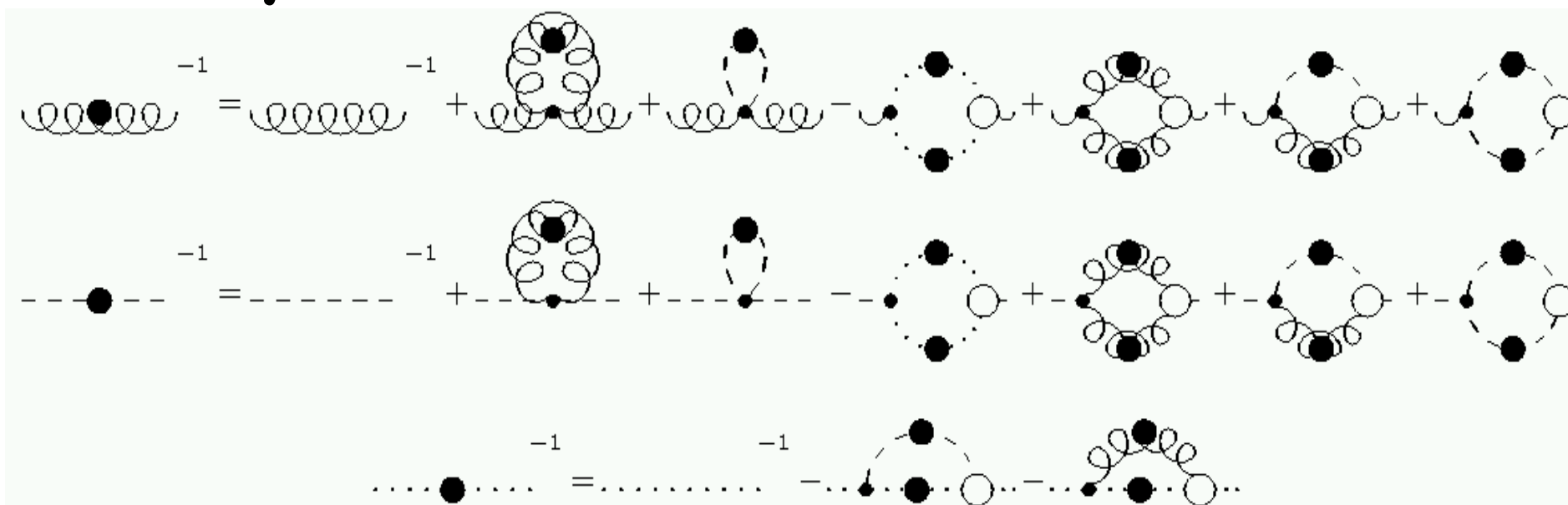
Dependence of the smallest FPO-eigenvalue on L_s Dependence of the smallest FPO-eigenvalue on TV_s 

- Qualitatively unaltered by temperature
- Quantitative effects only in the temporal sector

DSE-System

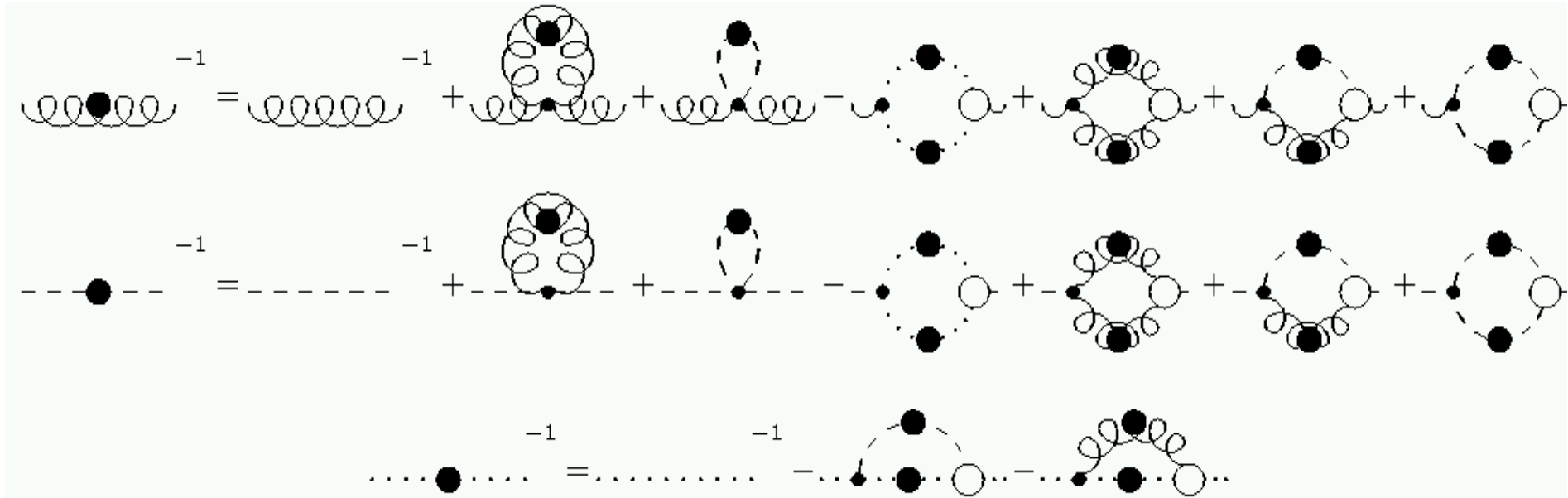


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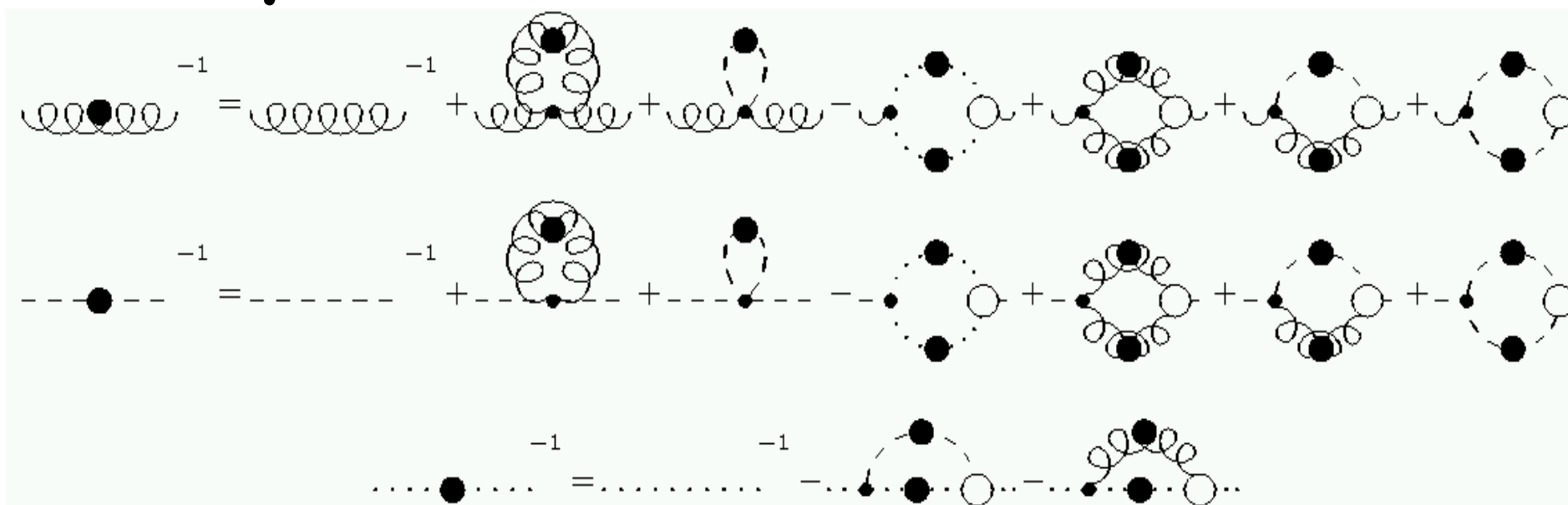
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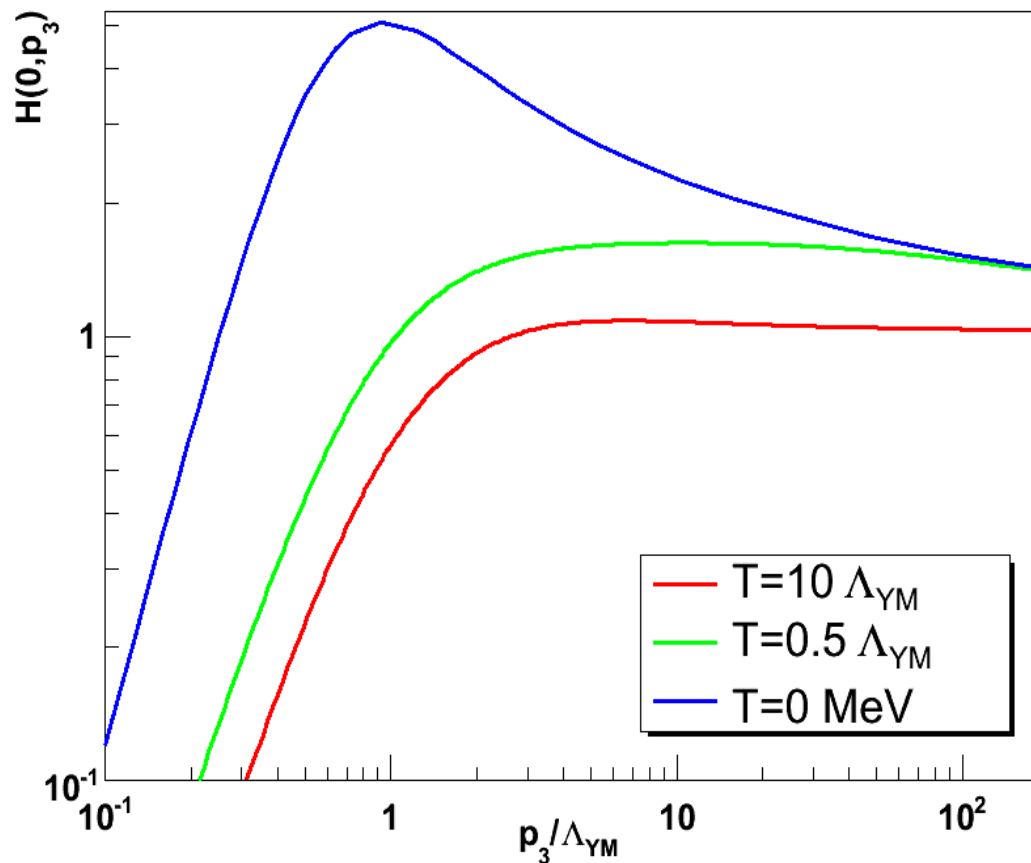
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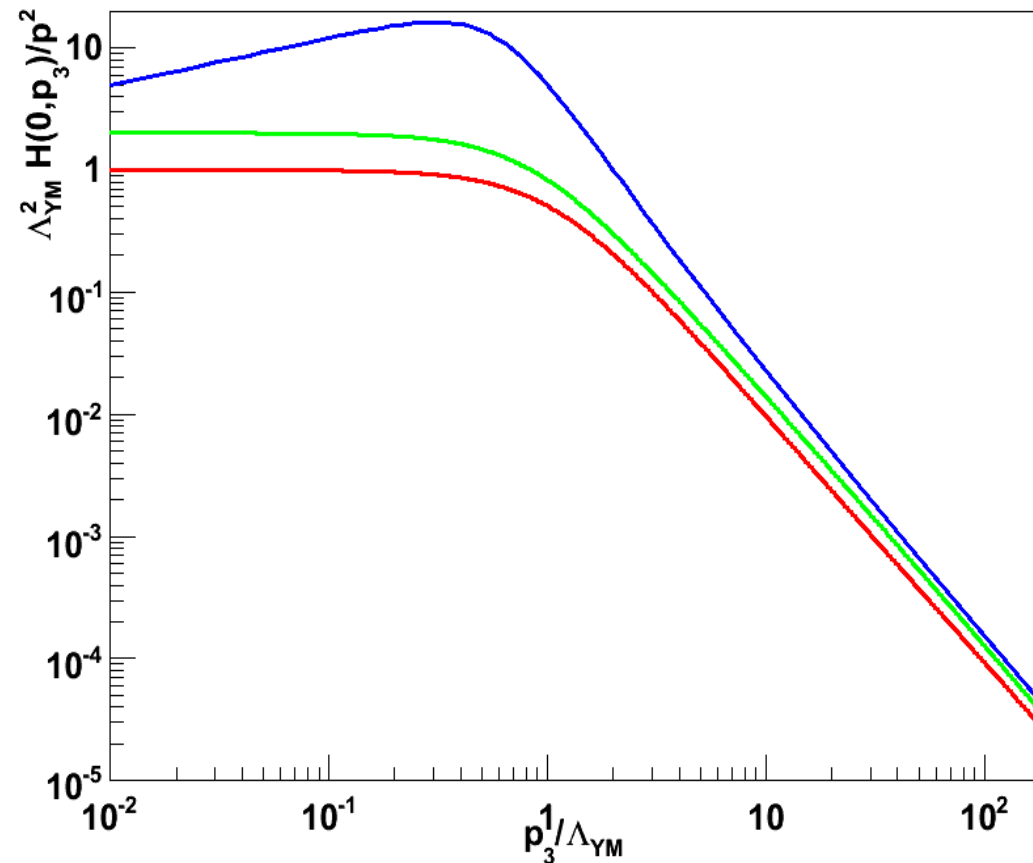
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3d-longitudinal gluon dressing function



3d-longitudinal gluon propagator

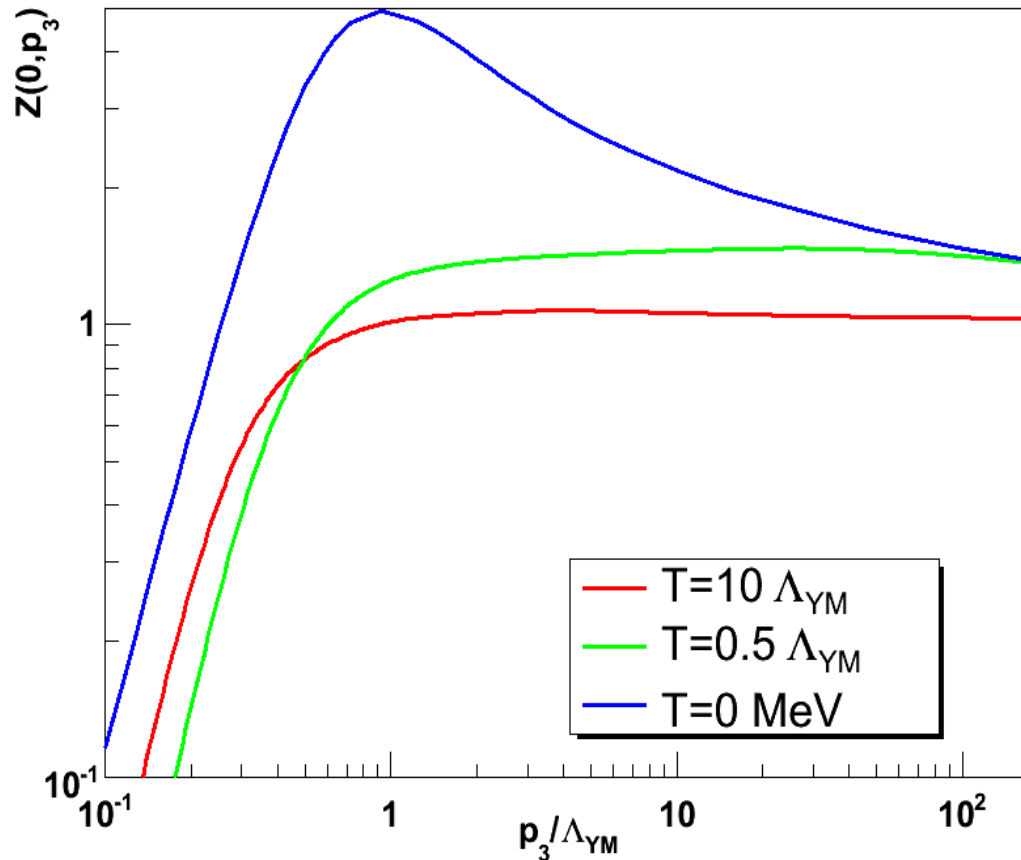


- Acquires a screening mass
 - Value cannot be determined

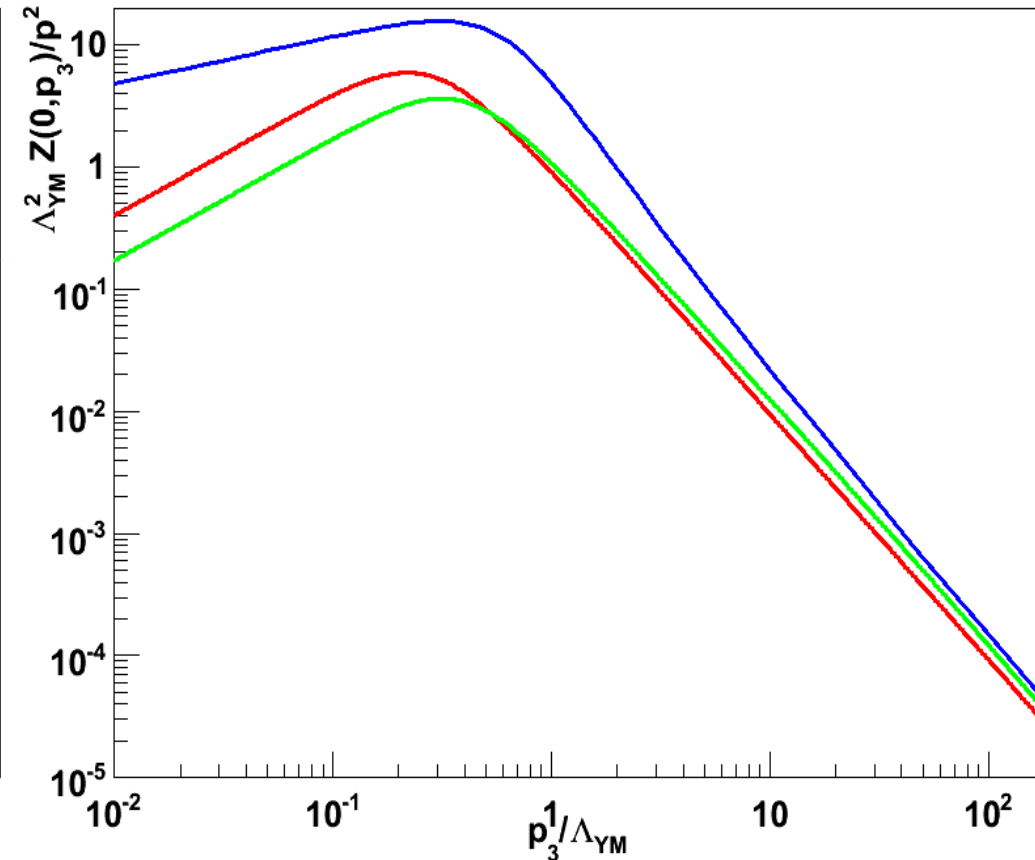
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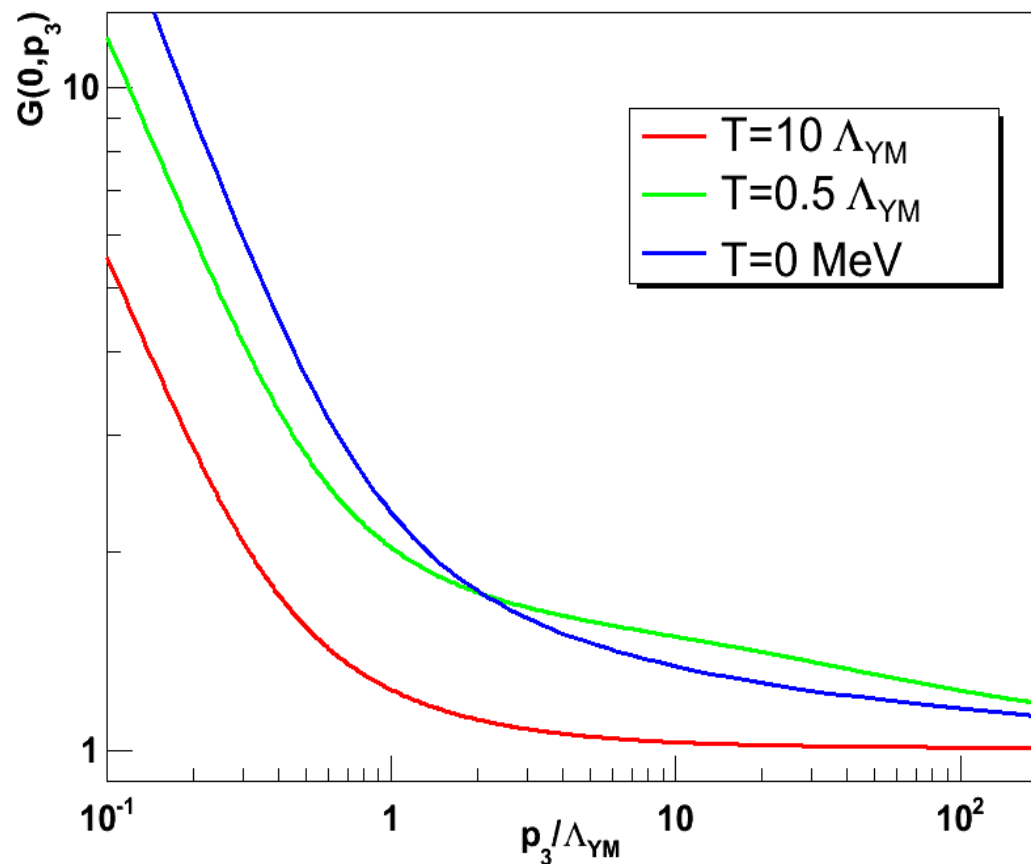


- Infrared suppressed – vanishing at zero momentum
 - 3d-like behavior: Stronger suppression than at zero temperature – as on the lattice

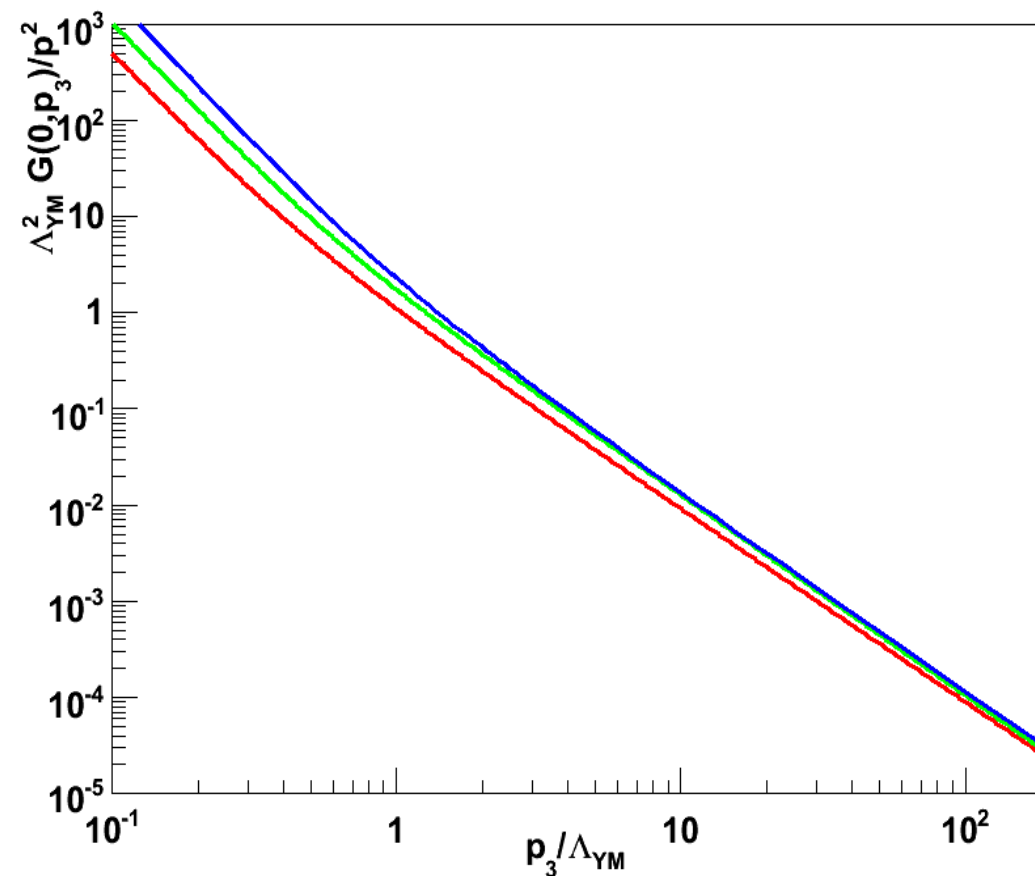
Ghost propagator

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Ghost dressing function



Ghost propagator



- Infrared enhanced at all temperatures
 - Enhancement as in the 3d-theory

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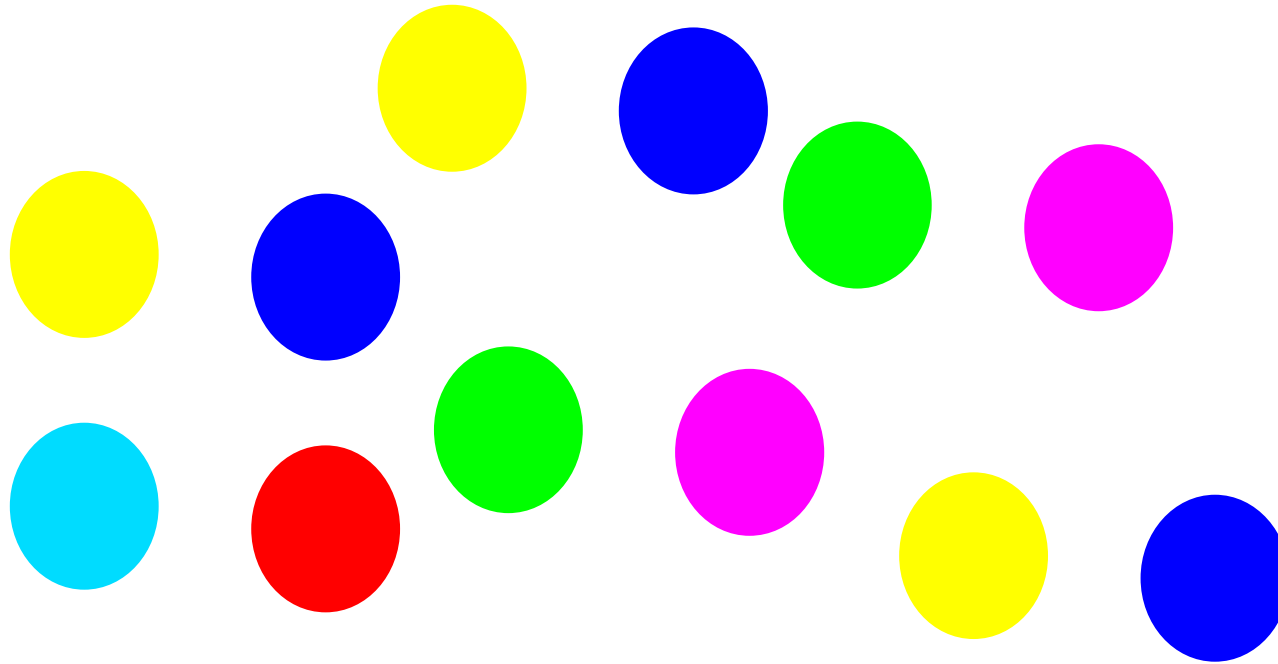
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- **No gluons in the physical spectrum at all temperatures** - independent of the phase transition

Picture of the high-temperature phase

- How does the high-temperature phase look?

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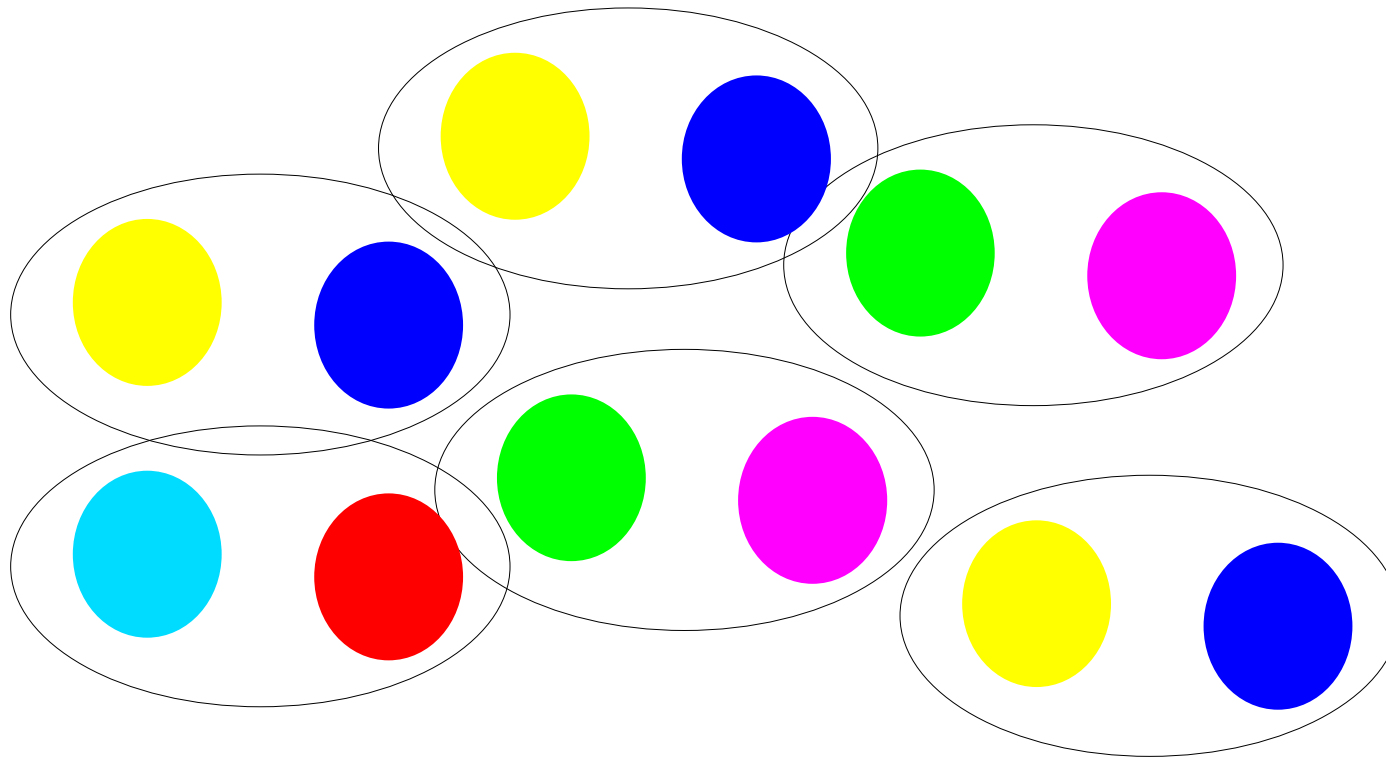
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- Original idea: Gas of non-interacting constituent gluons

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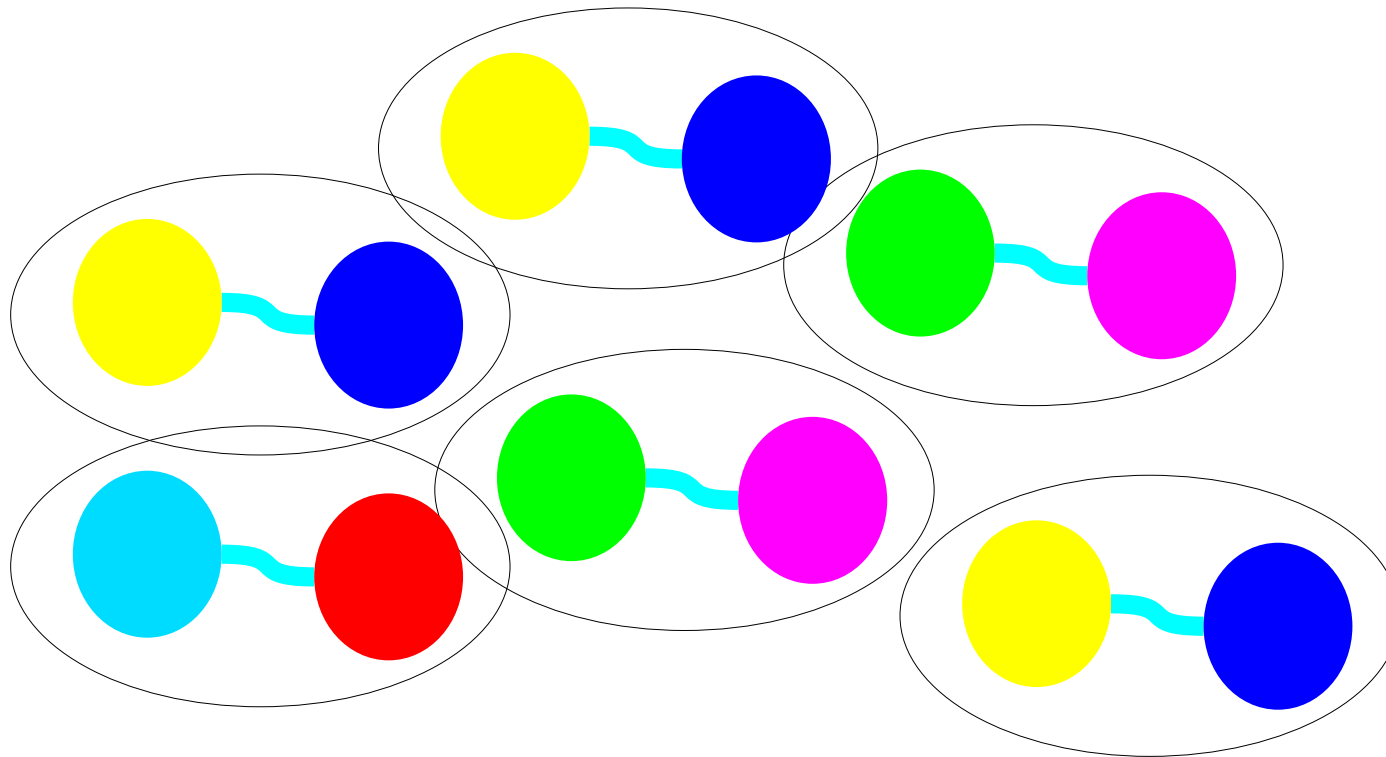
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- But these are confined - only glueballs observable
- The glueballs may overlap?

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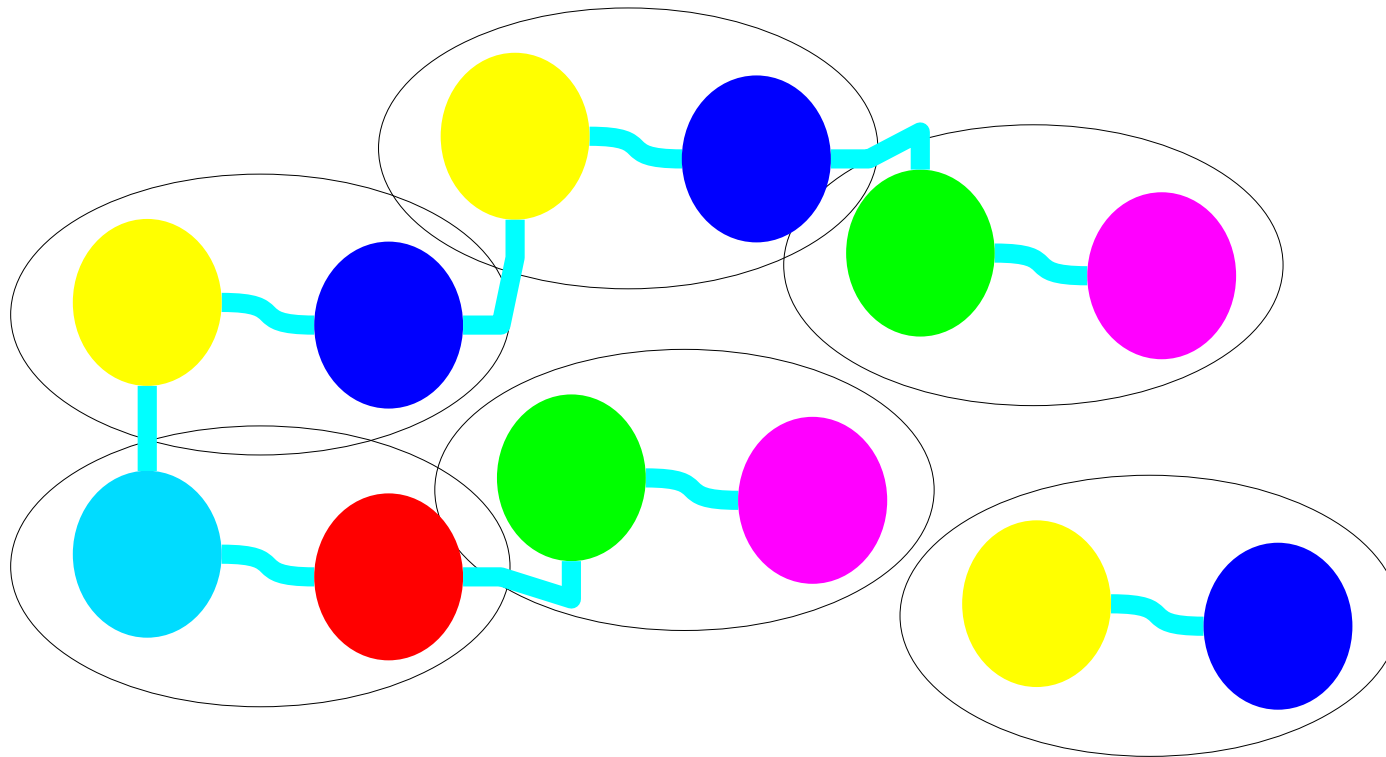
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- Constituent gluons have to interact via gluon exchange

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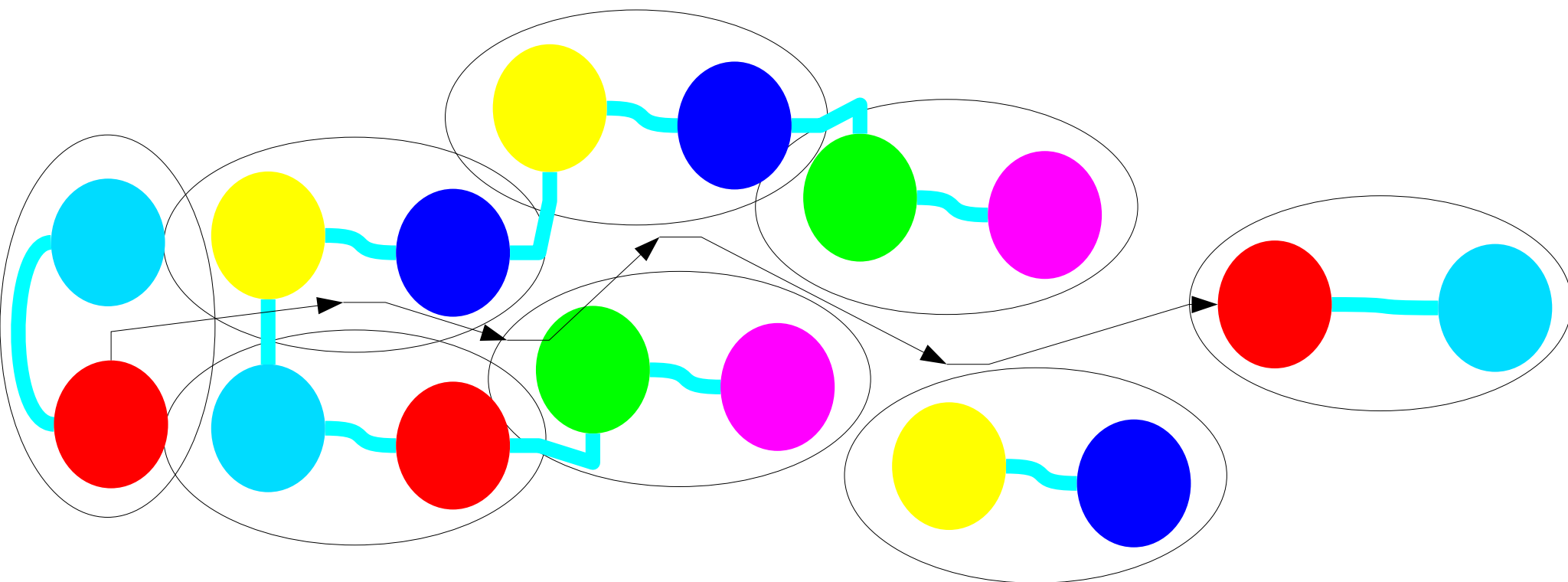
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- If glueballs overlap, they may form glue-bridges
- No distinct, stable bound-states

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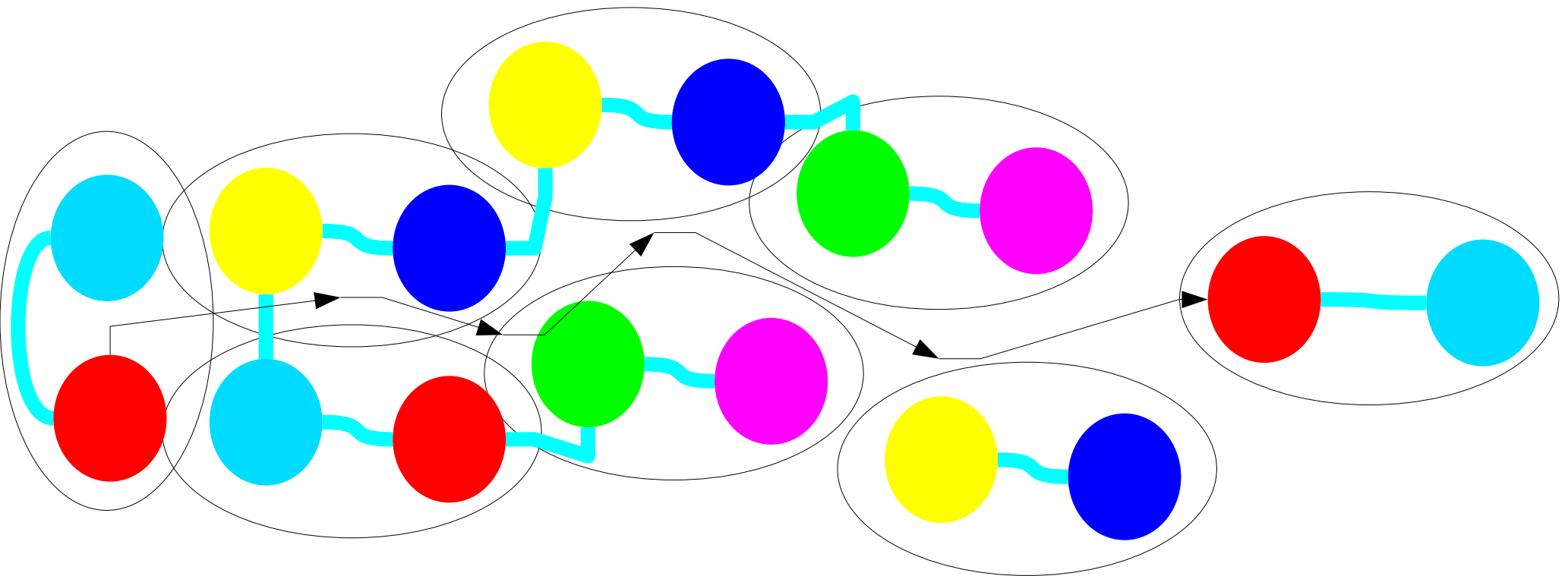
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- This permits long-distance travel of constituent gluons by exchange processes - may make behavior similar to free constituent gluons

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- Strongly interacting molecular liquid with constituent-exchange - but constituents unobservable

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- **High-temperature limit of bulk quantities unaffected** [Maas et al., EPJC 2004, Zwanziger PRL 2004, 2006]
 - Thermodynamic potential, pressure, ... reach Stefan-Boltzmann limit
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- **Contributions relevant at the phase transition**
 - E.g. relevant for the interaction measure [Zwanziger, PRL 2004, 2006]

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 - Unknown. If you like speculations: Look at glueballs

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