Romain Contant
Advisor : Markus Q. Huber

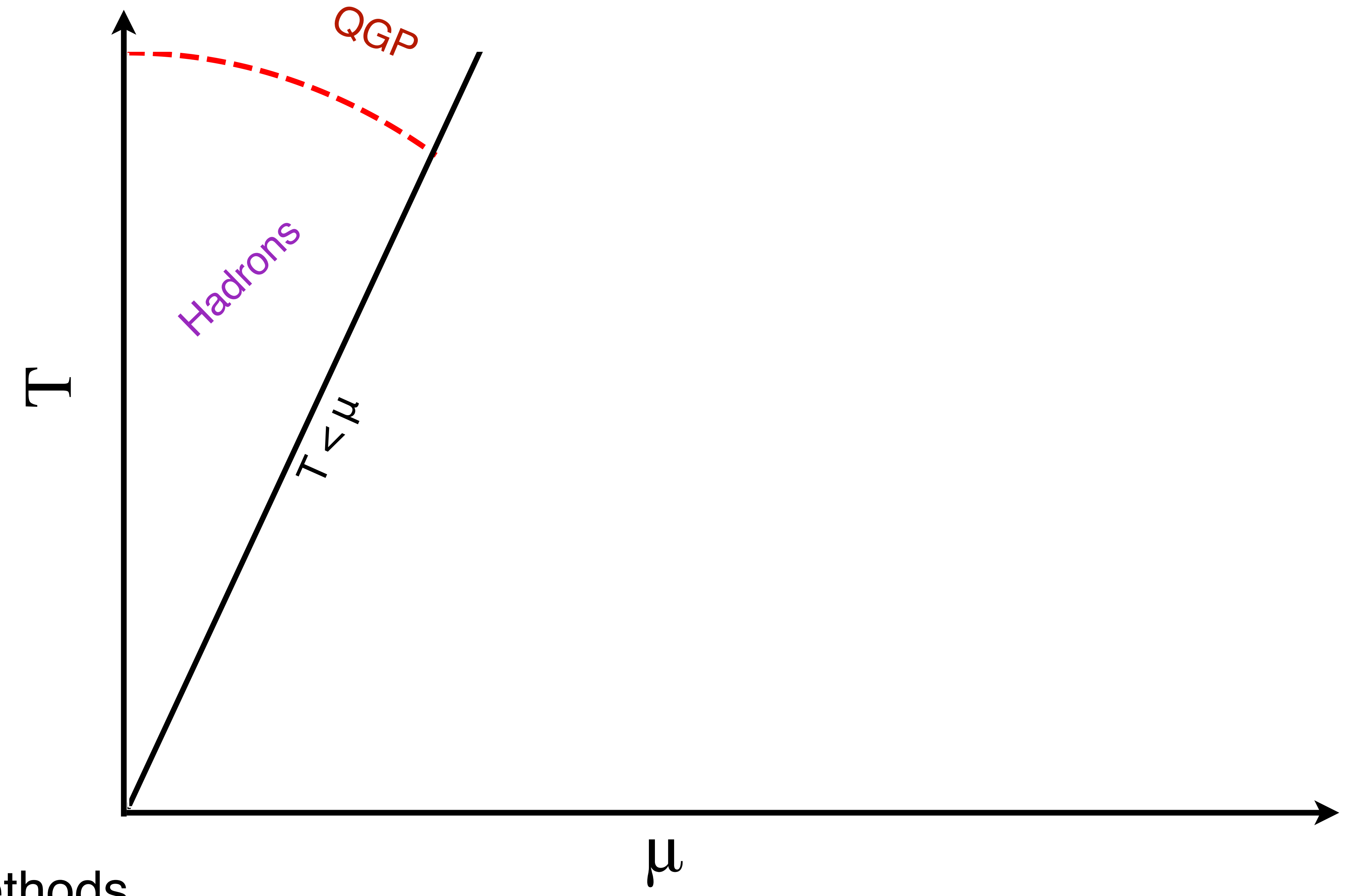
Phase transitions of QCD and QCD-like theories from Dyson-Schwinger equations

arXiv:1706.00943

arXiv:1709.03326

ACHT Zalakaros : 20 September 2017

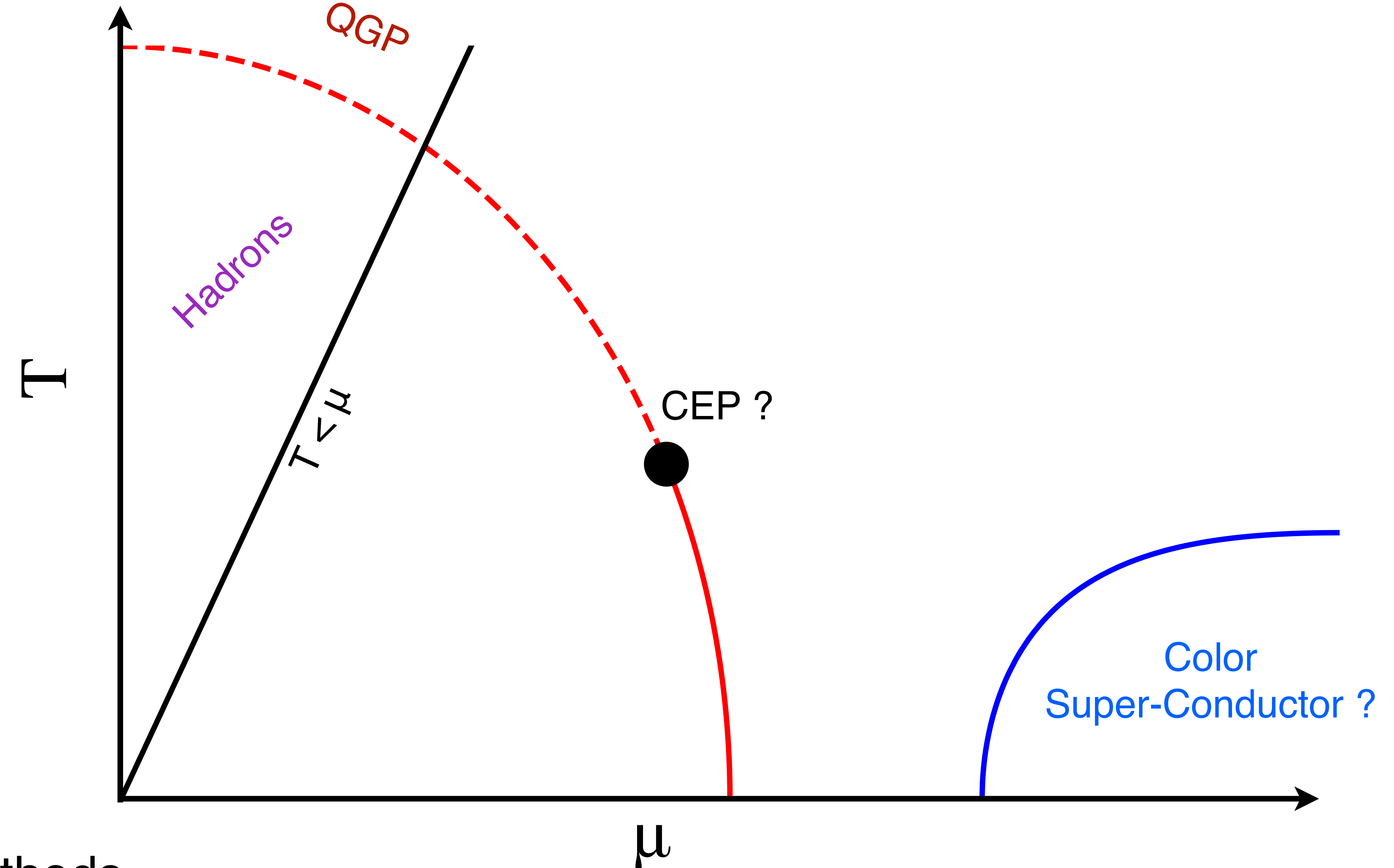
- The phase diagram of QCD



- Methods
  - Lattice QCD

  → Sign problem

- The phase diagram of QCD



- Methods
  - Lattice QCD → Sign problem
  - Effective Models → Fixing parameters
  - Functional methods → Truncation and modeling

QCD

Lattice QCD | sign problem

Functional Methods | Truncation

QCD-like

→ A theory with dynamical mass generation

→ Confinement and asymptotic freedom

→ A positive fermion determinant

Minimal modification of QCD

Lattice QCD ⟷ ~~sign problem~~

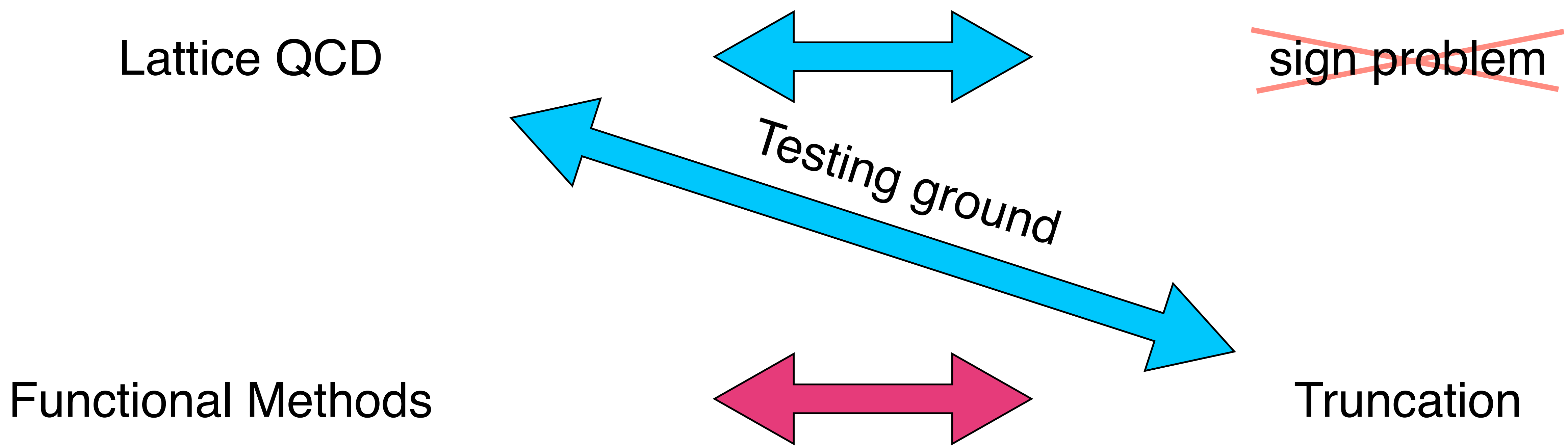
Functional Methods ⟷ Truncation

Contant Romain

QCD-like

- A theory with dynamical mass generation
- Confinement and asymptotic freedom
- A positive fermion determinant

Minimal modification of QCD



→ Apply the truncation to physical QCD

Motivation for QCD-like theories

- SU(2)

→ SU(2) for even number of degenerated quark flavors possesses a positive quark determinant

- G_2
  - Subgroup of SO(7) which satisfies an additional cubic constraint

→ All representations are real, allow lattice simulation at $\mu > 0$

Motivation for QCD-like theories

- SU(3) SU(2) and G_2 have many properties in common

→ Asymptotically free, chiral symmetry breaking, confinement

→ Chiral and deconfinement transition coincide in the quenched case

- Similar functional equations

→ Different Casimir operators of the gauge groups

1 Introduction
Motivation for QCD-like theories

- SU(3) SU(2) and G2 have many properties in common
  - → Asymptotically free, chiral symmetry breaking, confinement
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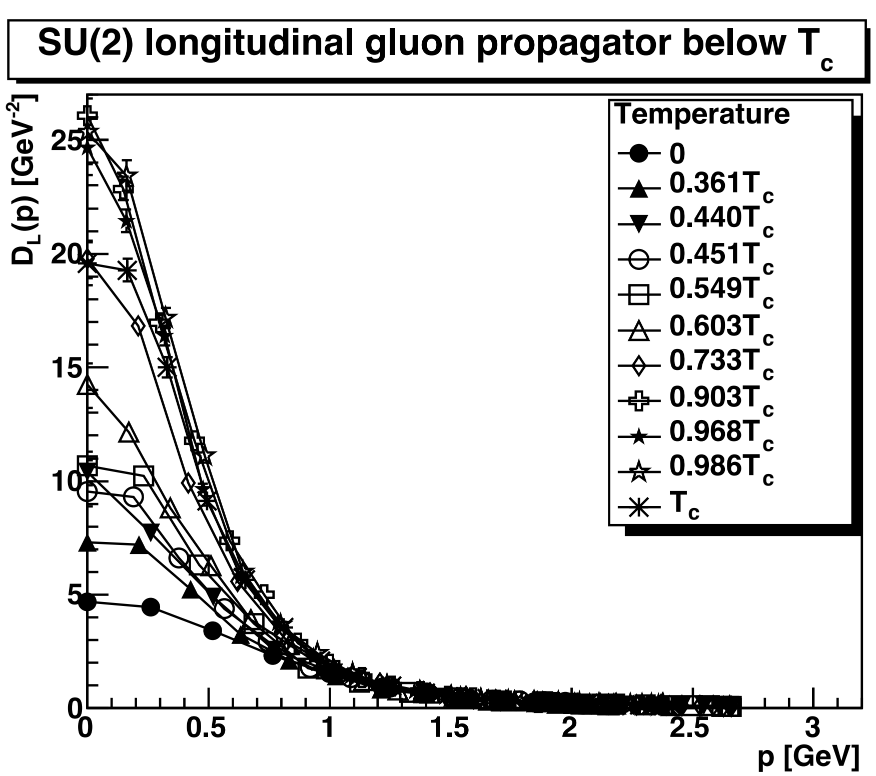
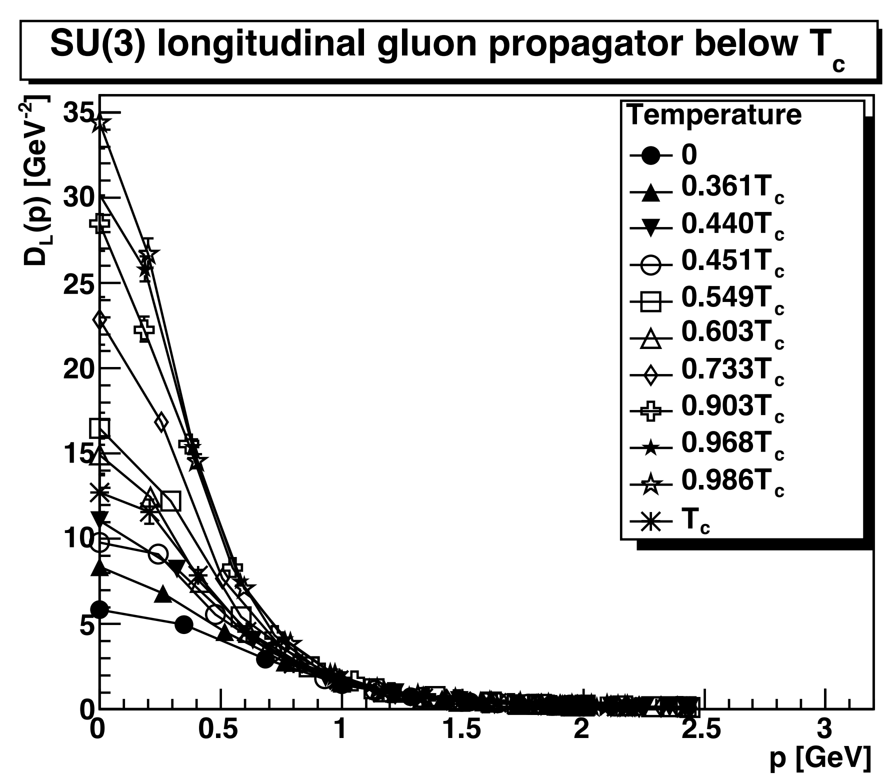
- Similar functional equations
  - → Different Casimir operators of the gauge groups
- Similarities of the correlation function :   SU(2) vs SU(3)





See talk of O. Hajizadeh

[C.S. Fischer, A. Maas, J.A. Muller (2010)]

1 Introduction
Motivation for QCD-like theories

- SU(3) SU(2) and G_2 have many properties in common
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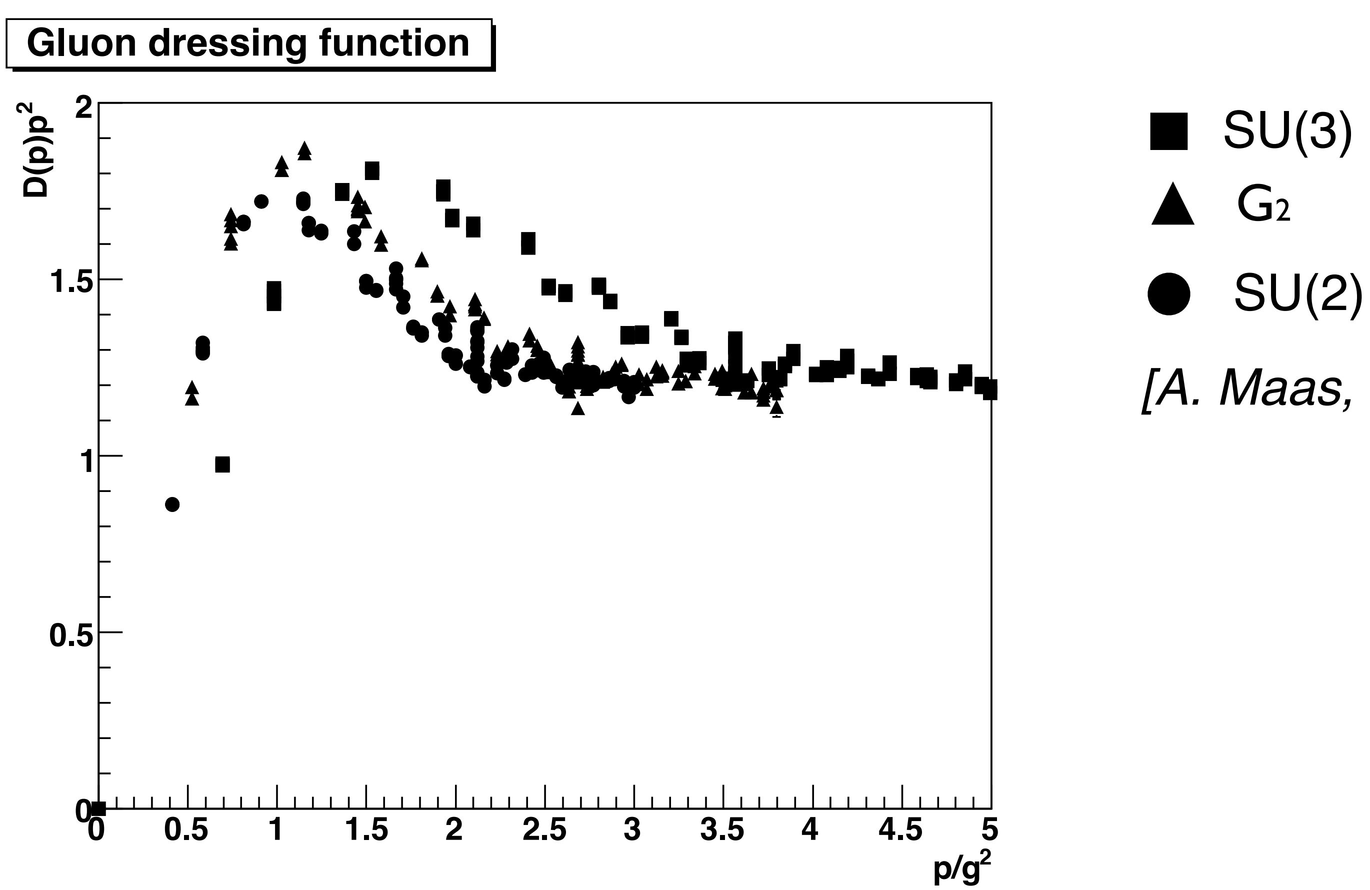
- Similarities of the correlation functions : G_2 vs SU(3) vs SU(2) (3 dimensional)



[A. Maas, S. Olejník (2008)]

Difference with QCD

- SU(2)

→ Expected to be second order transition for the chiral condensate
(For the quenched system)

→ Bosonic baryons

- G_2

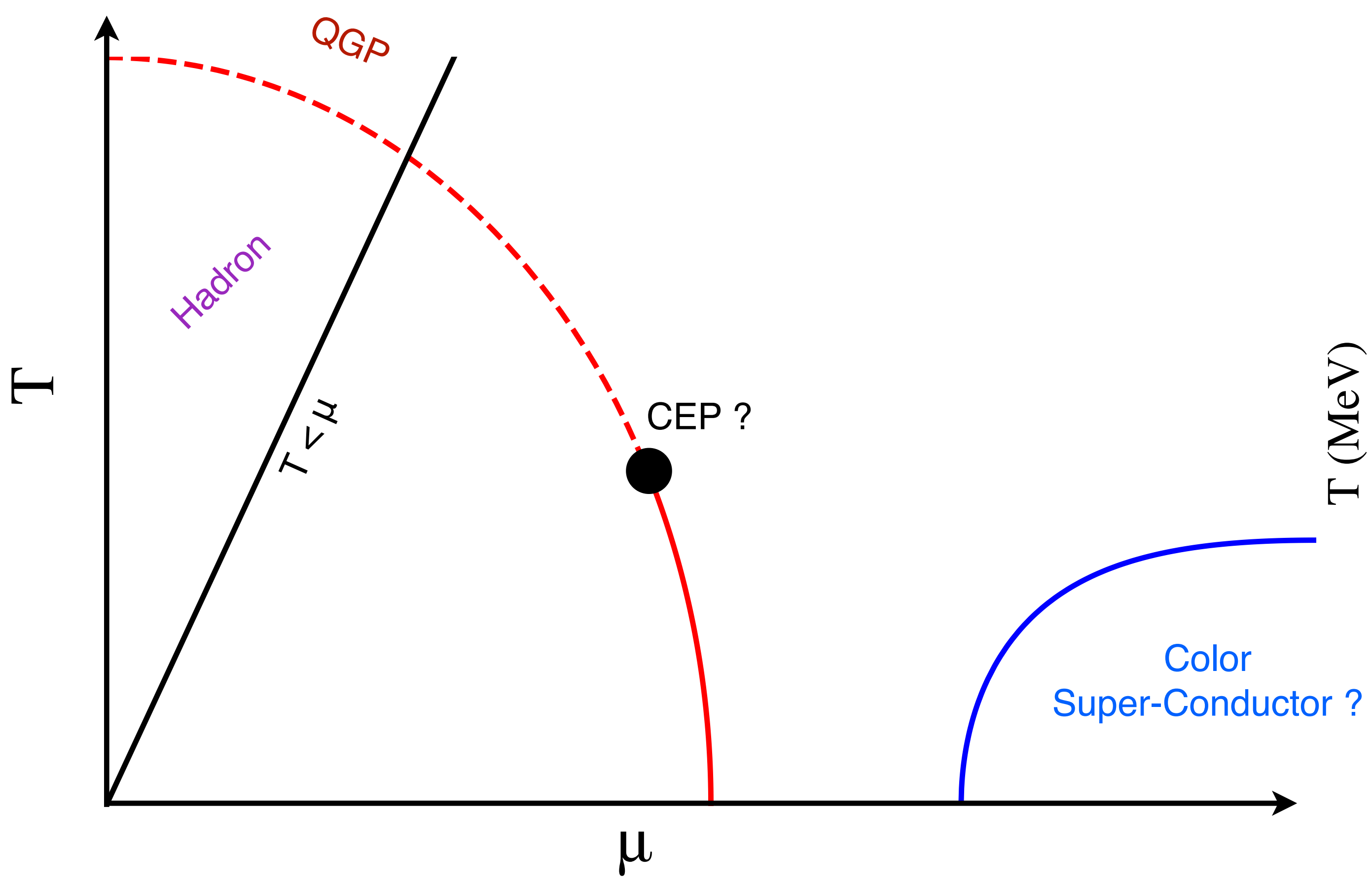
→ Centerless

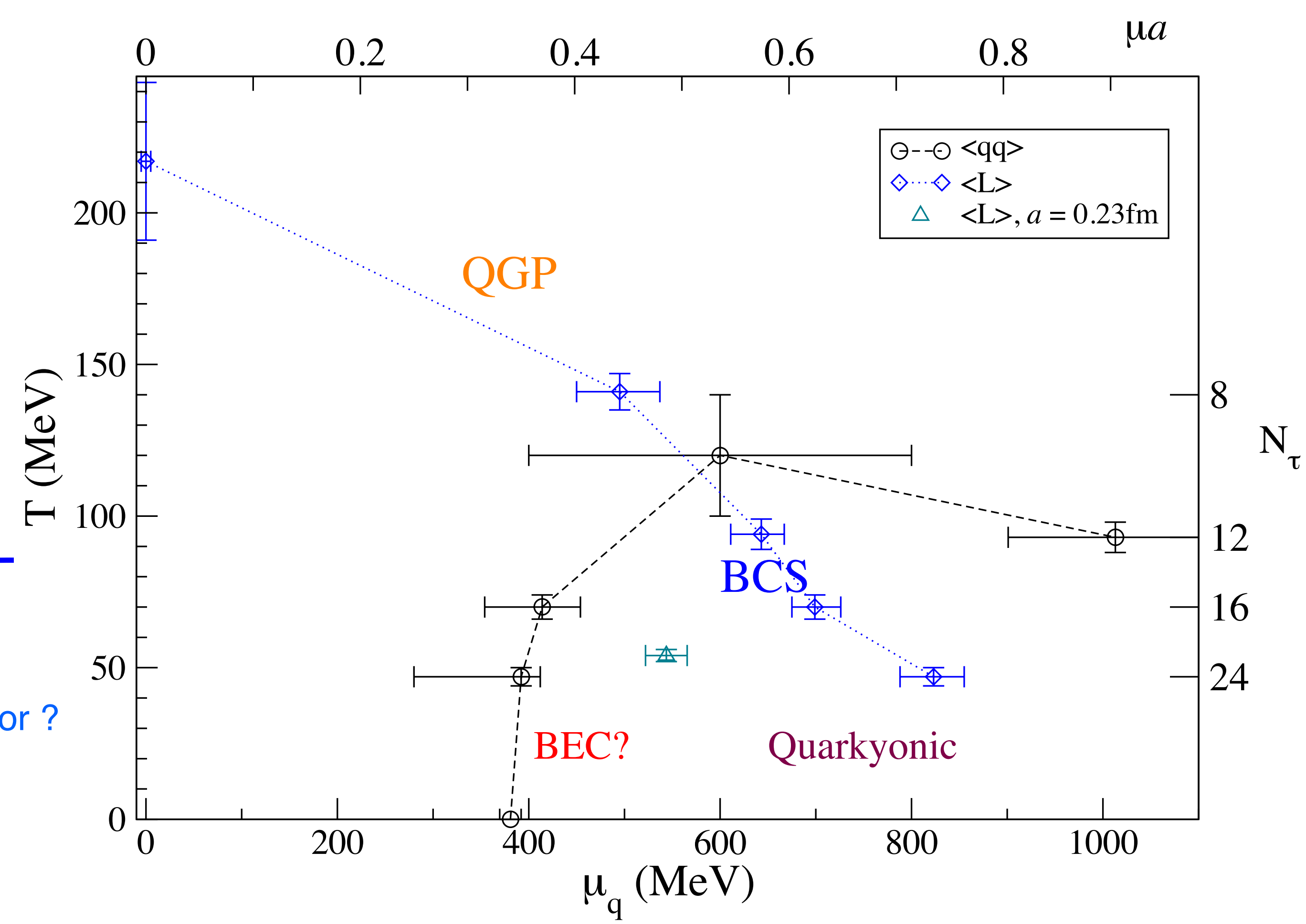
→ Lattice simulations show a first order transition for confinement
[G. Cossu, M. D'Elia, A. Di Giacomo, B. Lucini, and C. Pica (2007)]

→ Fermionic baryons

1 Introduction
QCD-like phase diagram

- Phase diagrams of QCD-like theories
  - QCD sketch
  - SU(2)





→ Is the same truncation sufficient to describe different gauge groups ?

Diquark condensate : *[S. Cotter et al. Phys.rev., vol. D87, pp. 034507, (2013)]*

Polyakov loop : *[S. Hands et al. Eur.phys.j., vol. C48, pp. 193, (2006)]*

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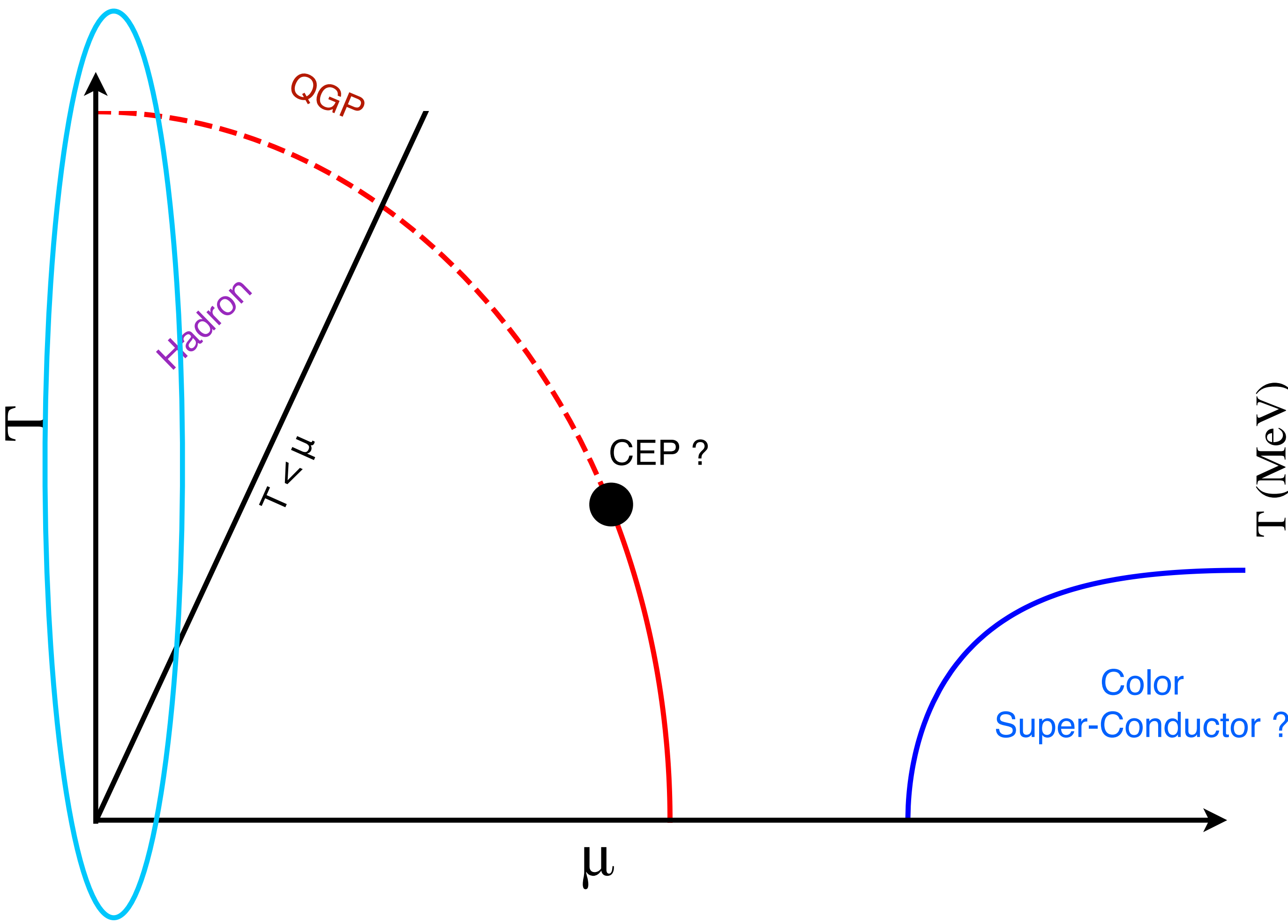

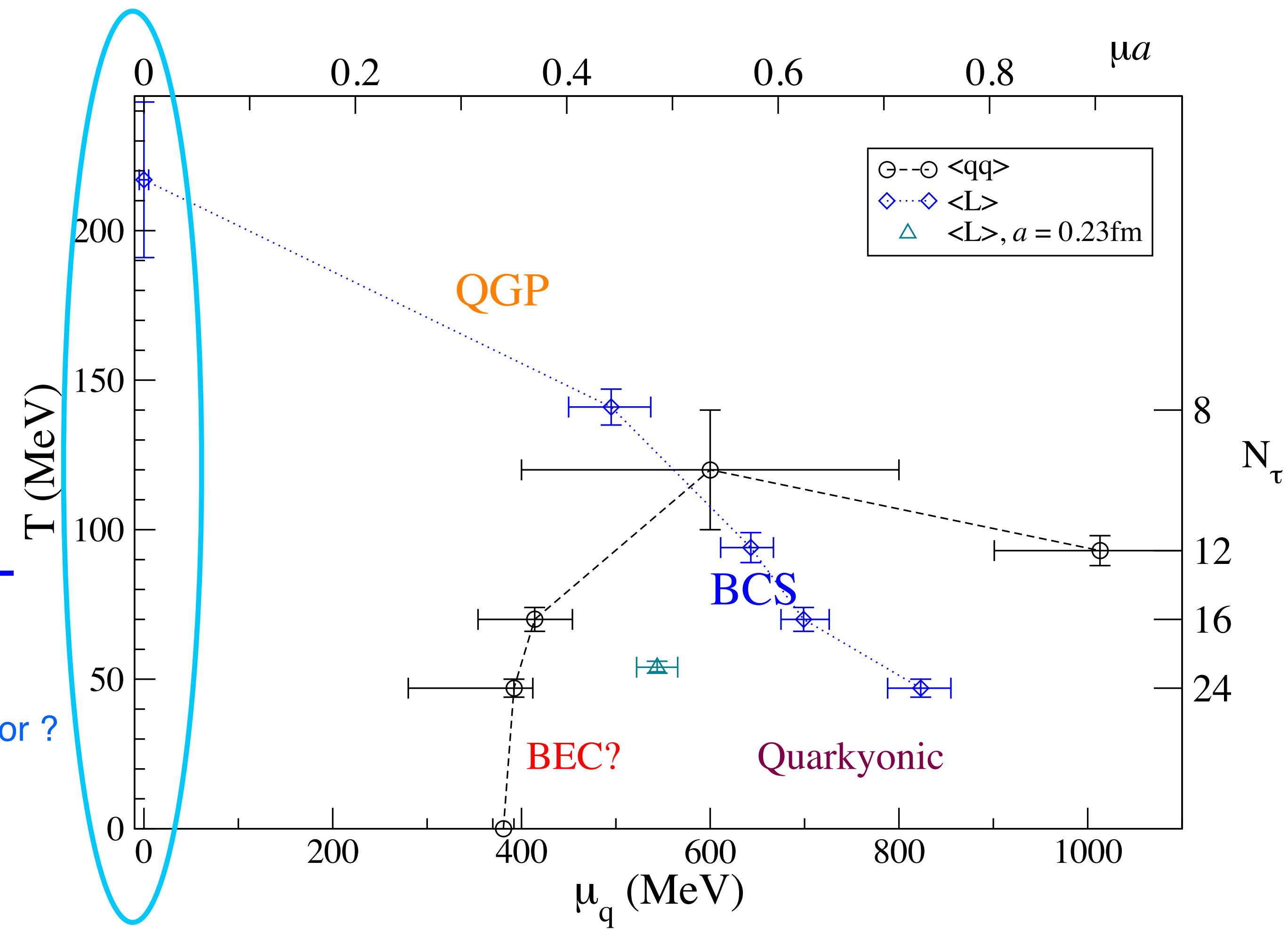

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➔ Study the quark propagator at finite T for QCD and QCD-like theories

Synopsis

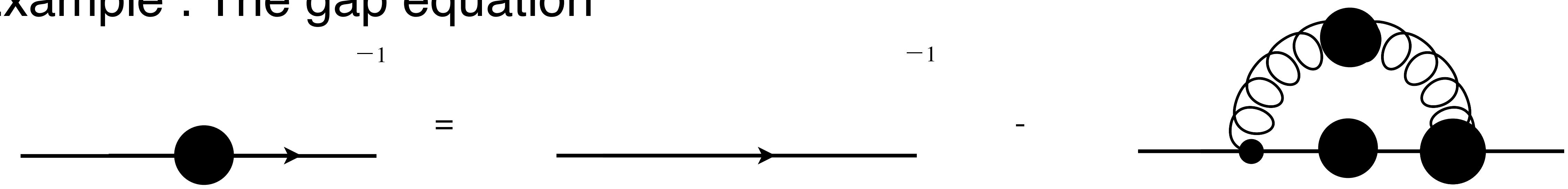
2 Setup

Dyson-Schwinger Equation

$$Z = \int d\,[\Phi]\,\mathrm{Exp}\Big[-\int S[\Phi] + \Phi J\Big] \longrightarrow W[\Phi] = \mathrm{Log}[Z] \longrightarrow \Gamma[J]$$

Z : Partition function → *W :* Connected Diagrams → *Γ :* irreducible Diagrams

- Example : The gap equation



→ Describe all possible ways of propagation of a quark

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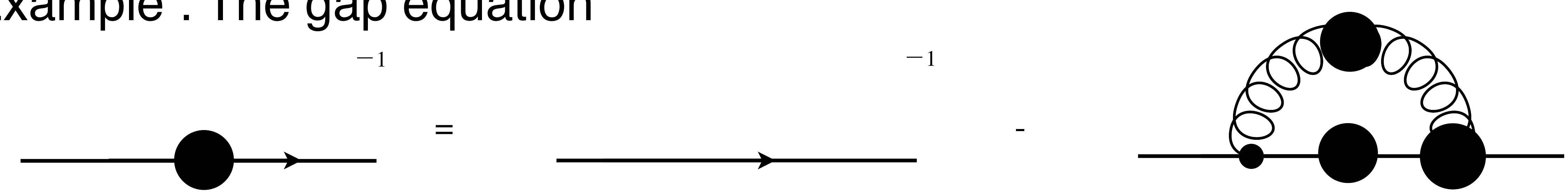
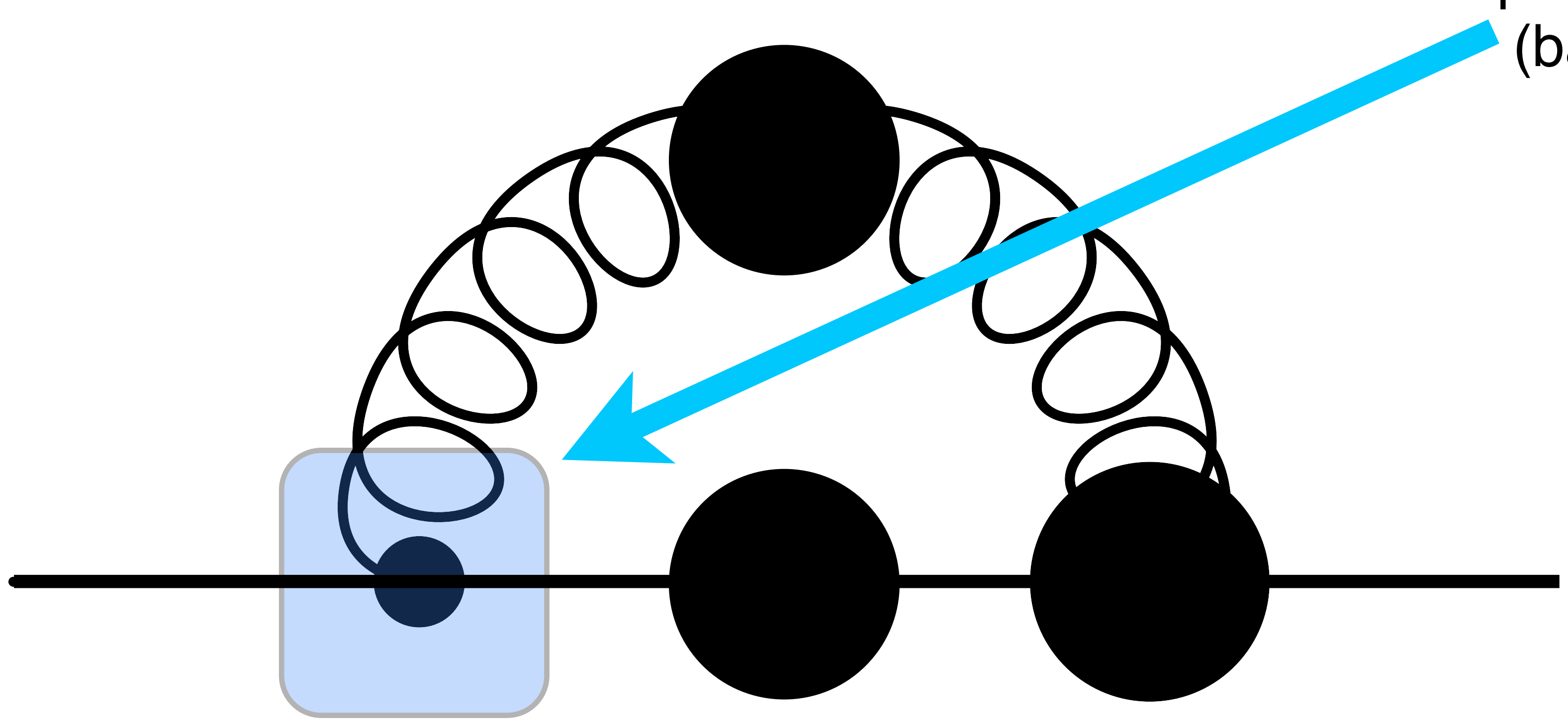


→ Describe all possible ways of propagation of a quark

Can only split into
a quark and a gluon
(bare vertex)



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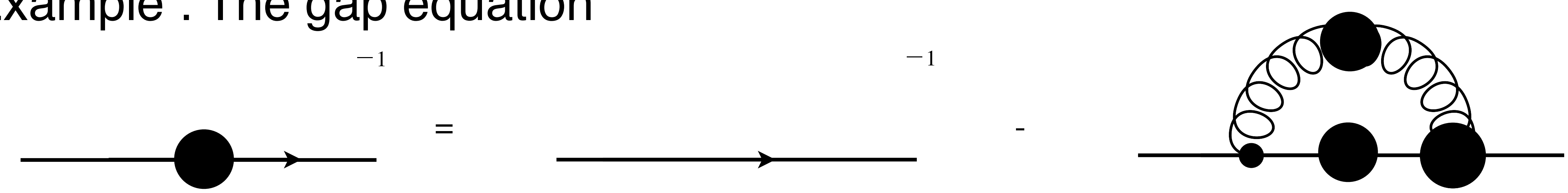
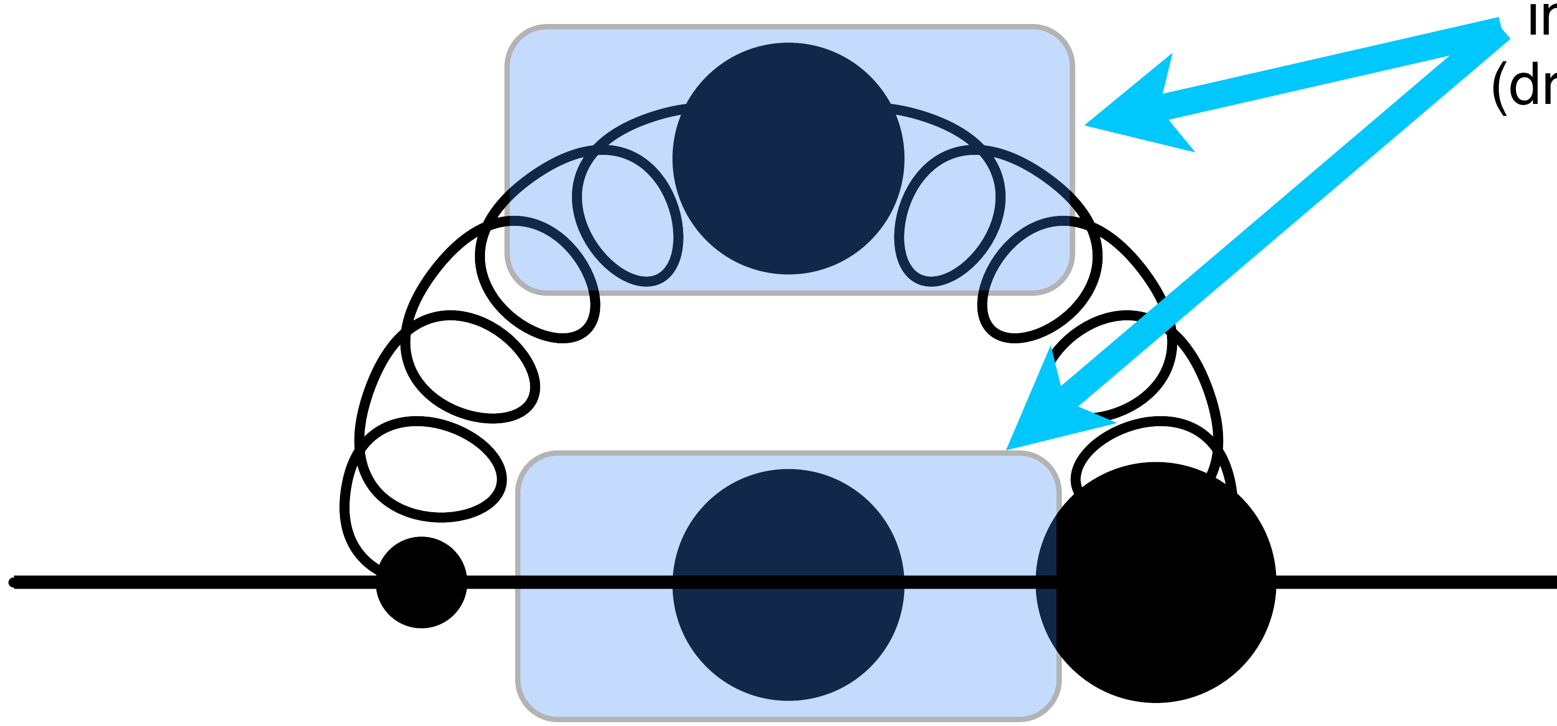


→ Describe all possible ways of propagation of a quark

The quark and gluon propagate in all possible ways (dressed propagators)



Dyson-Schwinger Equation

$$Z \quad = \int d\,[\Phi]\,\mathrm{Exp}\Big[-\int S[\Phi] \;+\; \Phi\, J\Big] \longrightarrow W[\Phi] \;=\; \mathrm{Log}[Z] \longrightarrow \Gamma[J]$$

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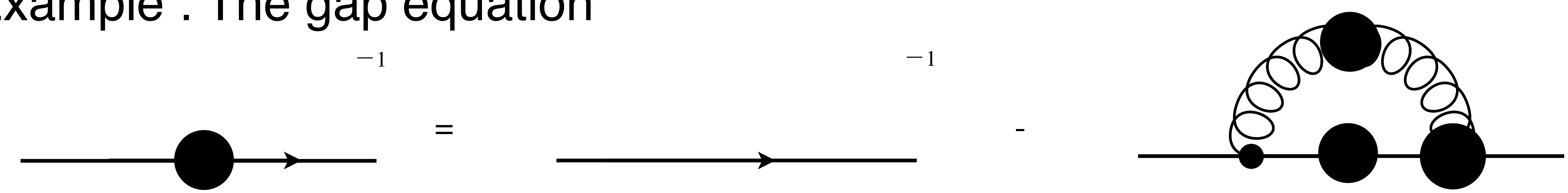
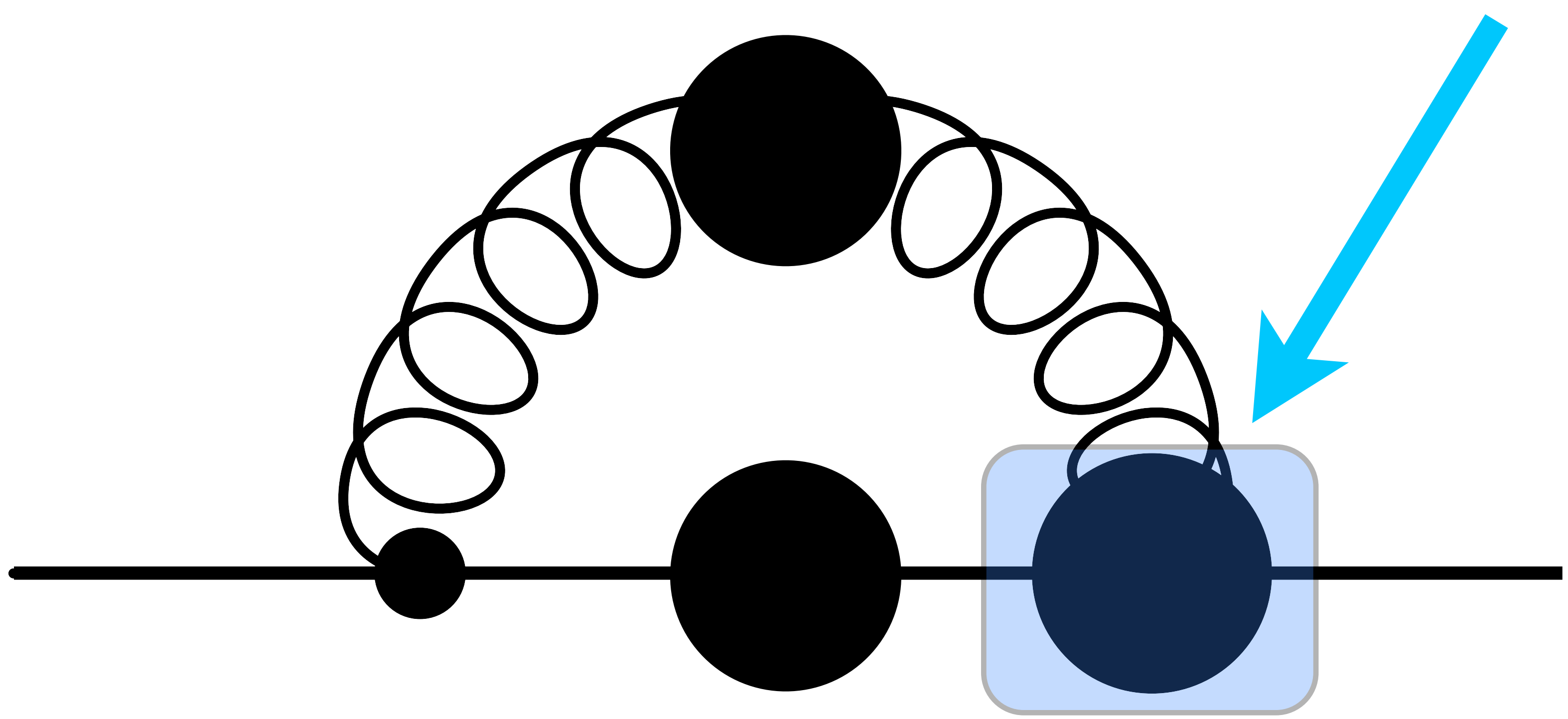


→ Describe all possible ways of propagation of a quark

And finally recombine in all possible ways (dressed vertex)



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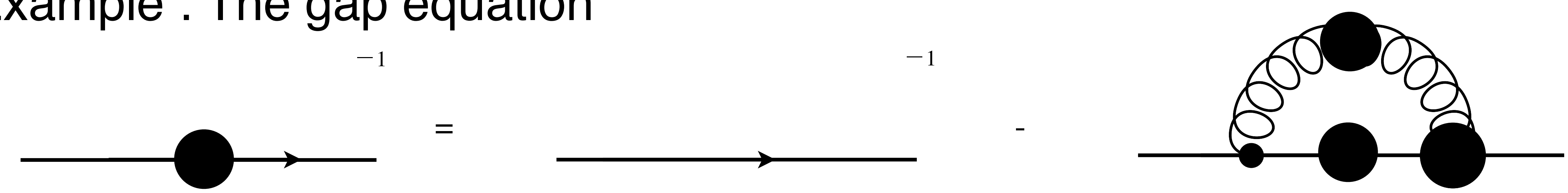
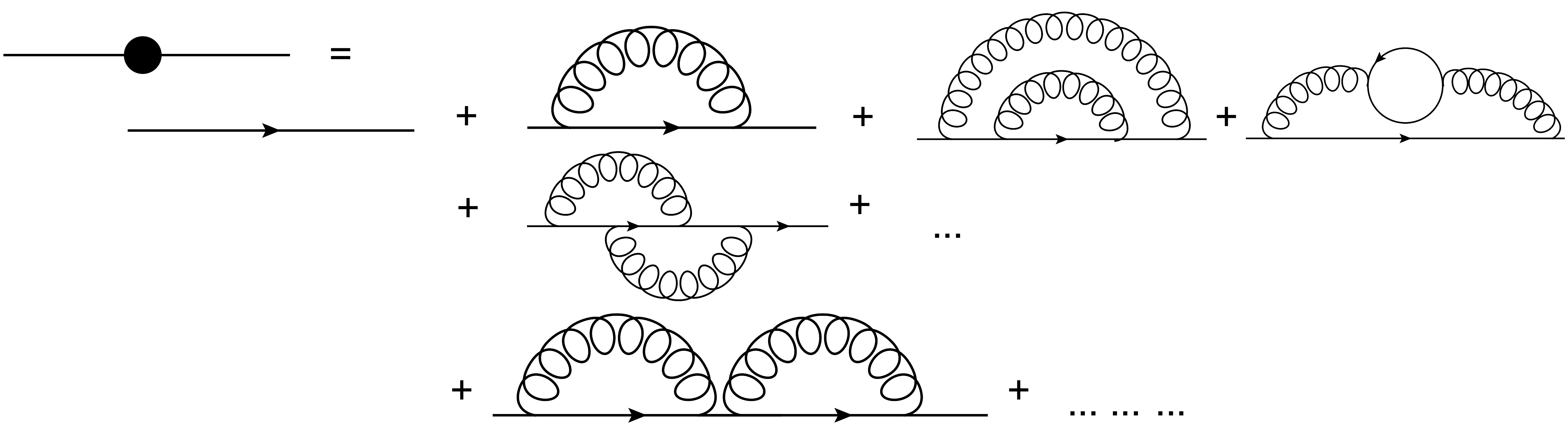


→ Describe all possible ways of propagation of a quark

- Contains perturbation theory :



2 Setup
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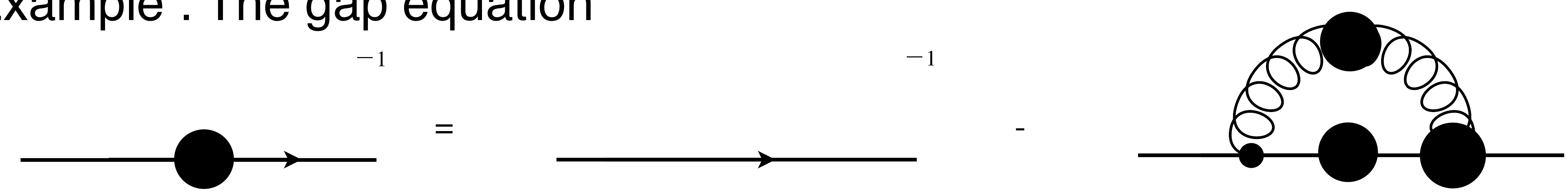

➡ Describe all possible ways of propagation of a quark

- Contains perturbation theory :
- Contains non-perturbative information
  - Confinement and dynamical chiral symmetry breaking
  - Bound states studies
  - ...

➡ Multi-scale problems feasible

➡ No sign problem

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Dyson-Schwinger Equation

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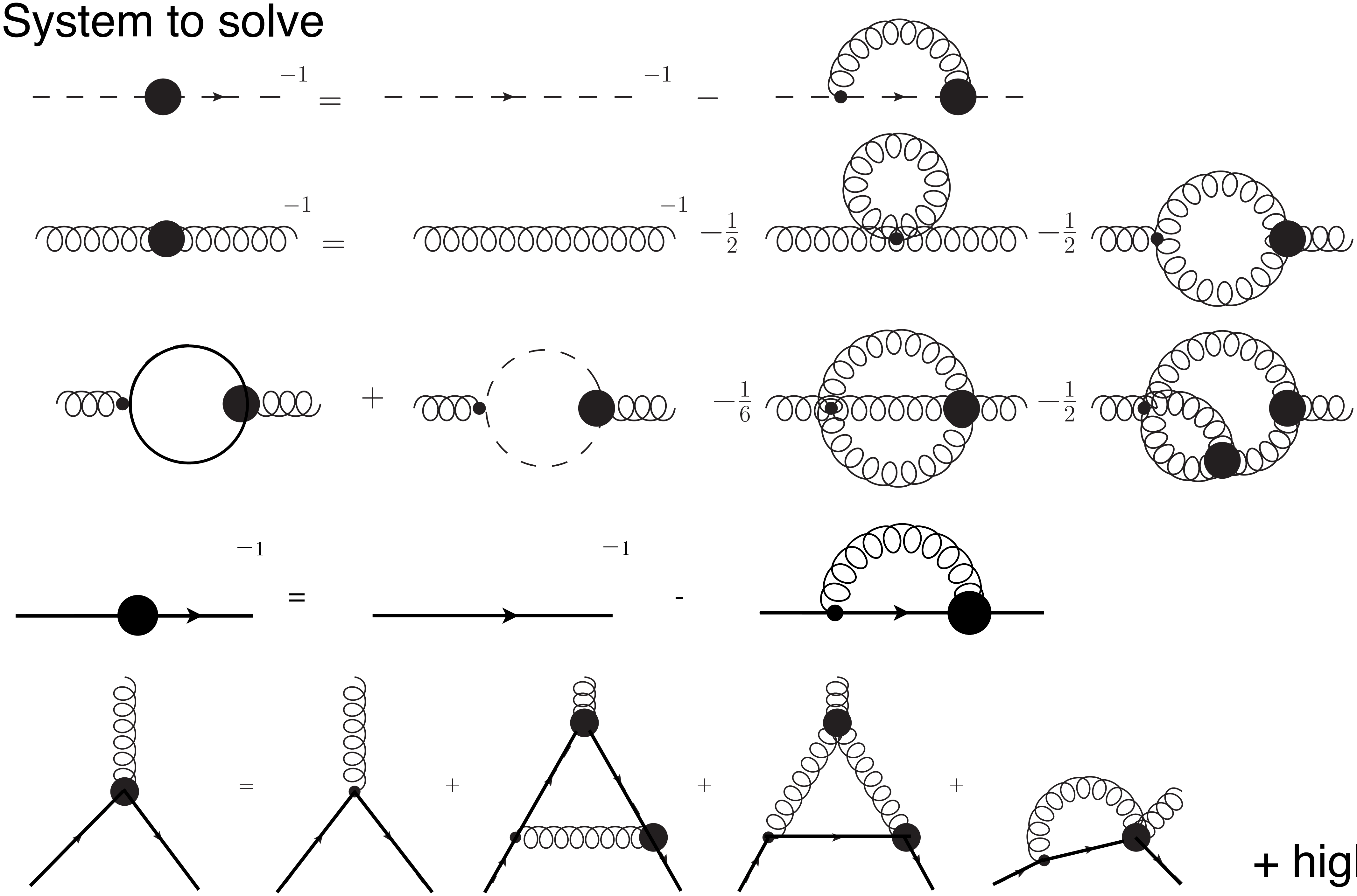
- System to solve

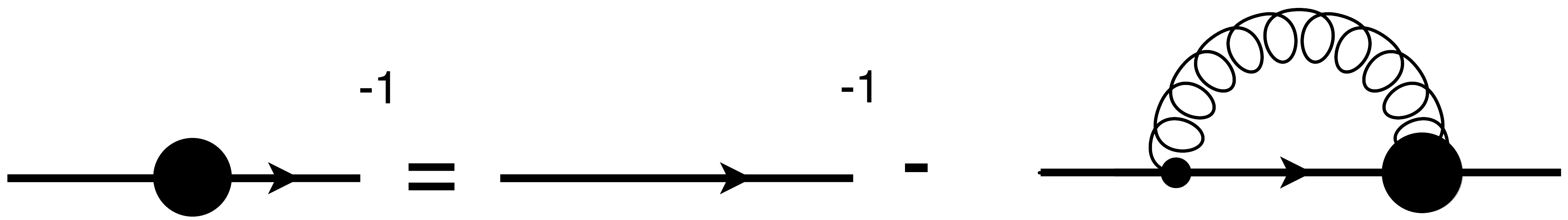


+ higher equations

- System to solve
  - Truncations are mandatory

→ We want a realistic temperature dependence of the gluon

$$S^{-1}(\vec{p},\omega_n) = A(\vec{p},\omega_n)\,\vec{\gamma}\,\vec{p} + C(\vec{p},\omega_n)\,\omega_n\gamma_4 + B(\vec{p},\omega_n) + \omega_n\gamma_4\,\vec{p}\,\vec{\gamma}\,D(\vec{p},\omega_n)$$



2 Setup
The truncation and modeling

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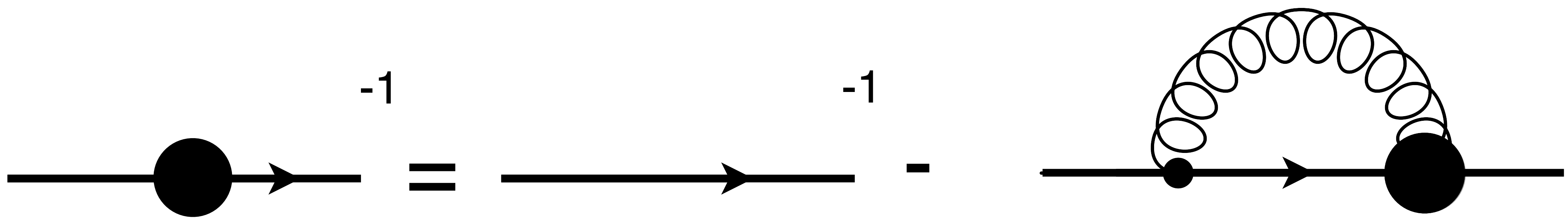
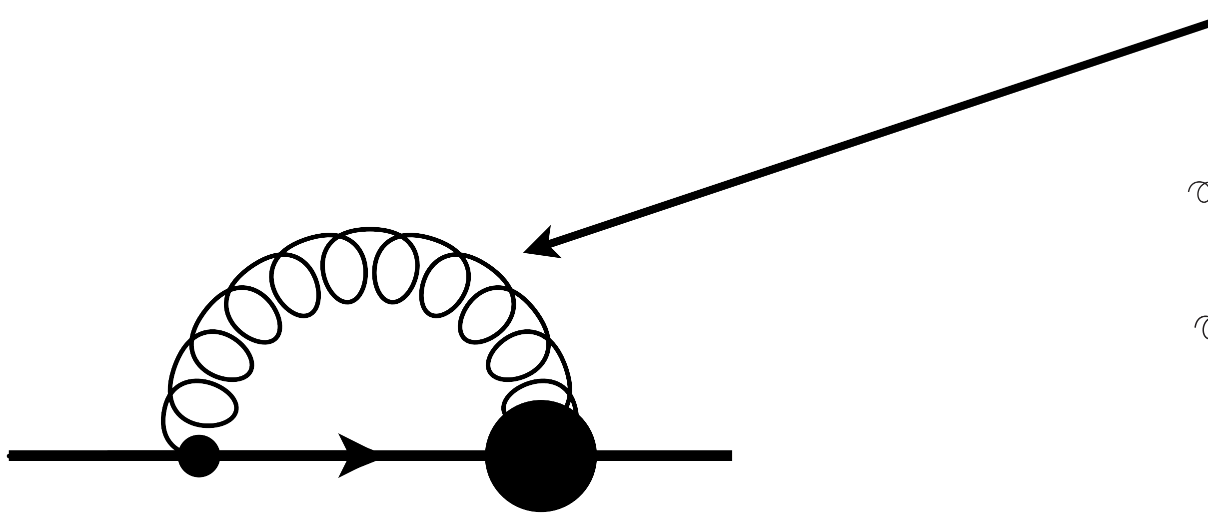
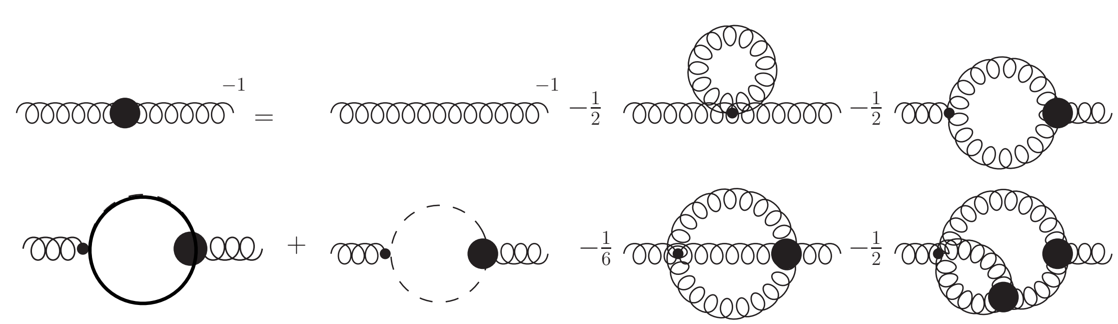


$$D_{\mu\nu}(p) = \frac{1}{p^2}\left(Z_T(p) P^T_{\mu\nu} + Z_L(p) P^L_{\mu\nu}\right)$$





→ Spuriously divergent terms

→ Accessible on lattice

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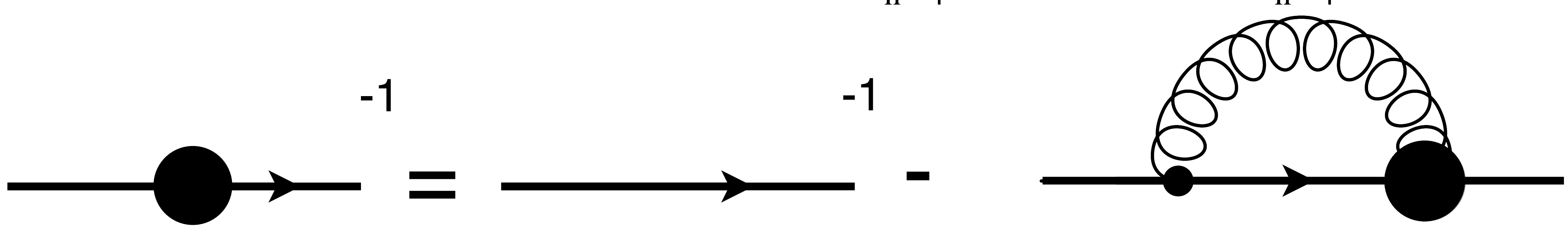
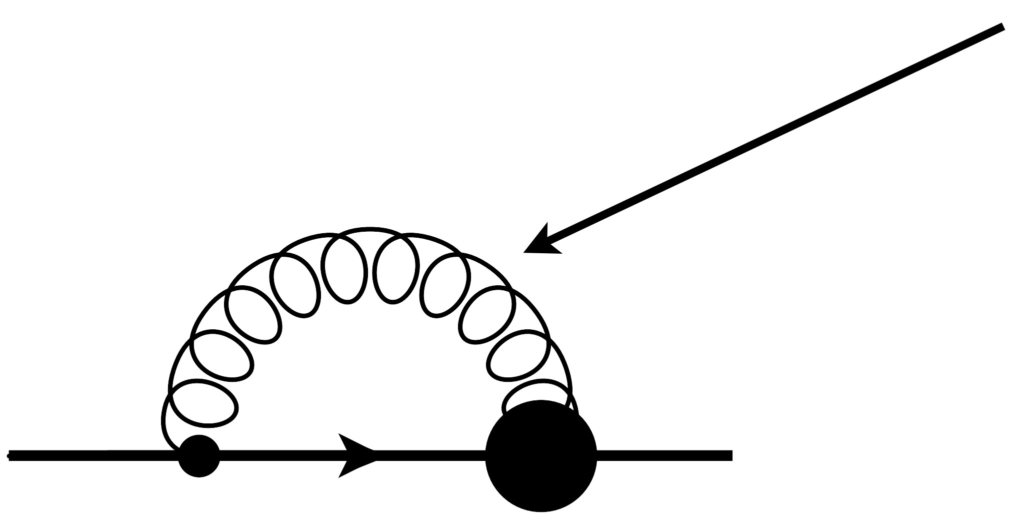


$$Z_{T,L}(x) = \frac{x}{(x+1)^2}\left(\left(\frac{c}{x+a_{T,L}(T)}\right)^{b_{T,L}(T)} + x\left(\frac{\beta_0\alpha(\mu)}{4\pi}\ln(x+1)\right)^{\gamma}\right)$$



Coefficients are fitted to reproduce lattice data

[A. Maas, J.M Pawlowski, L. von Smekal, D. Spielmann (2012)]
[C.S. Fischer, A. Maas, J.A. Muller (2010)]

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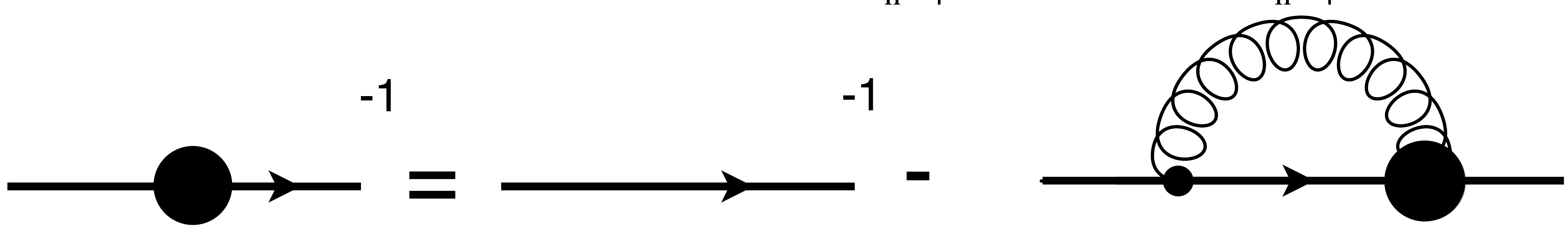
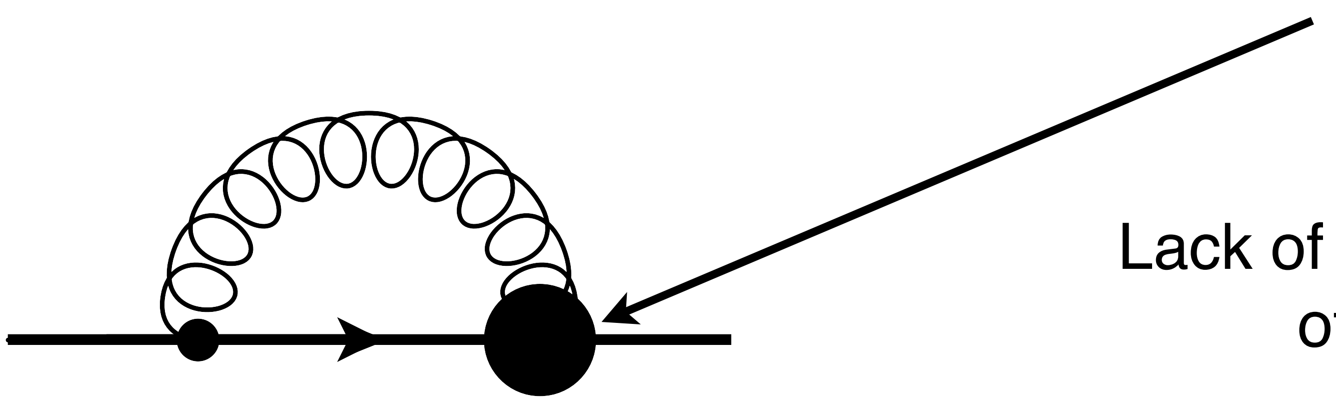


$\Gamma_{q\text{-}gl}(p,q,l)$

24 tensors parts

Difficult to obtain from lattice

Lack of information of the temperature dependence of this quantity from continuum studies



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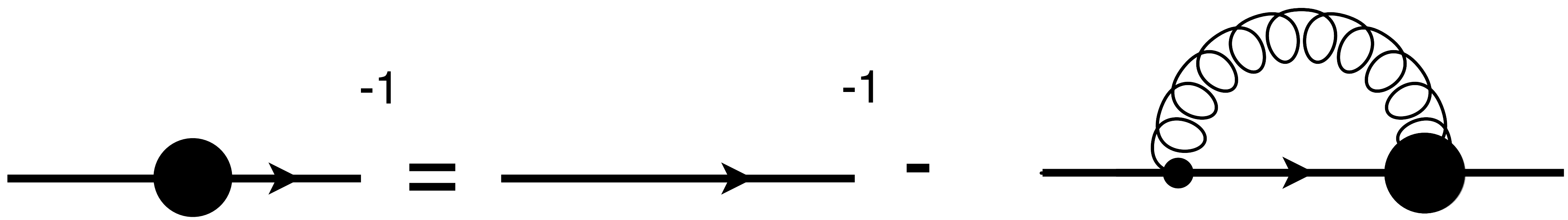
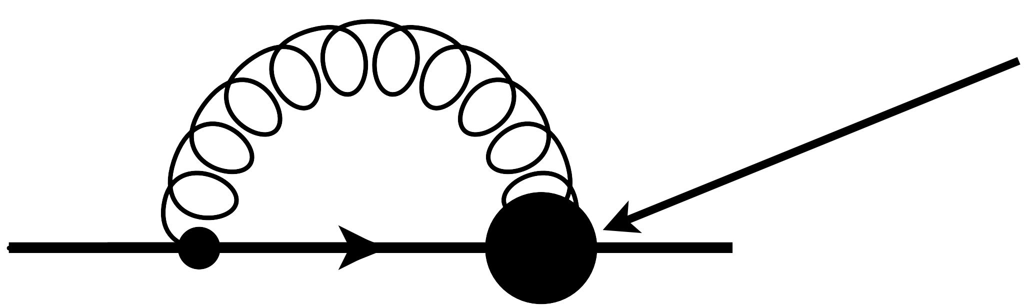


$$\Gamma_{q\text{-}gl}(p,q,l) = \left(\frac{A(p)+A(q)}{2}\vec{\gamma},\frac{C(p)+C(q)}{2}\gamma_4\right)W(p,q,l)$$

$$W(p,q,l) = \frac{d_1}{d_2+l^2} + \frac{l^2}{1+l^2}\left(\frac{\beta_0\,\alpha(\mu)}{4\pi}\ln(l^2+1)\right)^{2\delta}$$

[C.S. Fischer (2009)]



Setup

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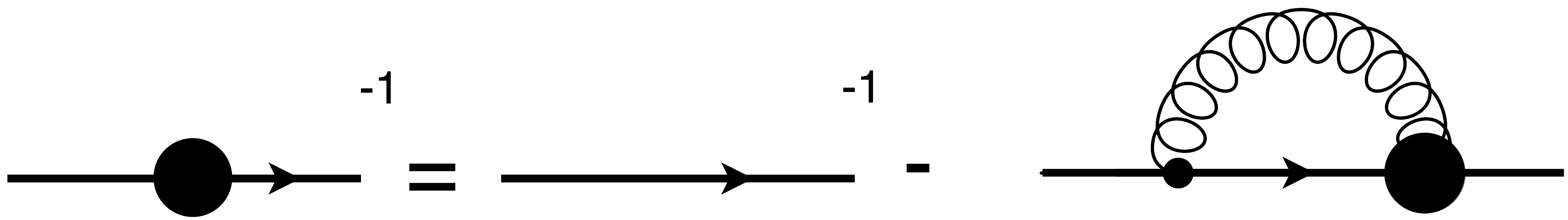

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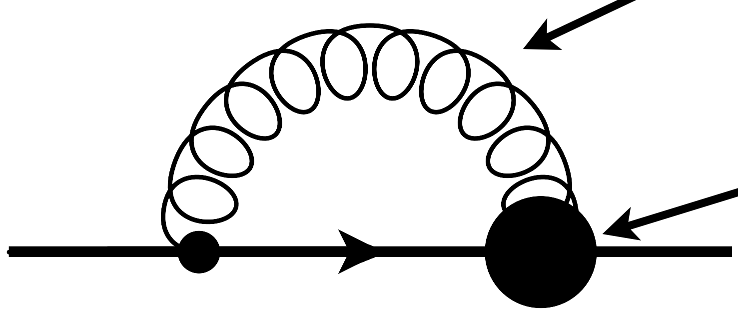


$$\Gamma_{q\text{-}gl}(p, q, l) = \left(\frac{A(p)+A(q)}{2}\vec{\gamma}, \frac{C(p)+C(q)}{2}\gamma_4\right)W(p,q,l)$$

→ The system can be solved

Chiral condensate

- Chiral Symmetry Breaking

$$S^{-1}(\vec{p},\omega_n) = A(\vec{p},\omega_n)\,\vec{\gamma}\,\vec{p} + C(\vec{p},\omega_n)\,\omega_n\gamma_4 + B(\vec{p},\omega_n) + \omega_n\gamma_4\,\vec{p}\,\vec{\gamma}\,D(\vec{p},\omega_n)$$

$$\Delta_\pi(T) = Z_2(Z_m)N_c\,T\sum_{\omega_n}\int_{\vec{p}}\frac{d^3\vec{p}}{(2\pi)^3}\mathrm{Tr}[S(\vec{p},\omega_n)]$$

- chiral limit $m_{bare} = 0$

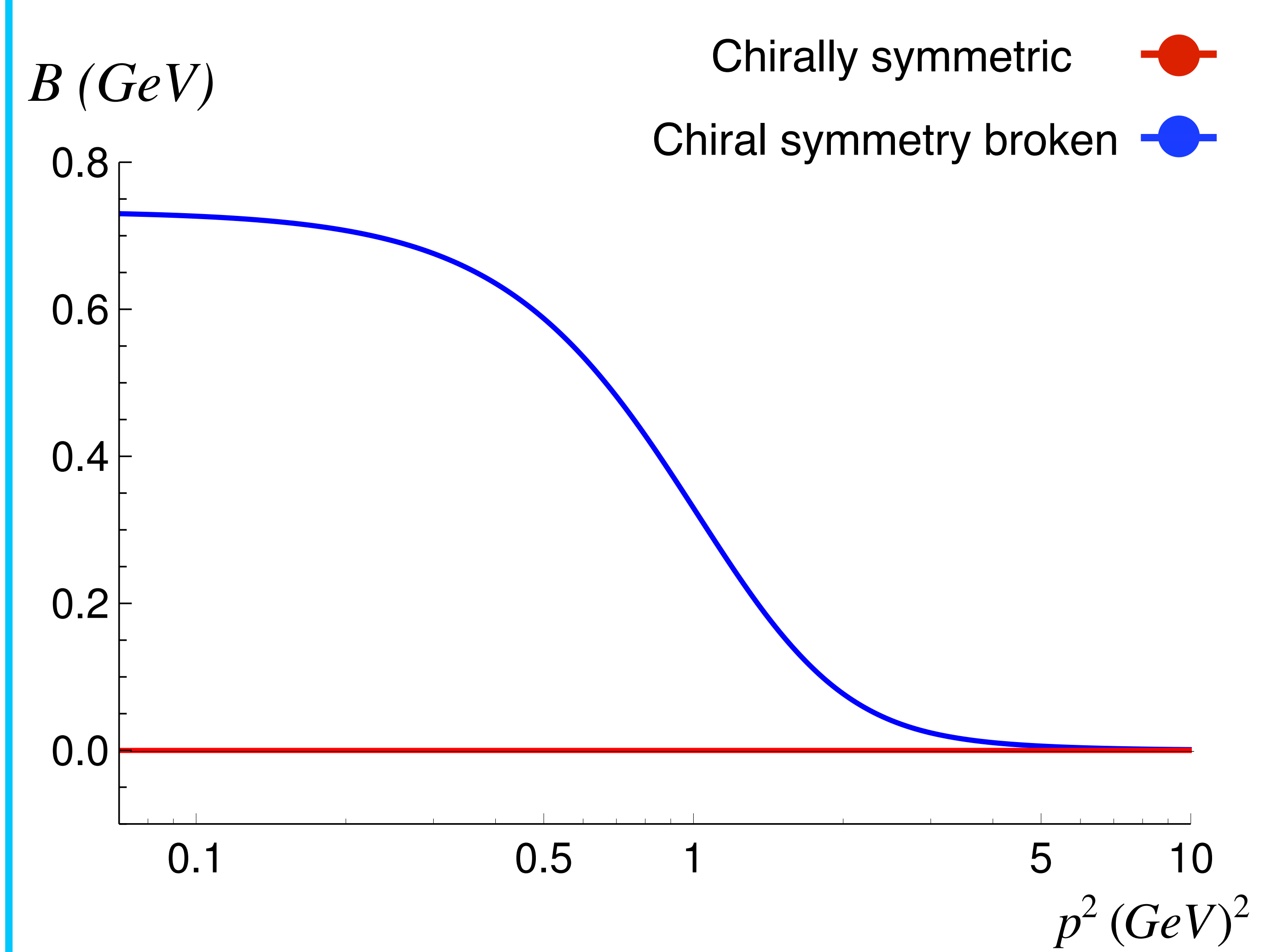
→ $B \neq 0$, formation of a chiral condensate

Chiral symmetry broken

→ $B = 0$, no chiral condensate

Chirally symmetric

order parameter



(Pseudo)-order parameter

- Chiral Symmetry Breaking

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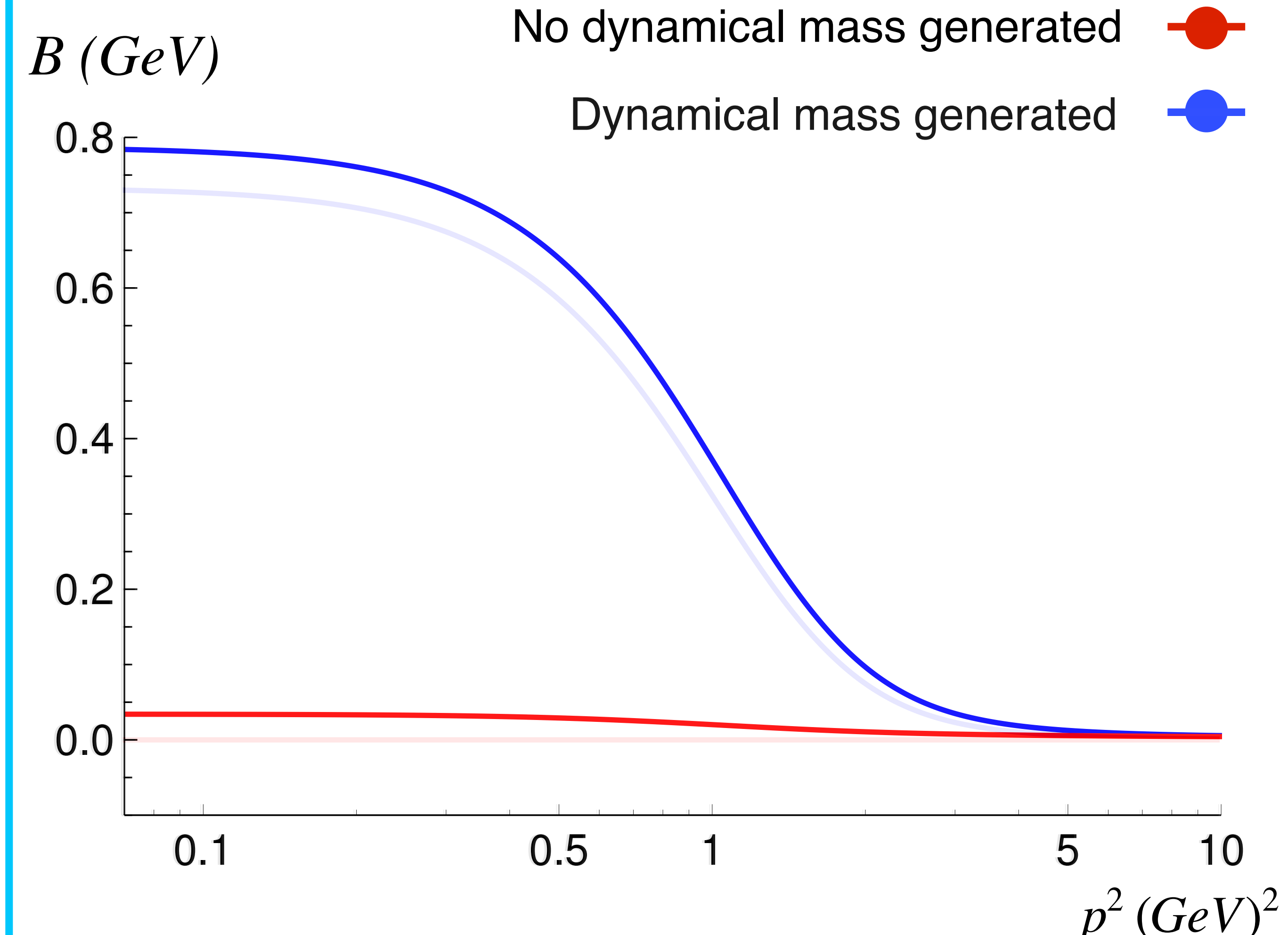
- $m_{bare} > 0$

→ $B \neq 0$, formation of a chiral condensate

Chiral symmetry broken

Pseudo-order parameter



D function

- Chiral Symmetry Breaking

$$S^{-1}(\vec{p},\omega_n) = A(\vec{p},\omega_n)\,\vec{\gamma}\,\vec{p} + C(\vec{p},\omega_n)\,\omega_n\gamma_4 + B(\vec{p},\omega_n) + \omega_n\gamma_4\,\vec{p}\,\vec{\gamma}\,D(\vec{p},\omega_n)$$

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→ $[\vec{p}\vec{\gamma}\,\omega_n\,\gamma_4\,,\gamma_5] = 0$ $\quad\quad$ $D \neq 0$

Chiral symmetry broken

→ $D = 0$ at $T = 0$

→ D power-law suppressed in UV

→ $D = 0$ in Rainbow ladder

→ D small after the chiral restoration

<u>We expect a small contribution of *D*</u>

- Quark confinement

$$S^{-1}(\vec{p},\omega_n) = A(\vec{p},\omega_n)\,\vec{\gamma}\,\vec{p} + C(\vec{p},\omega_n)\,\omega_n\gamma_4 + B(\vec{p},\omega_n) + \omega_n\gamma_4\,\vec{p}\,\vec{\gamma}\,D(\vec{p},\omega_n)$$

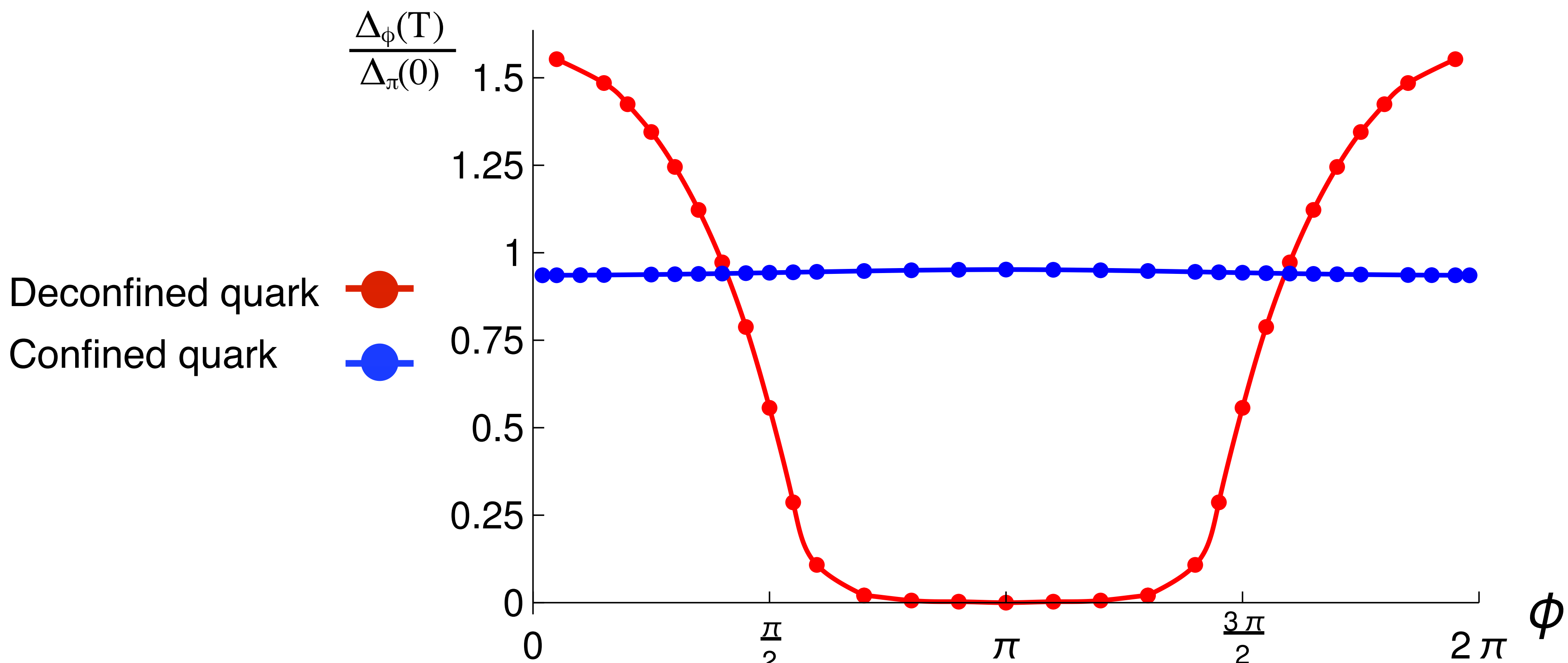
$$\Delta_\phi(T) = Z_2(Z_m)N_c\, T \sum_{\omega_n(\phi)} \int_{\vec{p}} \frac{d^3\vec{p}}{(2\pi)^3} \mathrm{Tr}[S(\vec{p},\omega_n(\phi))]$$

We introduce a phase dependence : $\omega_n = \pi T \left(2n + \frac{\phi}{\pi}\right)$

$$\Sigma_1 = \int_0^{2\pi} e^{i\phi}\, d\phi\, \Delta_\phi(T)$$

The dual quark condensate is proportional to the Polyakov Loop

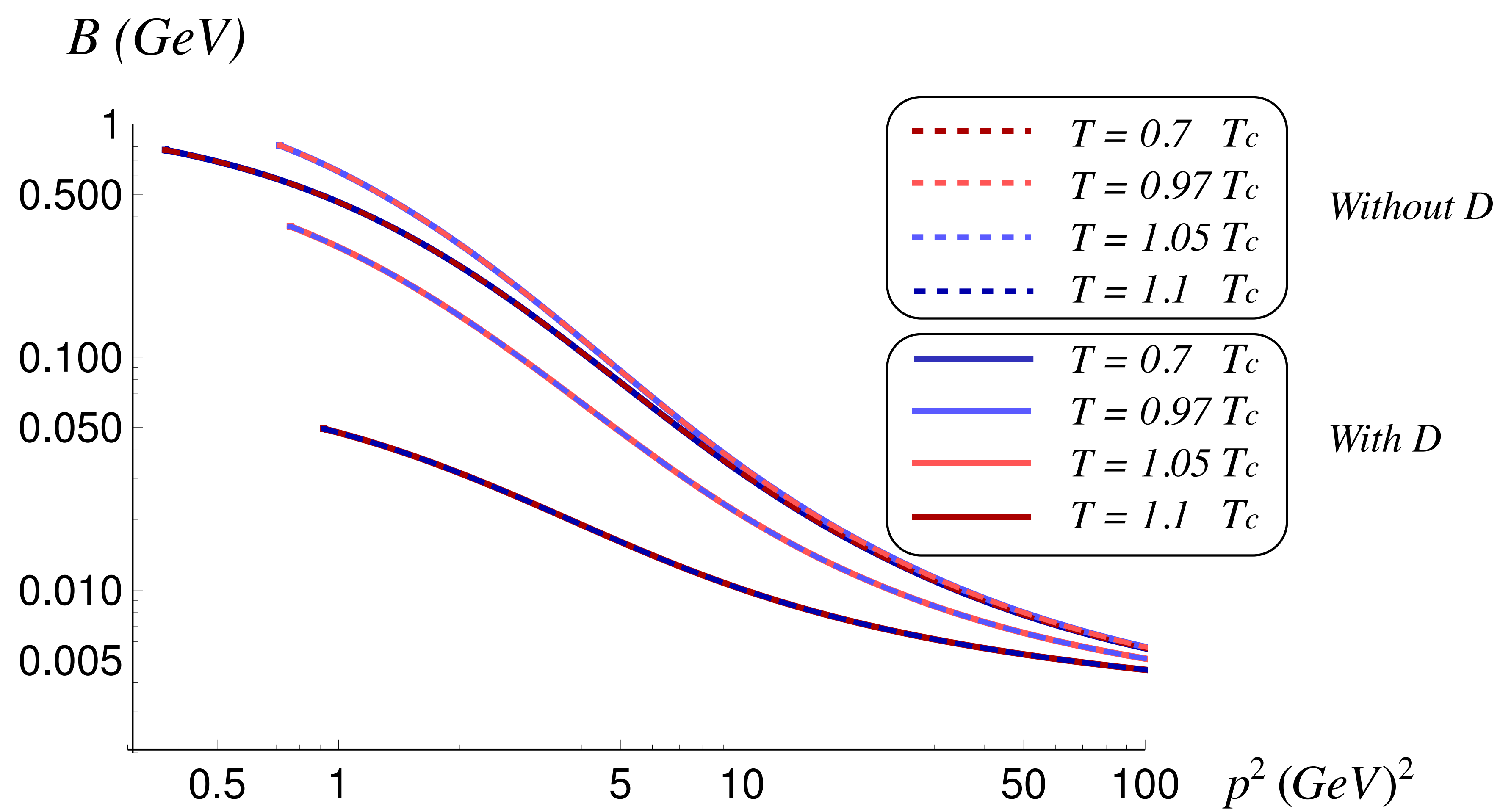
[E. Bilgici, F. Bruckmann, C. Gattringer, and C. Hagen (2008)]
[C.S. Fischer (2009)]



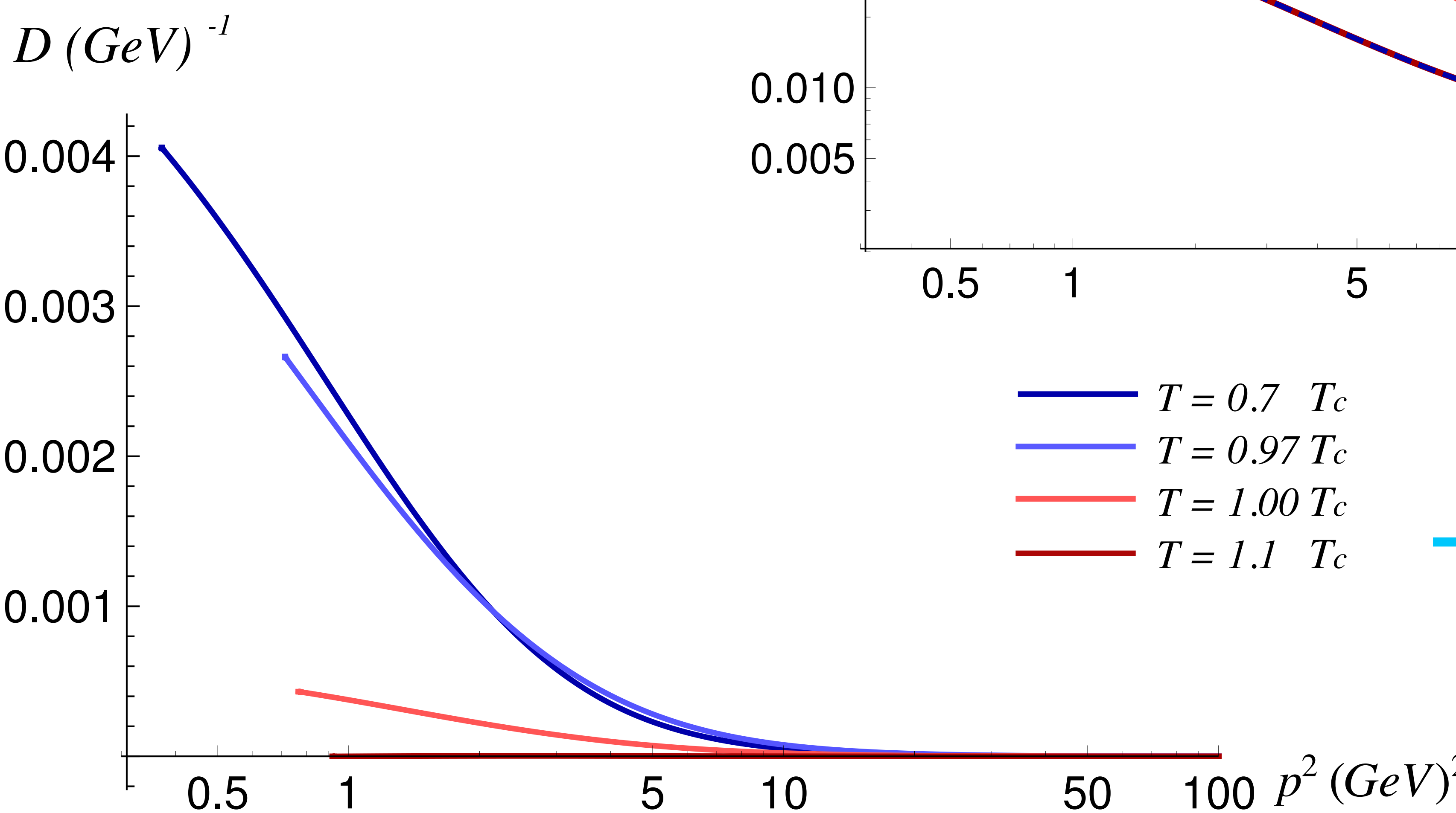
Quenched QCD

Effects of the *D* function

$$S^{-1}(\vec{p},\omega_0) = A(\vec{p},\omega_0)\,\vec{\gamma}\,\vec{p} + C(\vec{p},\omega_0)\,\omega_0\gamma_4 + B(\vec{p},\omega_0) + \omega_0\gamma_4\,\vec{p}\,\vec{\gamma}\,D(\vec{p},\omega_0)$$



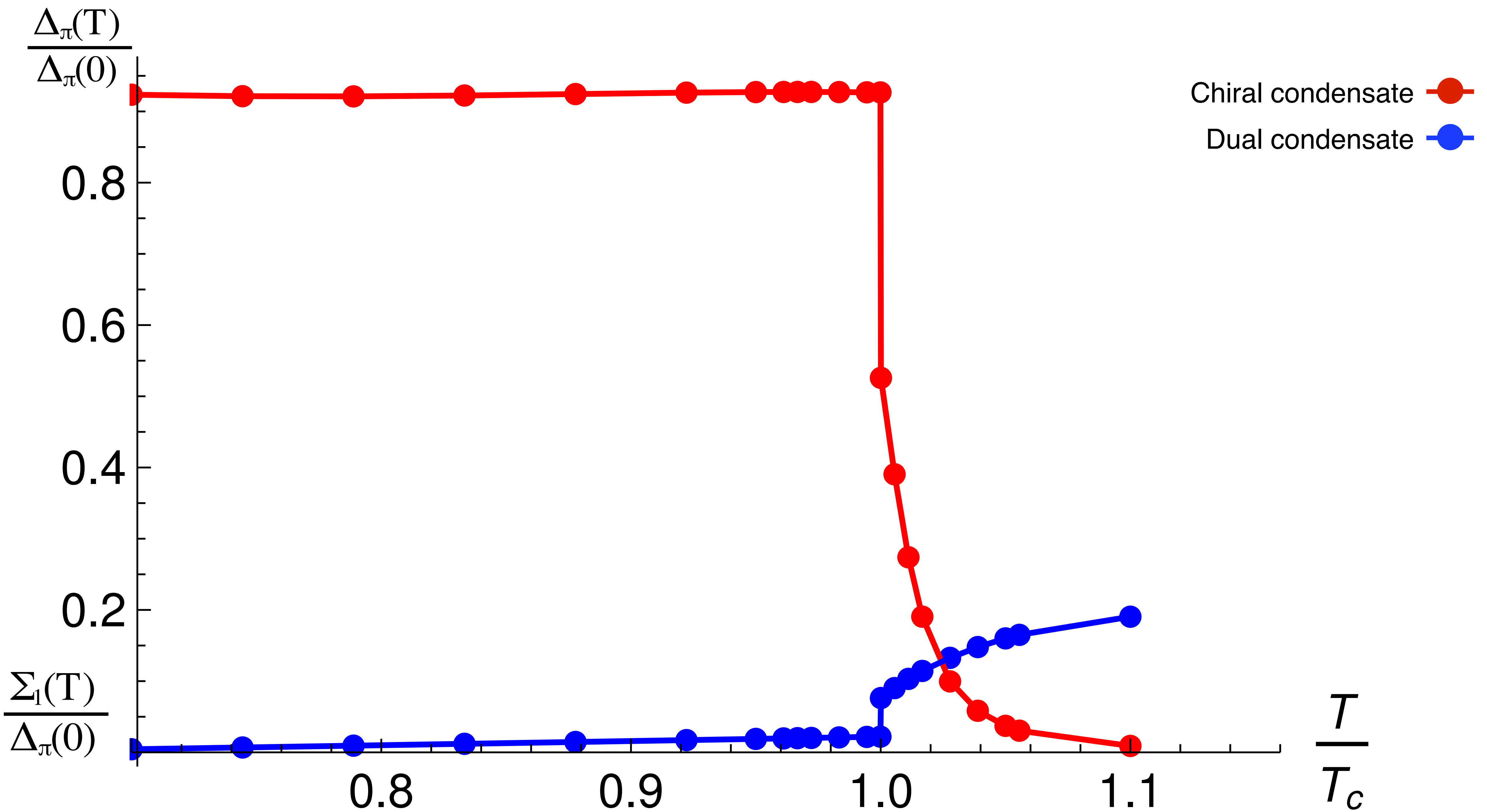
$$p^2 = (\omega_0)^2 + \vec{p}^{\,2}$$



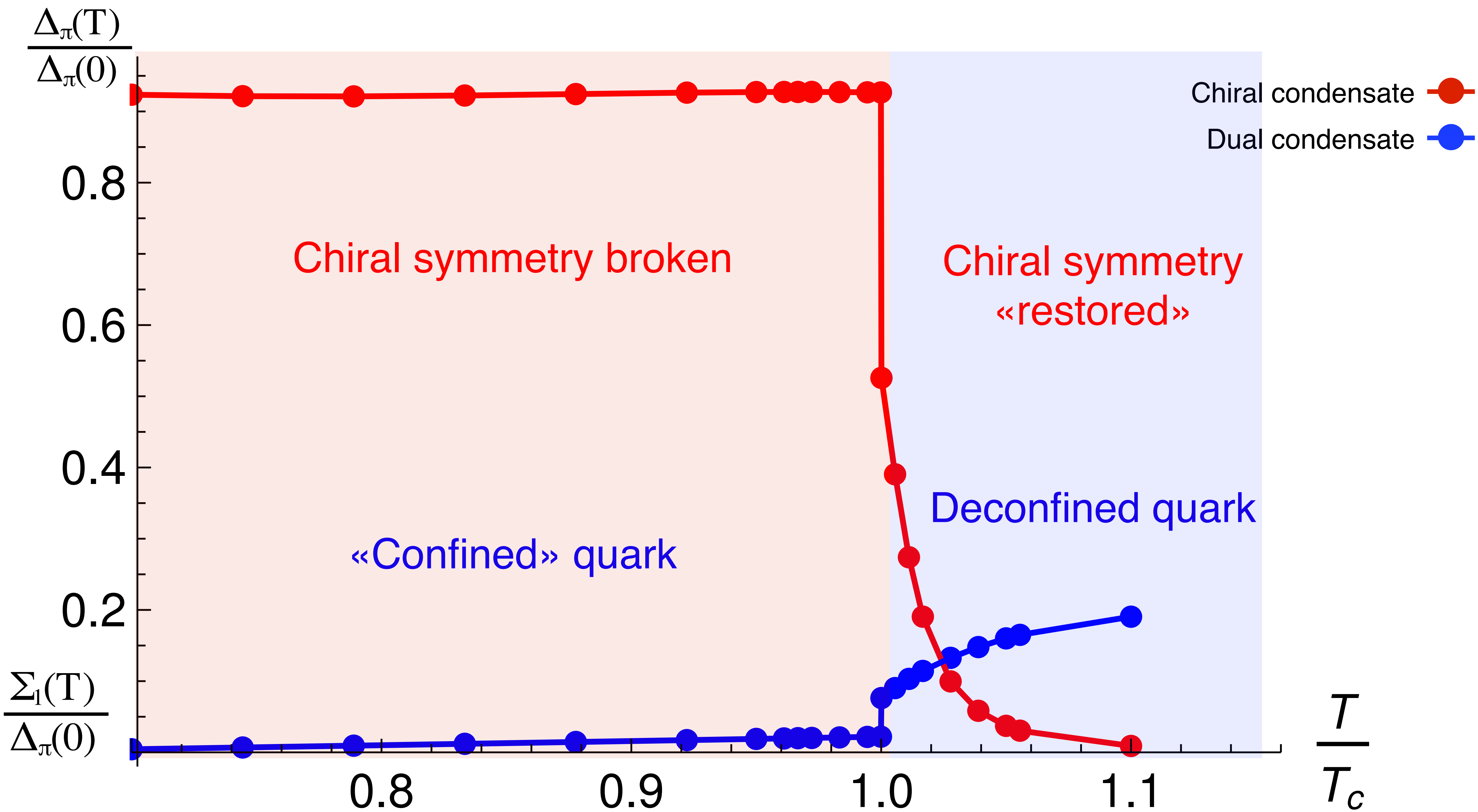
Relative contribution :

→ < 0.01 % to the *B* dressing

Chiral Condensate and dual condensate



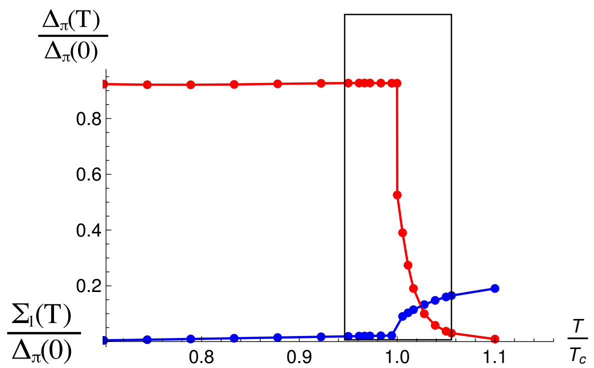
Chiral Condensate and dual condensate

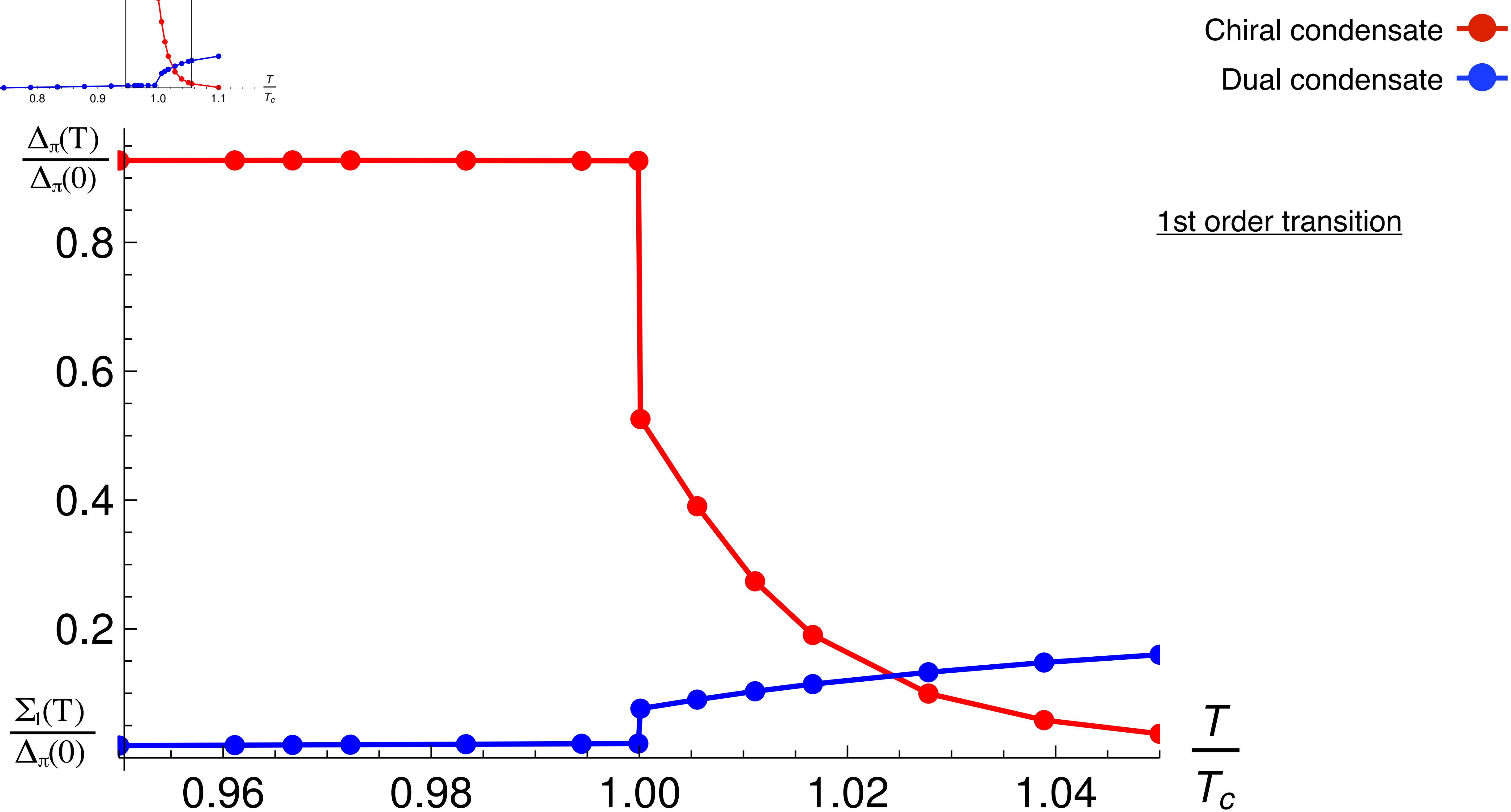


Contant Romain

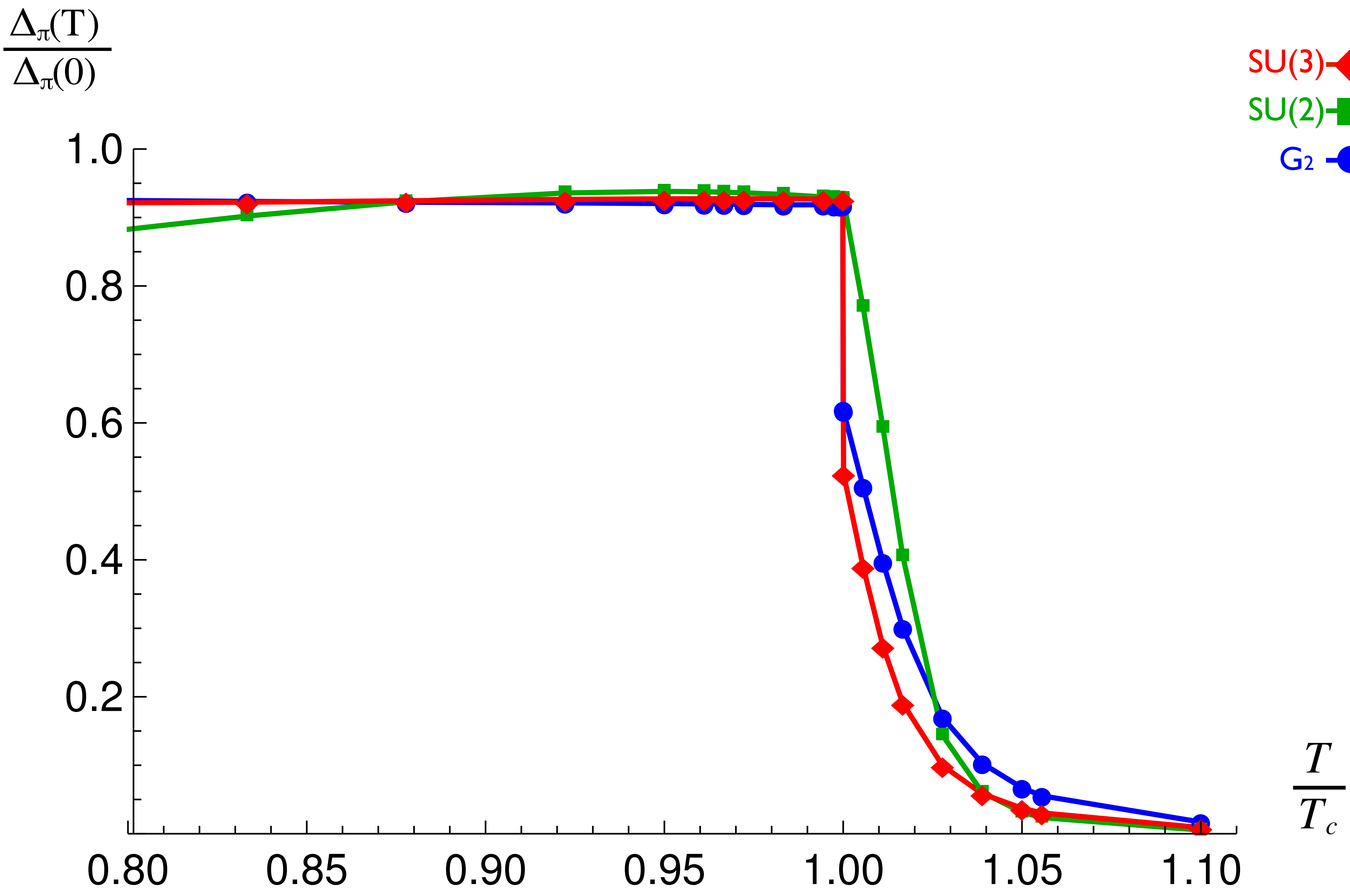
Chiral Condensate and Dual condensate

Type of transition

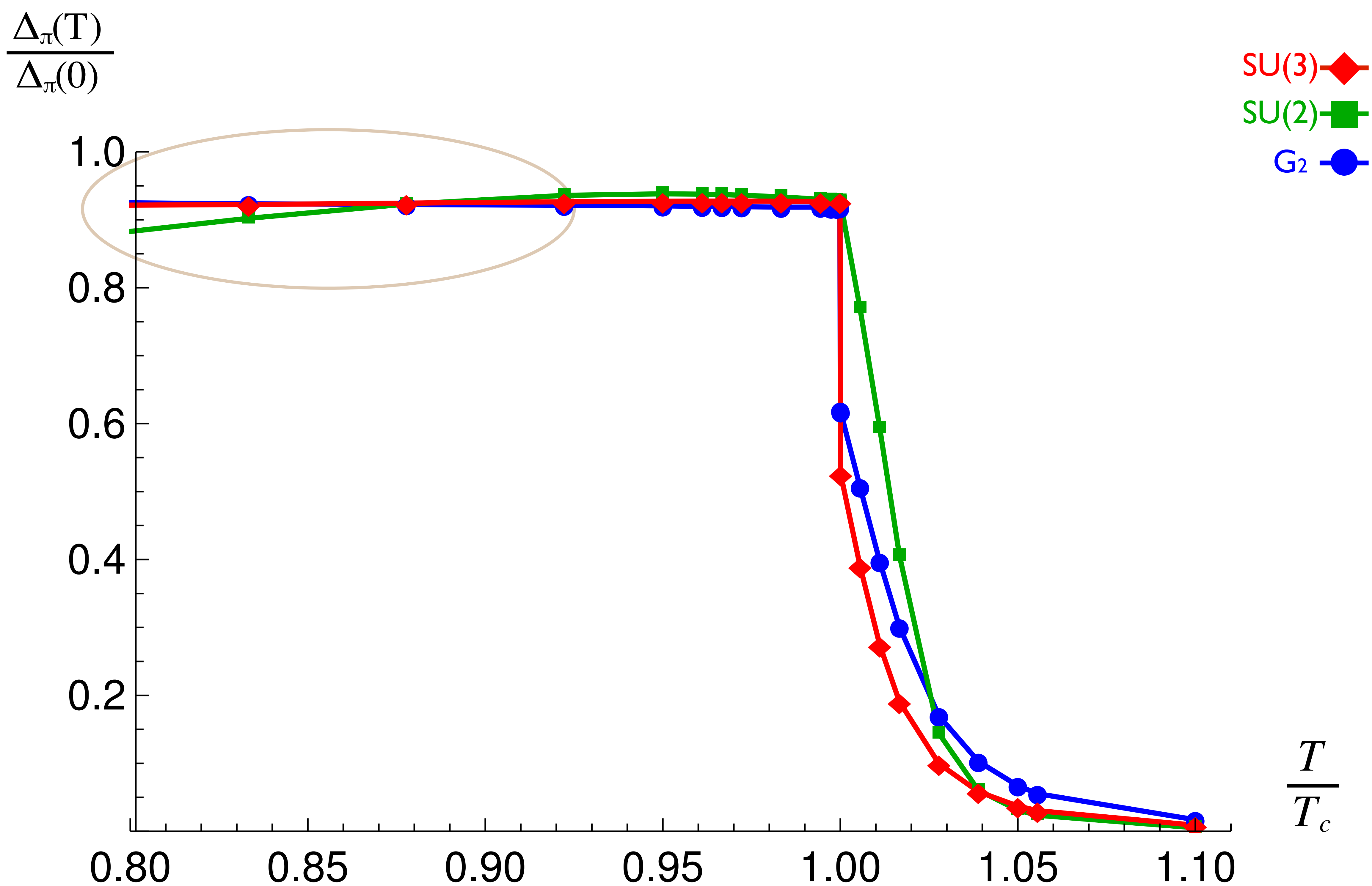




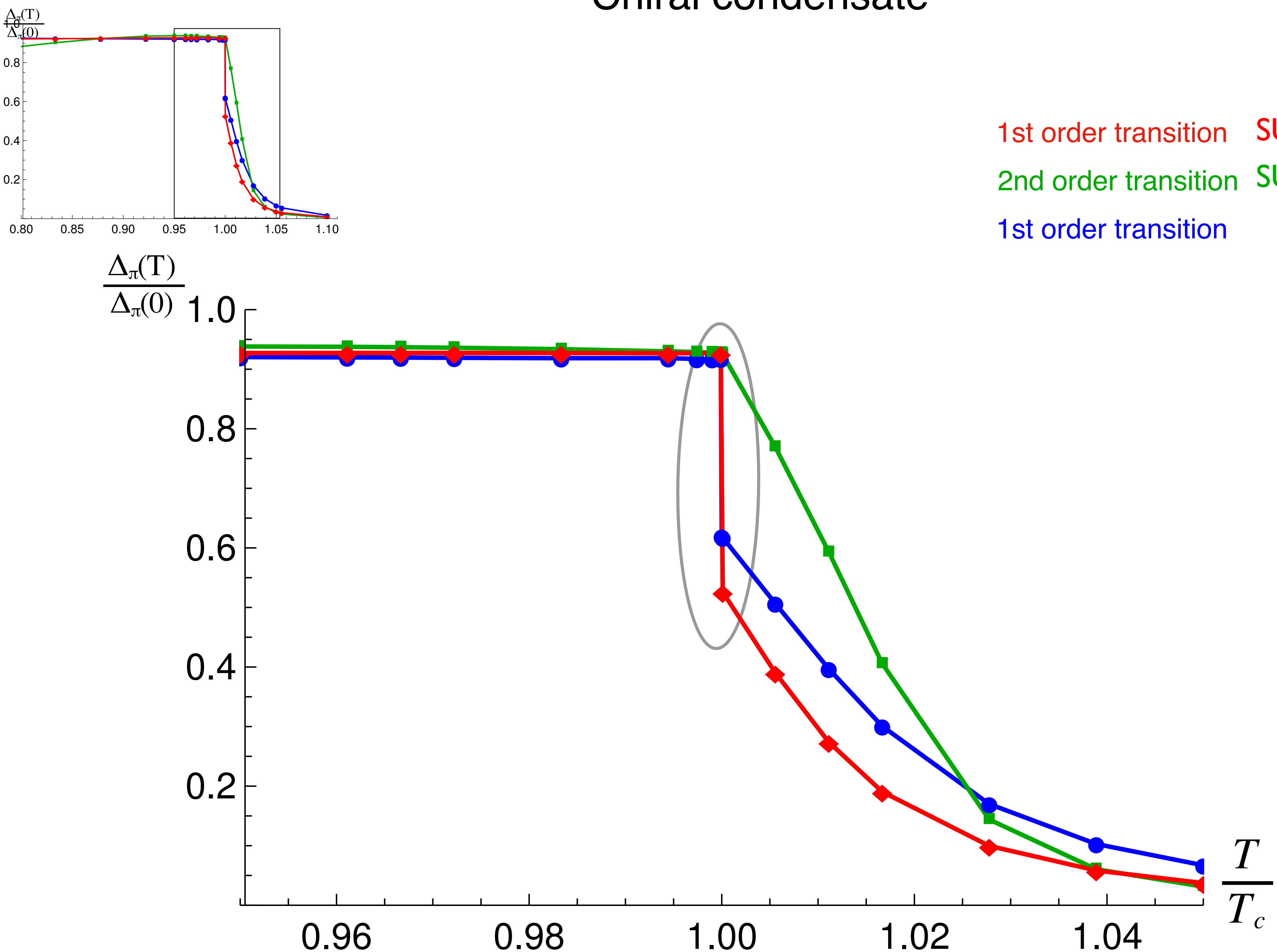
Chiral condensate



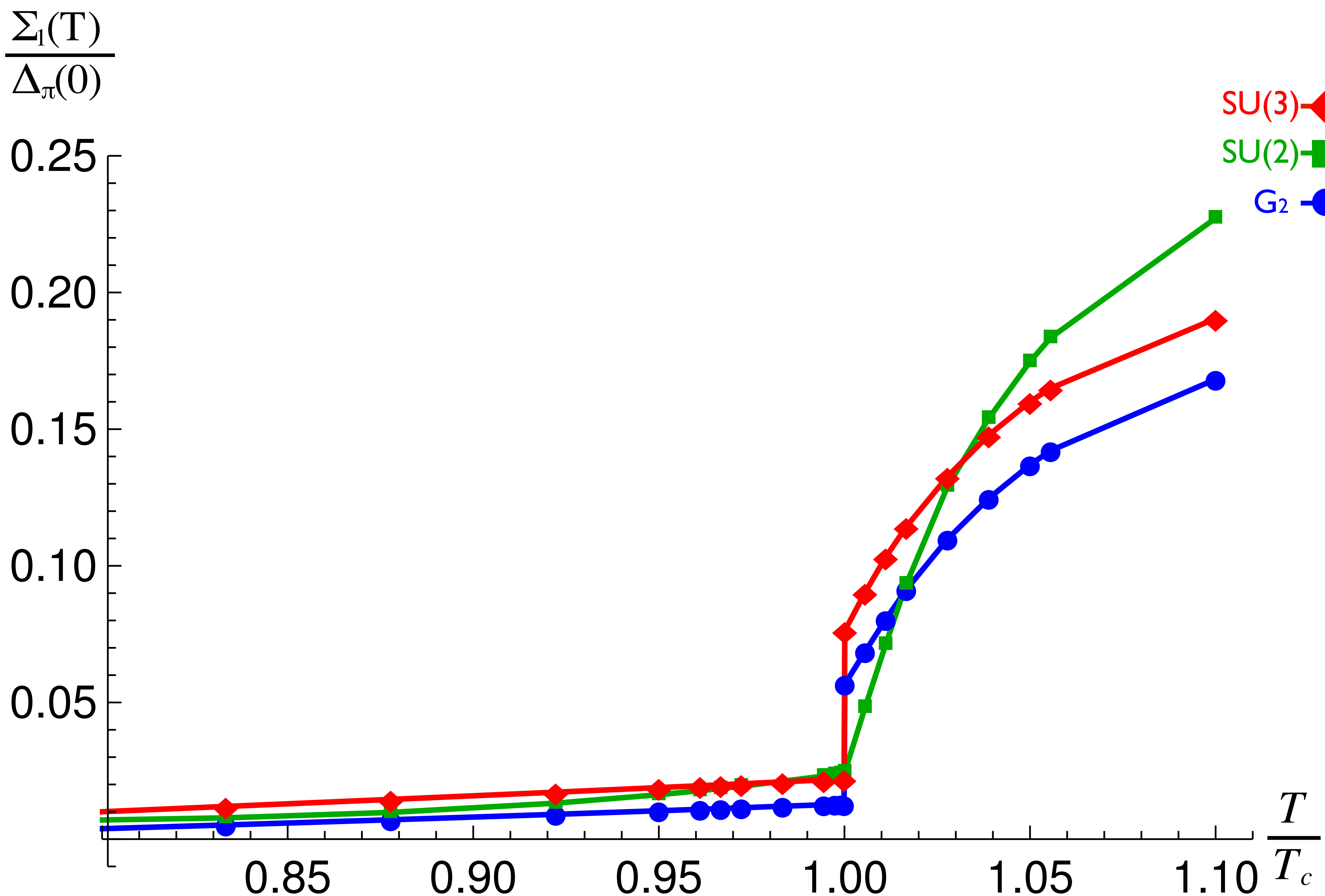
Chiral condensate



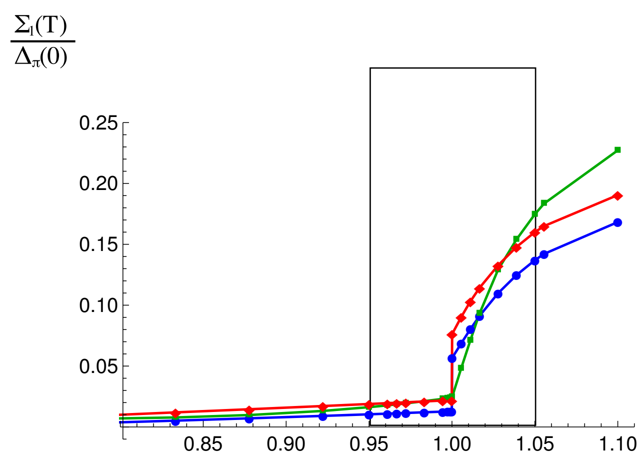
Chiral condensate

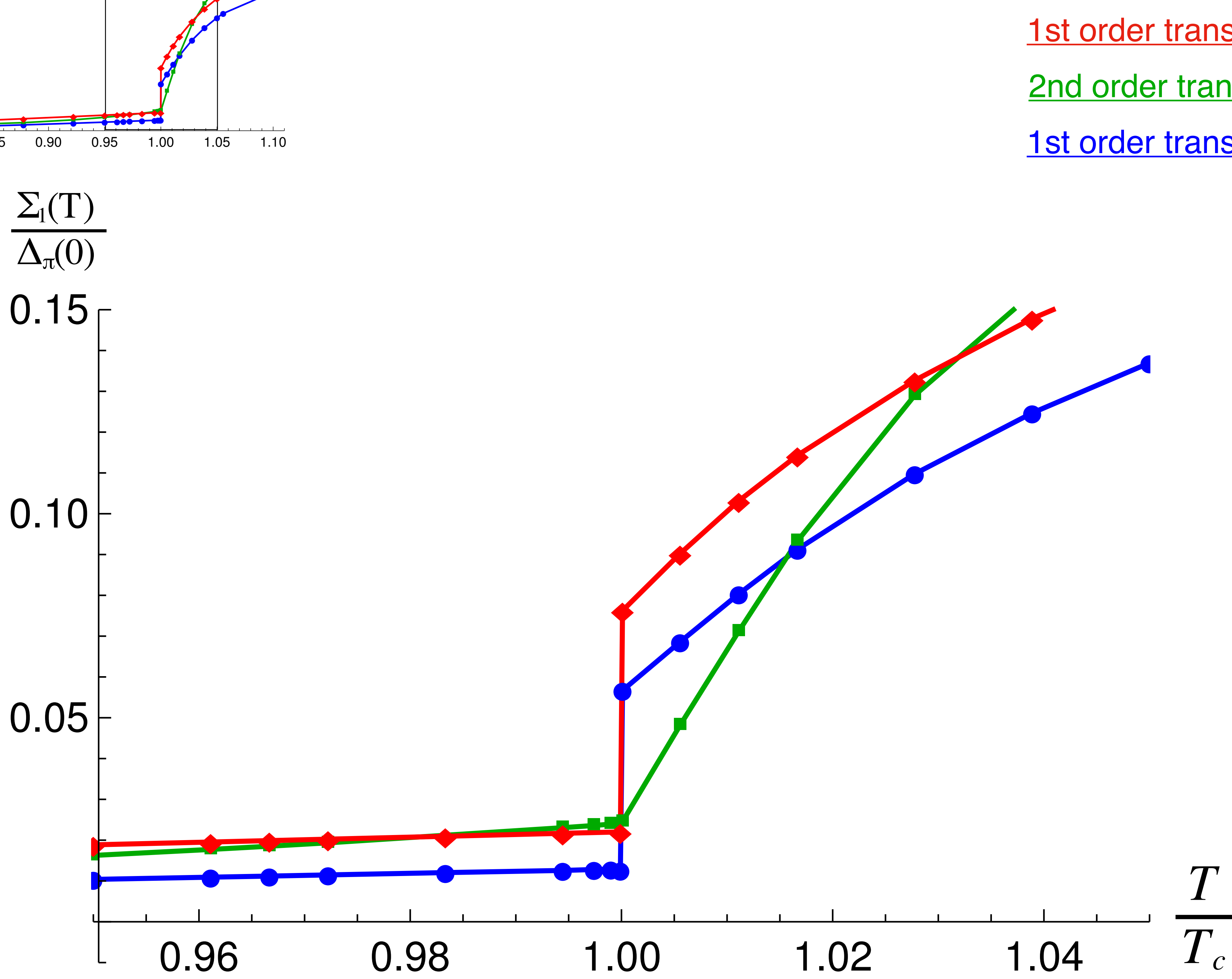


Dual condensate



Dual condensate

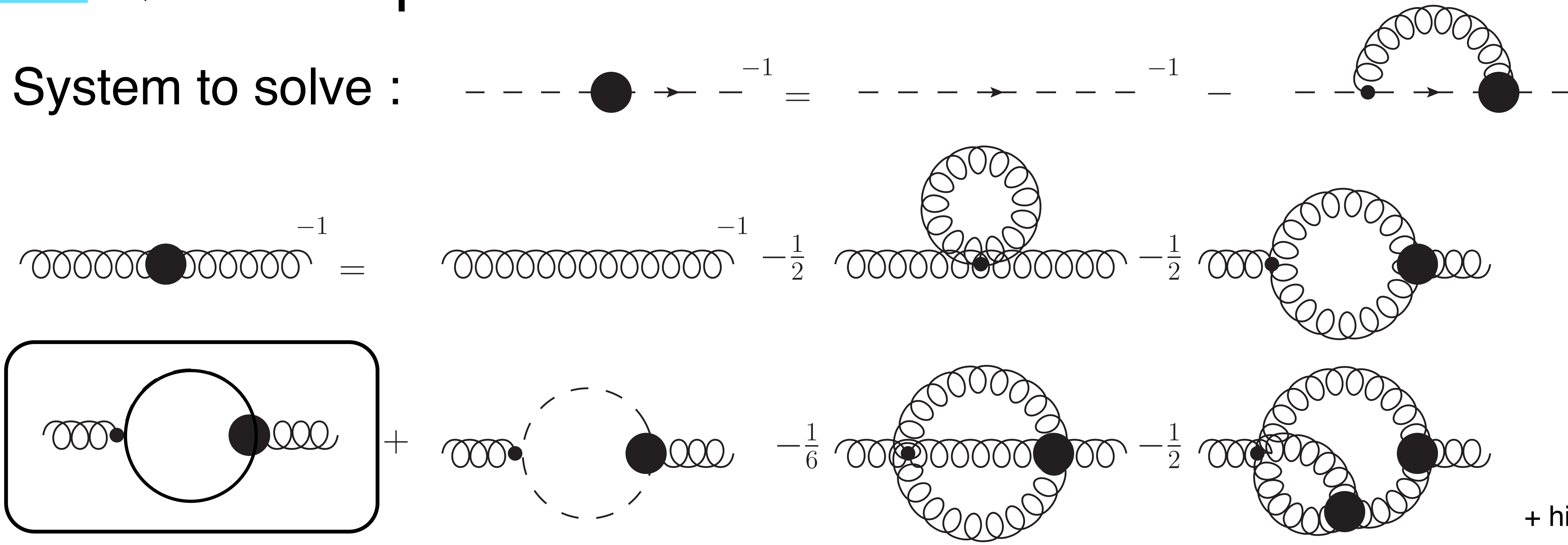




Quark loop

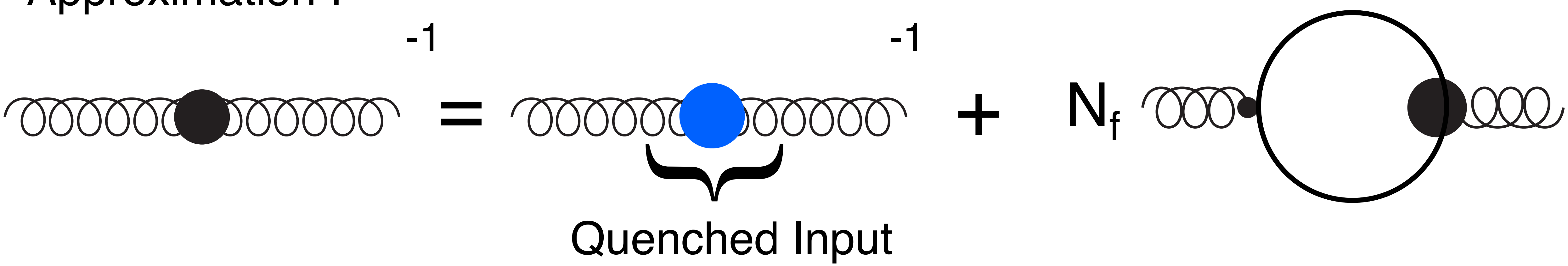
Contant Romain

- System to solve :



+ higher equations ...

- Approximation :

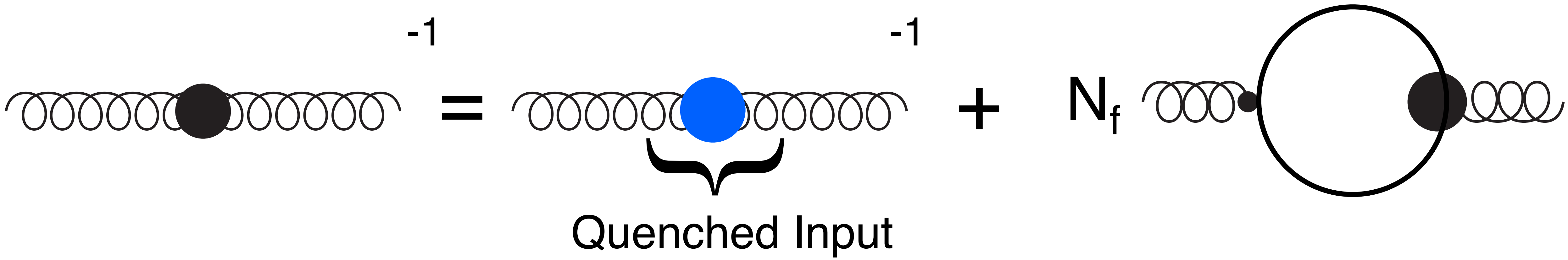


[C.S Fischer , J. Luecker (2012)]

→ Neglect all indirect quark contributions in the gluon dressing

→ Remove spurious divergence with a generalized Brown-Pennington projector

- Adding the quark loop

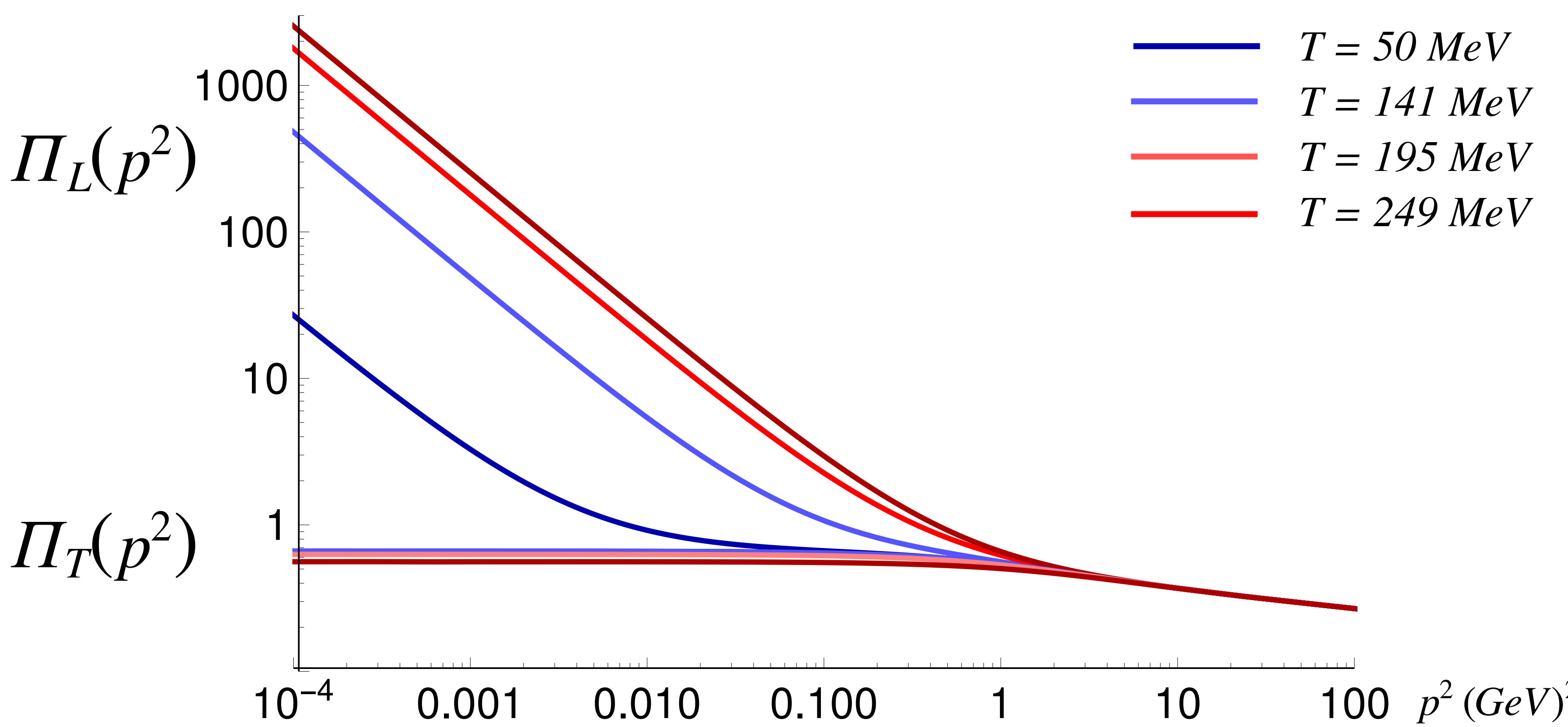


[C.S Fischer , J. Luecker (2012)]

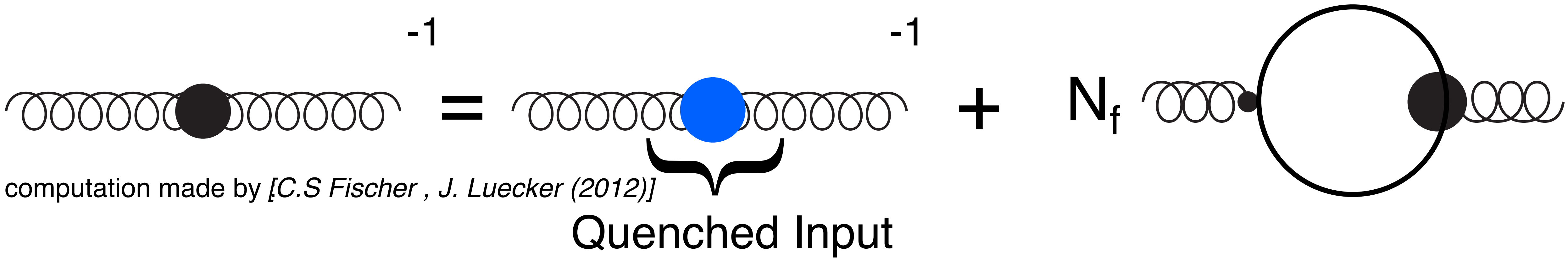
$$\Pi_L(p)p^2 \xrightarrow{p \to 0} (m_{th})^2$$

Debye Screening of the chromo-electric charge

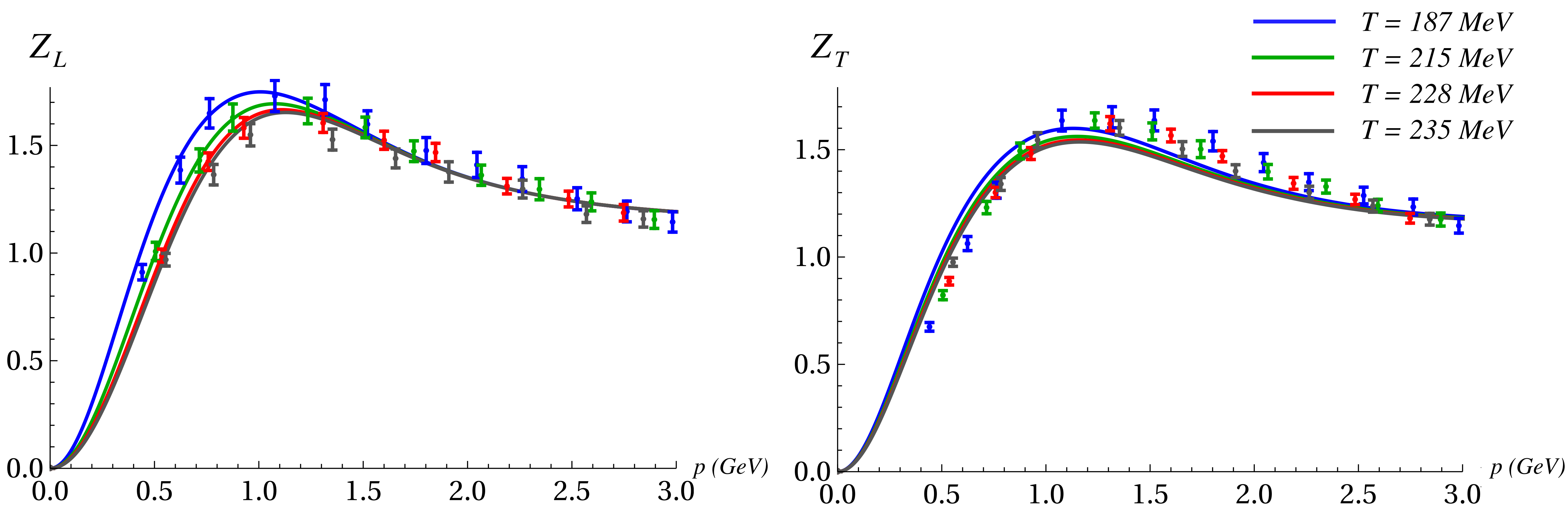
$$\Pi_T(p)p^2 \xrightarrow{p \to 0} 0$$



- Adding the quark loop



First computation made by *[C.S Fischer , J. Luecker (2012)]*

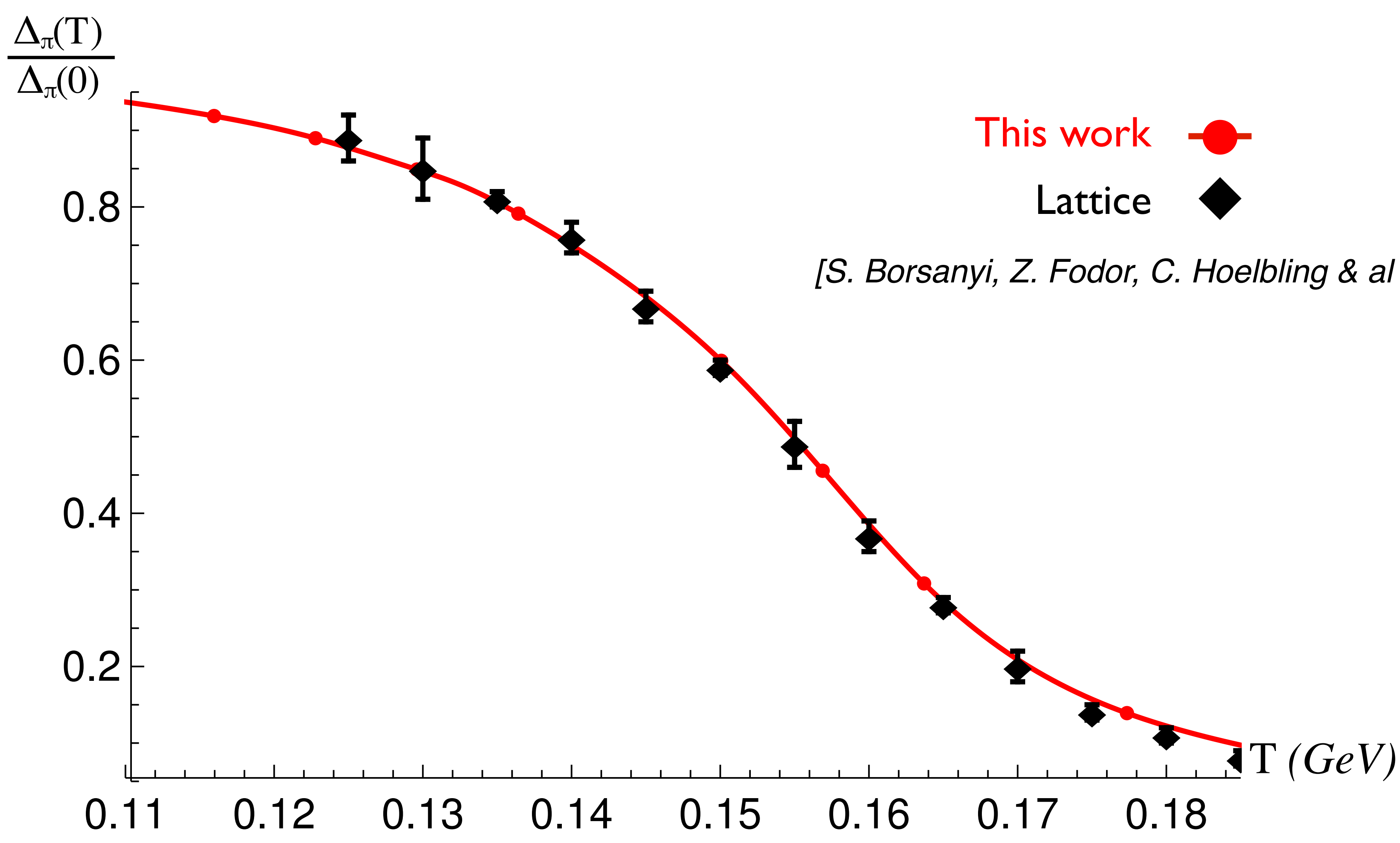


Compared to : *[R.Aouane, F. Burger E.-M. Illgenfritz & al (2012)]*

Chiral condensate

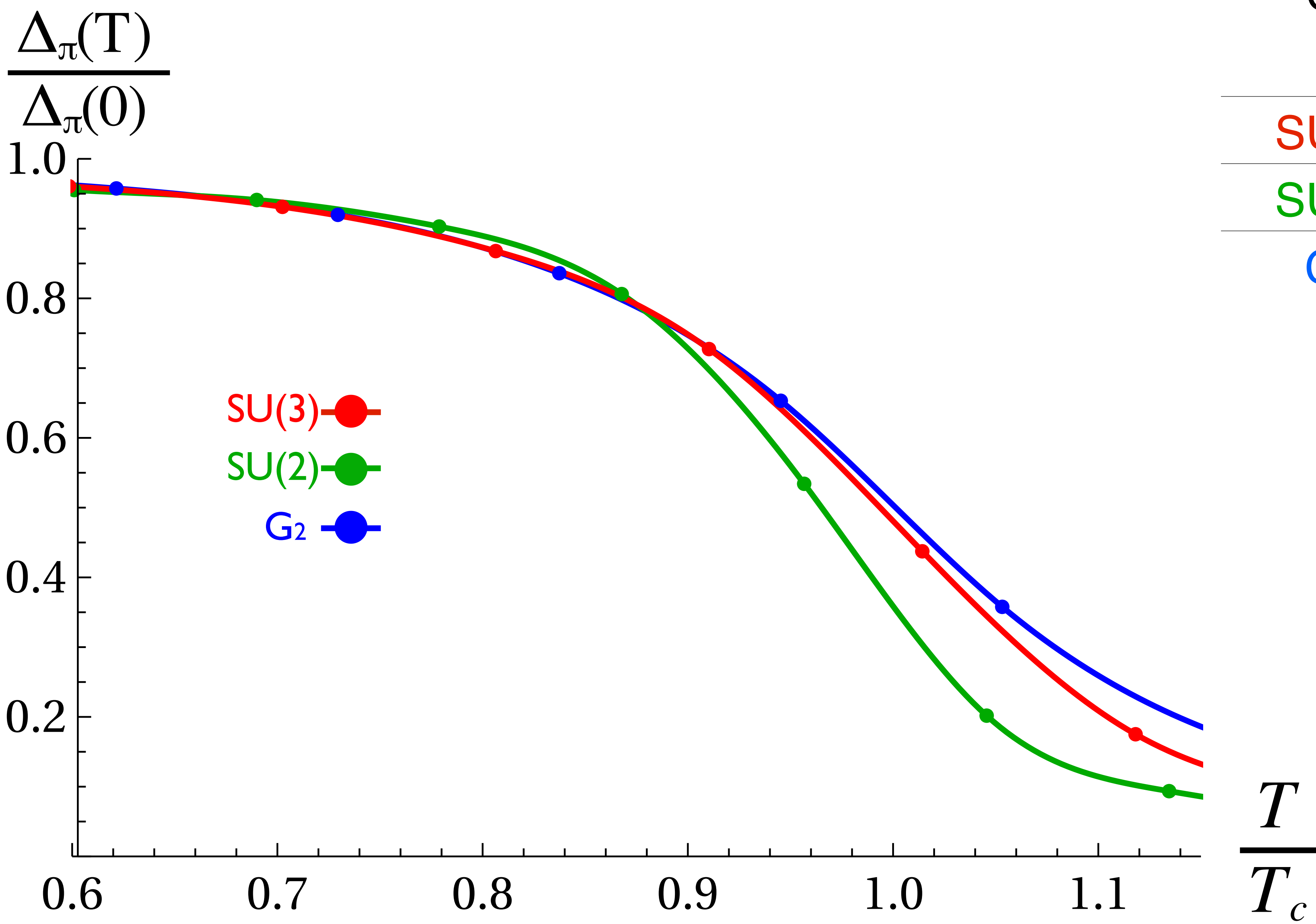
➡ For 2 light flavors <u>and a strange quark</u>, comparison with available lattice results is possible

First computation made by : *[C.S Fischer , J. Luecker (2012)]*



Chiral condensate

For 2 light flavors :

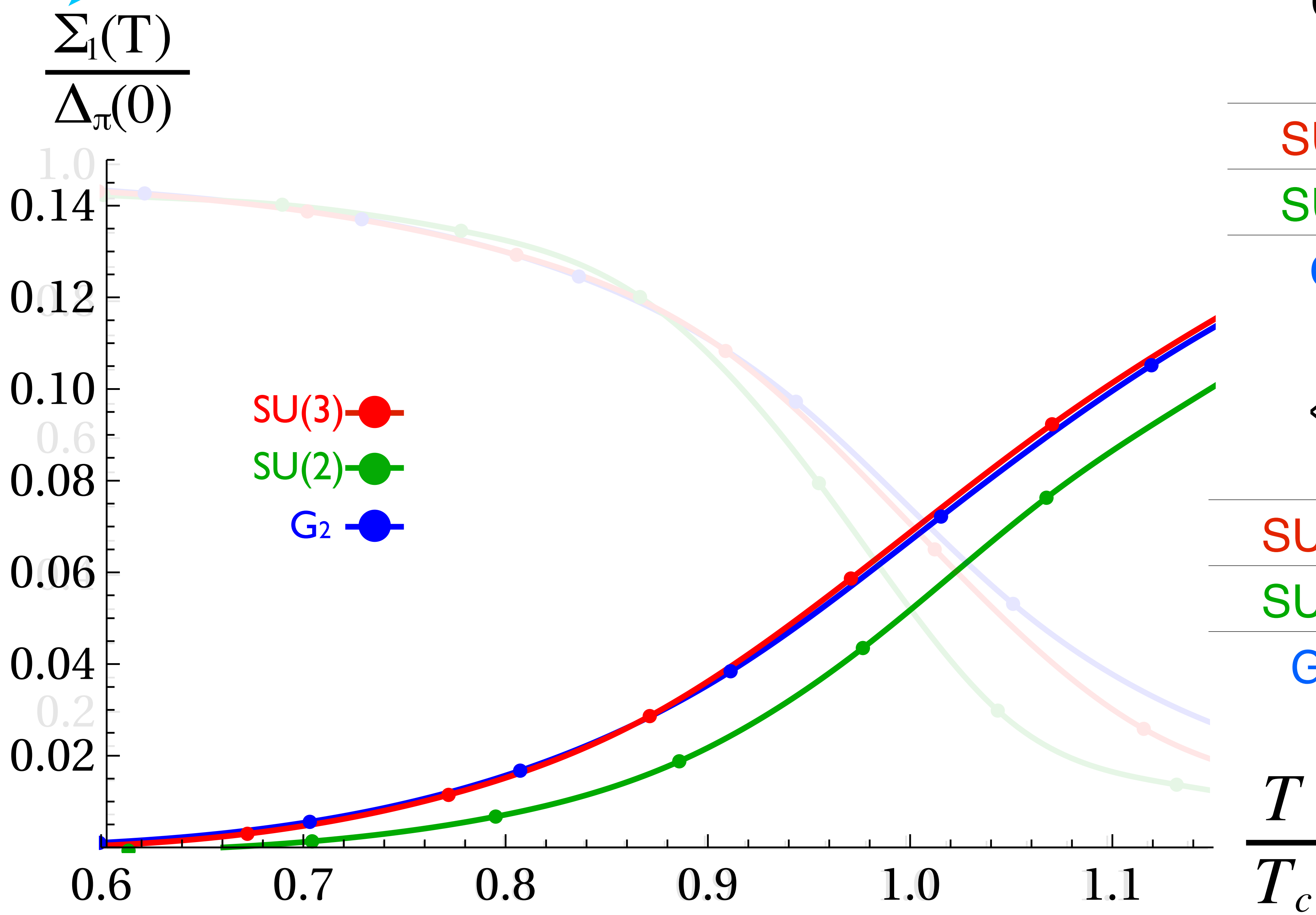


Chiral «restoration» Tc (MeV)

	quenched	2 flavors
SU(3)	277	174
SU(2)	303	218
G2	255	155

Dual condensate

For 2 light flavors :



Chiral «restoration» *Tc (MeV)*

	quenched	2 flavors
SU(3)	277	174
SU(2)	303	218
G2	255	155

«Deconfinement» *(MeV)*

	quenched	2 flavors
SU(3)	277	182
SU(2)	303	222
G2	255	160

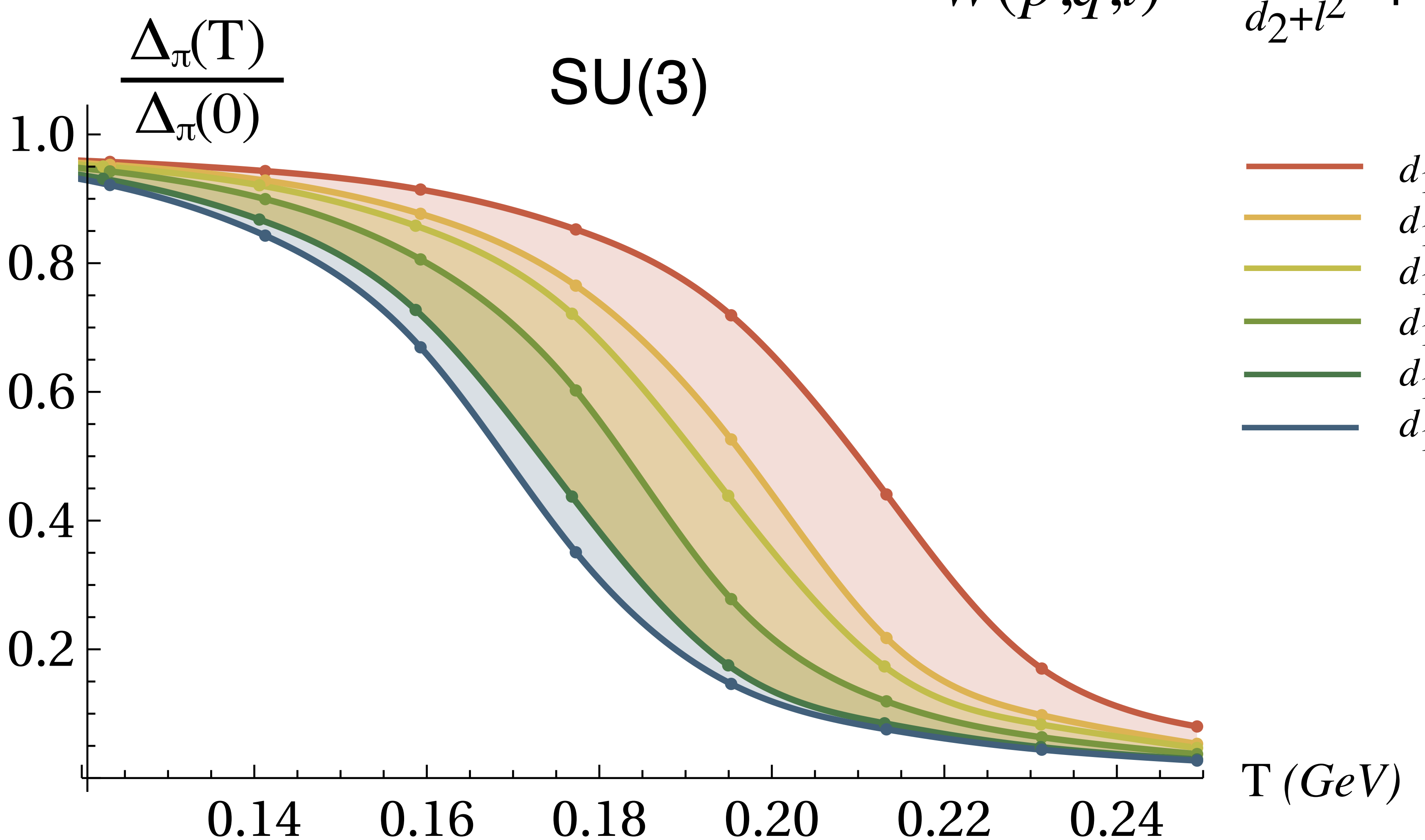
The confinement/deconfinement transitions and chiral transitions occur approximatively at the same temperatures

4 Unquenching
Parameter variation

$$\Gamma_{q\text{-}gl}(p,q,l) = \left(\frac{A(p)+A(q)}{2}\vec{\gamma}, \frac{C(p)+C(q)}{2}\gamma_4 \right) W(p,q,l)$$

$$W(p,q,l) = \frac{d_1}{d_2+l^2} + \frac{l^2}{1+l^2}\left(\frac{\beta_0\,\alpha(\mu)}{4\pi}\ln(l^2+1)\right)^{2\delta}$$

For 2 light flavors :



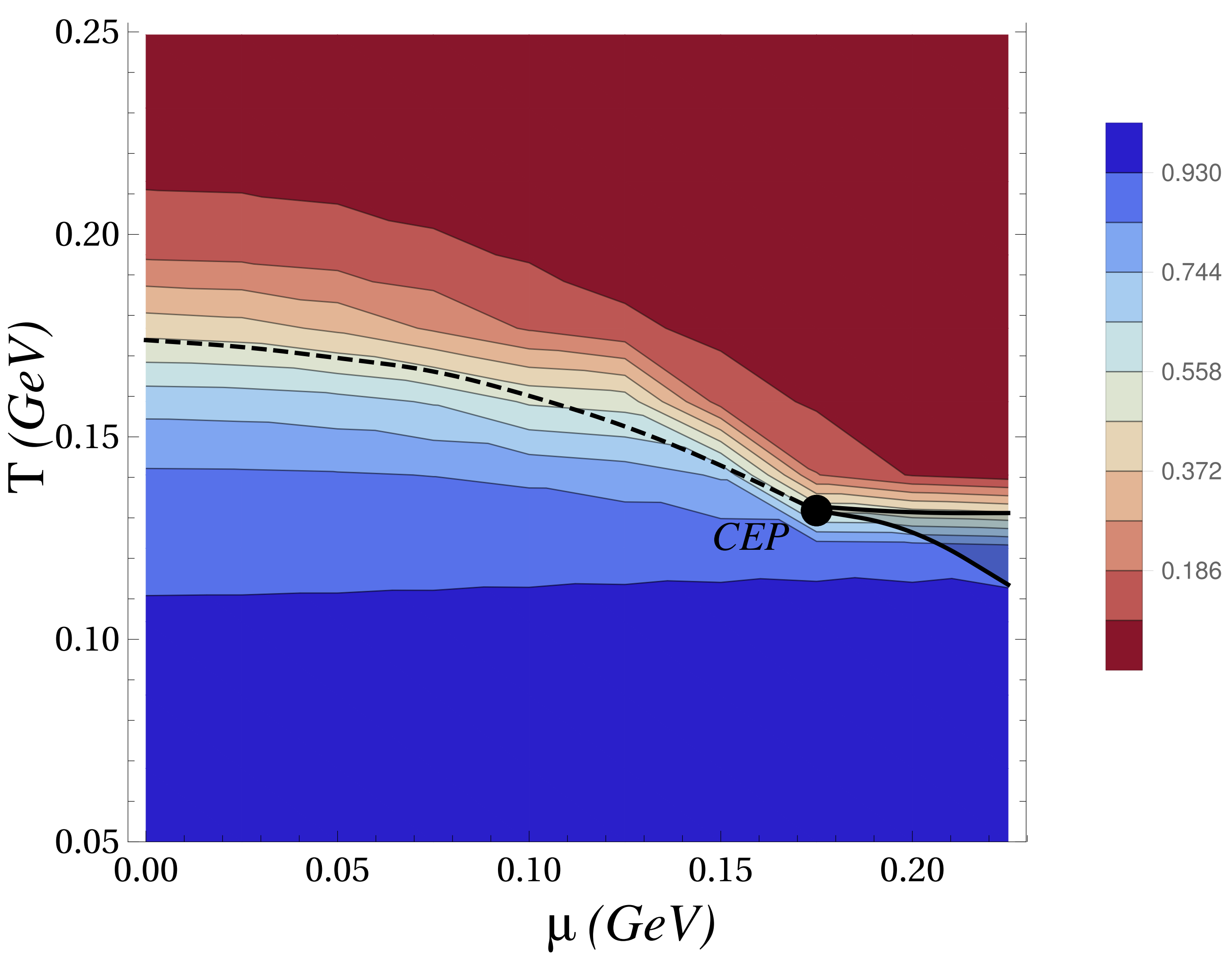
Similar results for the QCD-like theories

A large parameter dependence of the quark-gluon vertex
Require a lot of tuning

Finite μ
Chiral transition

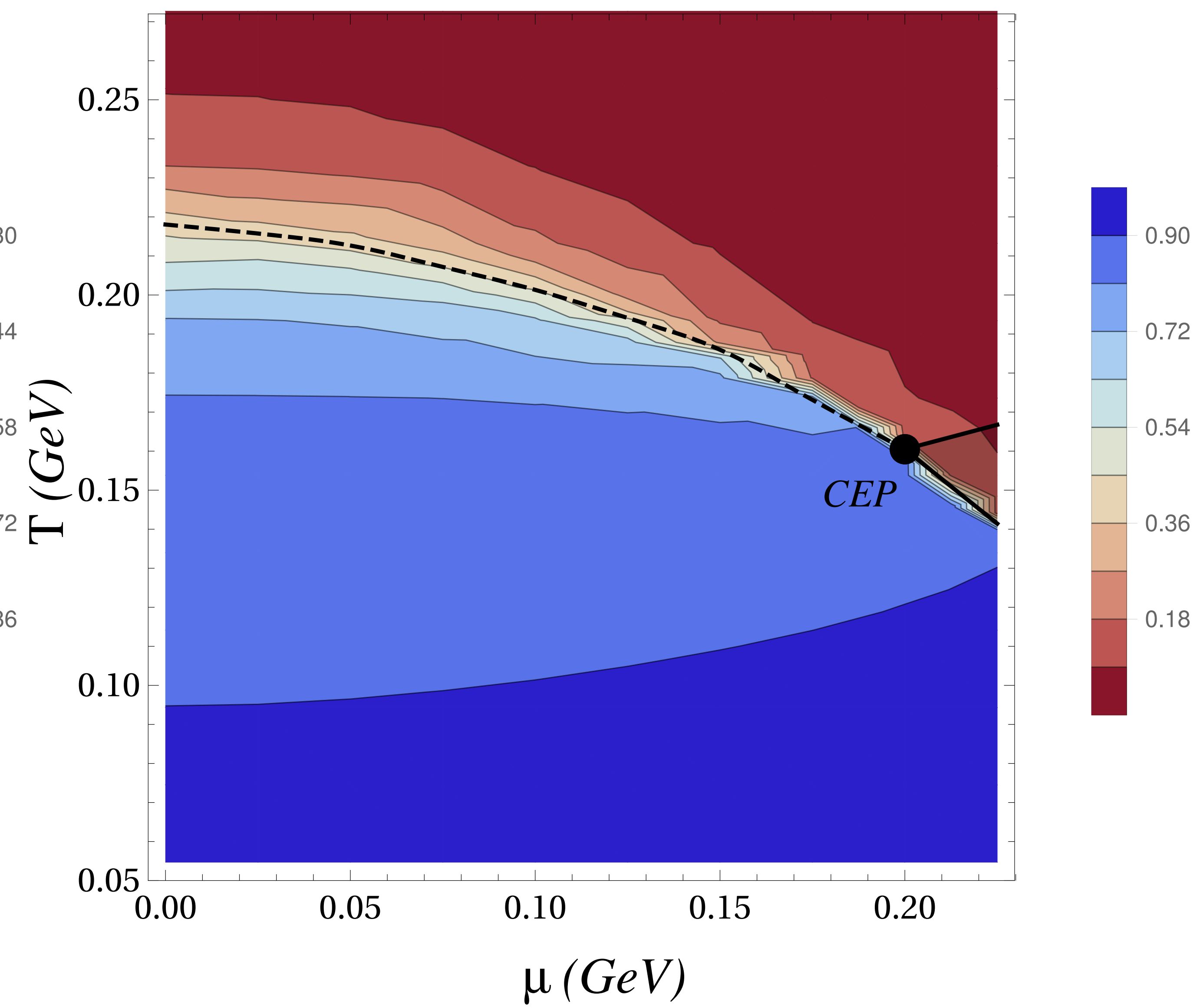
- Shift ω_n to $\omega_n + i\,\mu$
- For 2 light flavors

SU(3)



CEP ≈ (175, 132) MeV

SU(2)

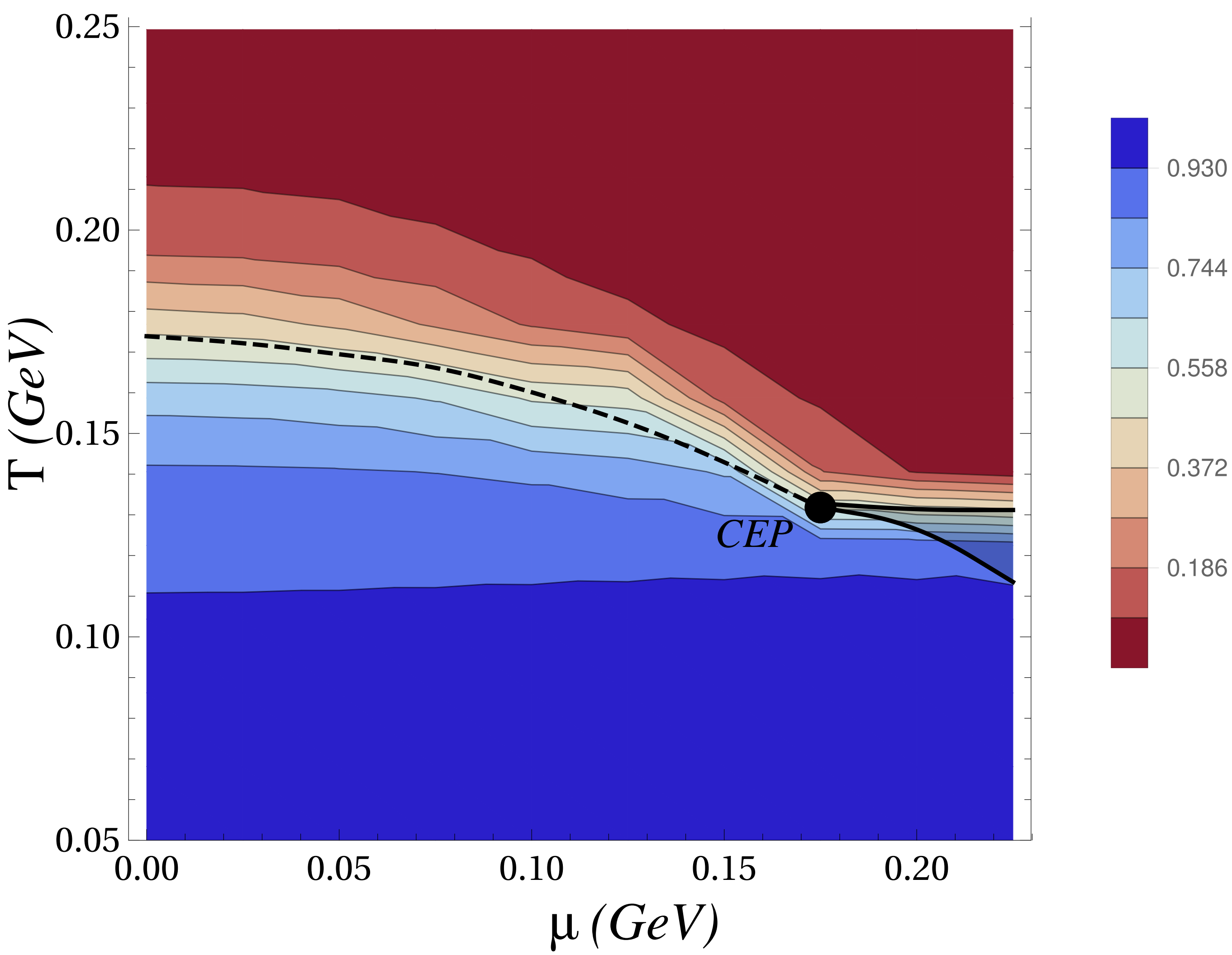


CEP ≈ (200, 160) MeV

Chiral transition

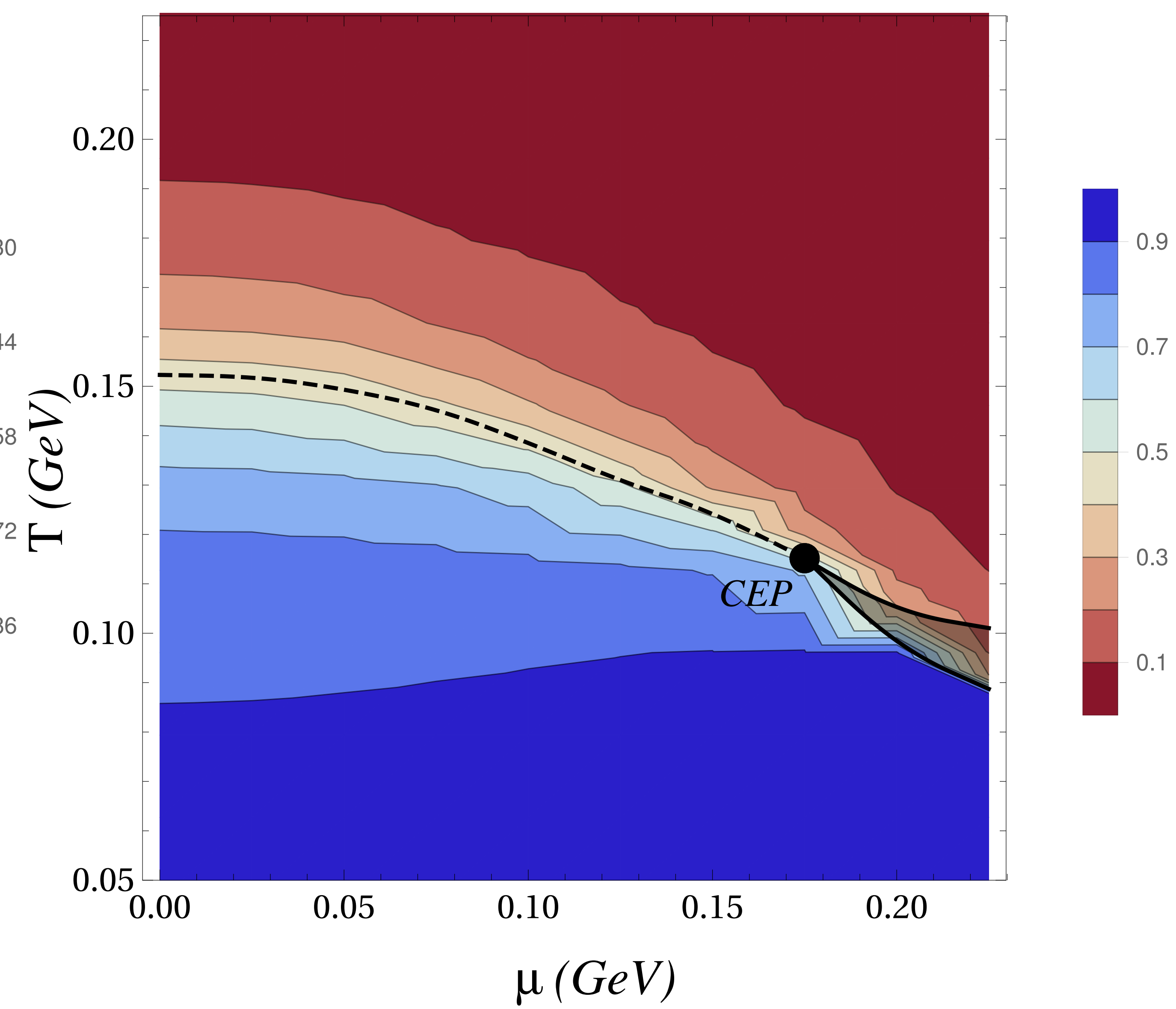
- Shift ω_n to $\omega_n + i\,\mu$
- For 2 light flavors

SU(3)



CEP ≈ (175, 132) MeV

G2



CEP ≈ (175, 115) MeV

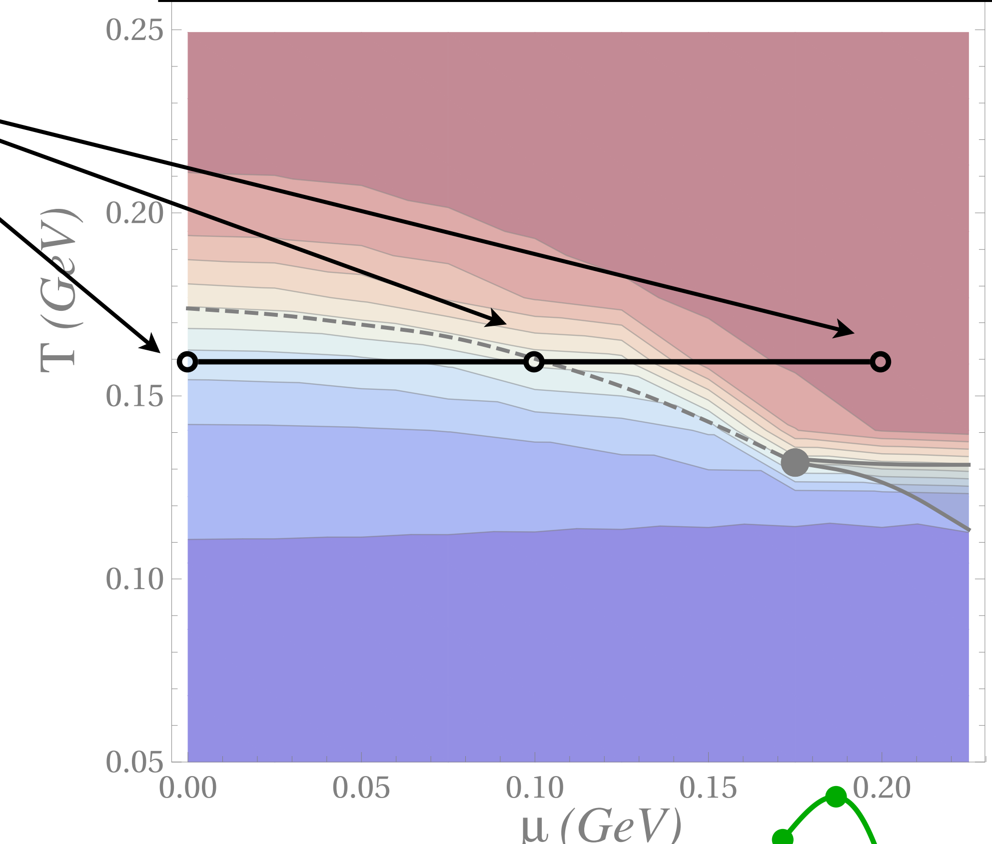
5 Finite μ
Preliminary : confinement

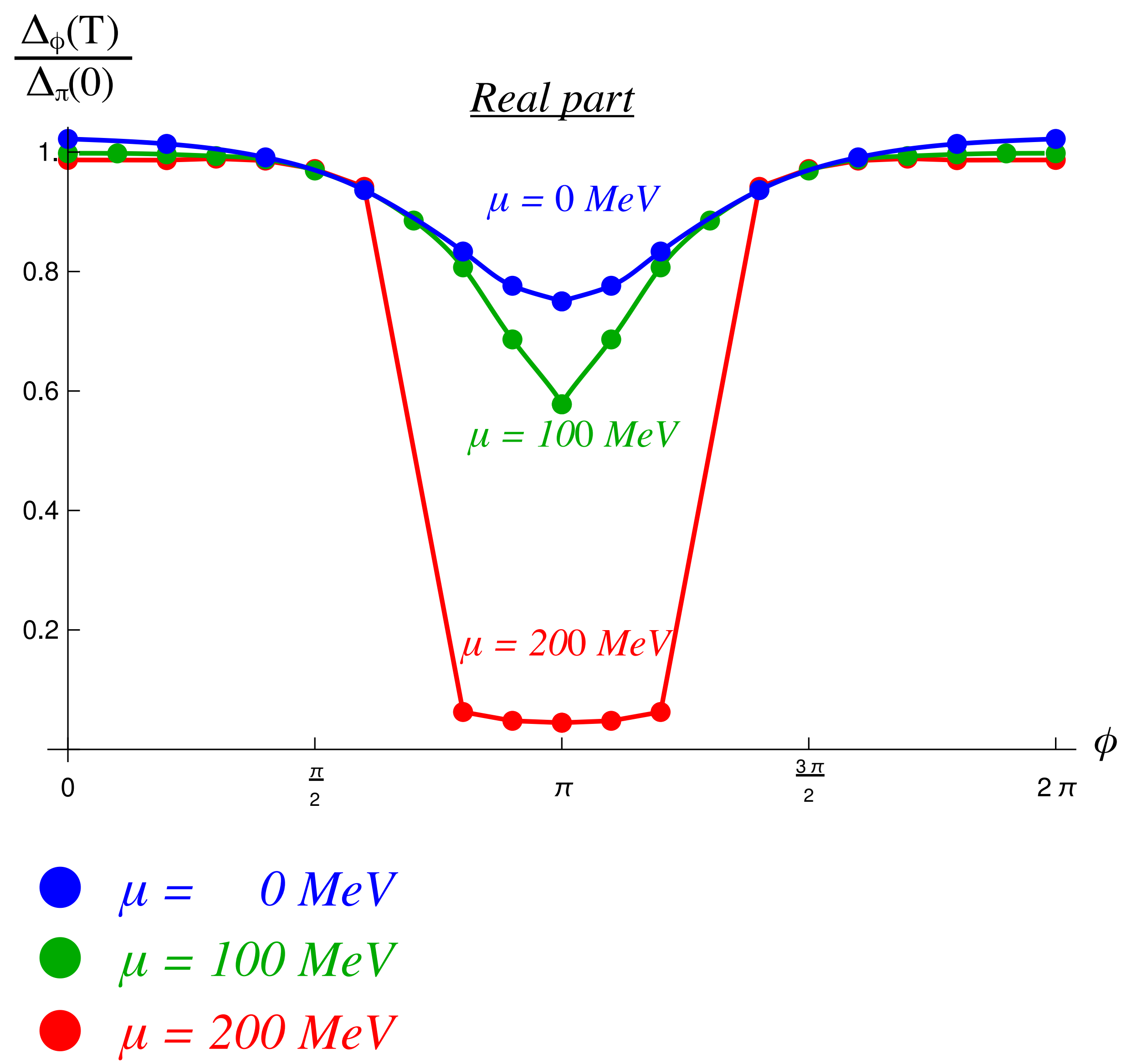
Computation on-going

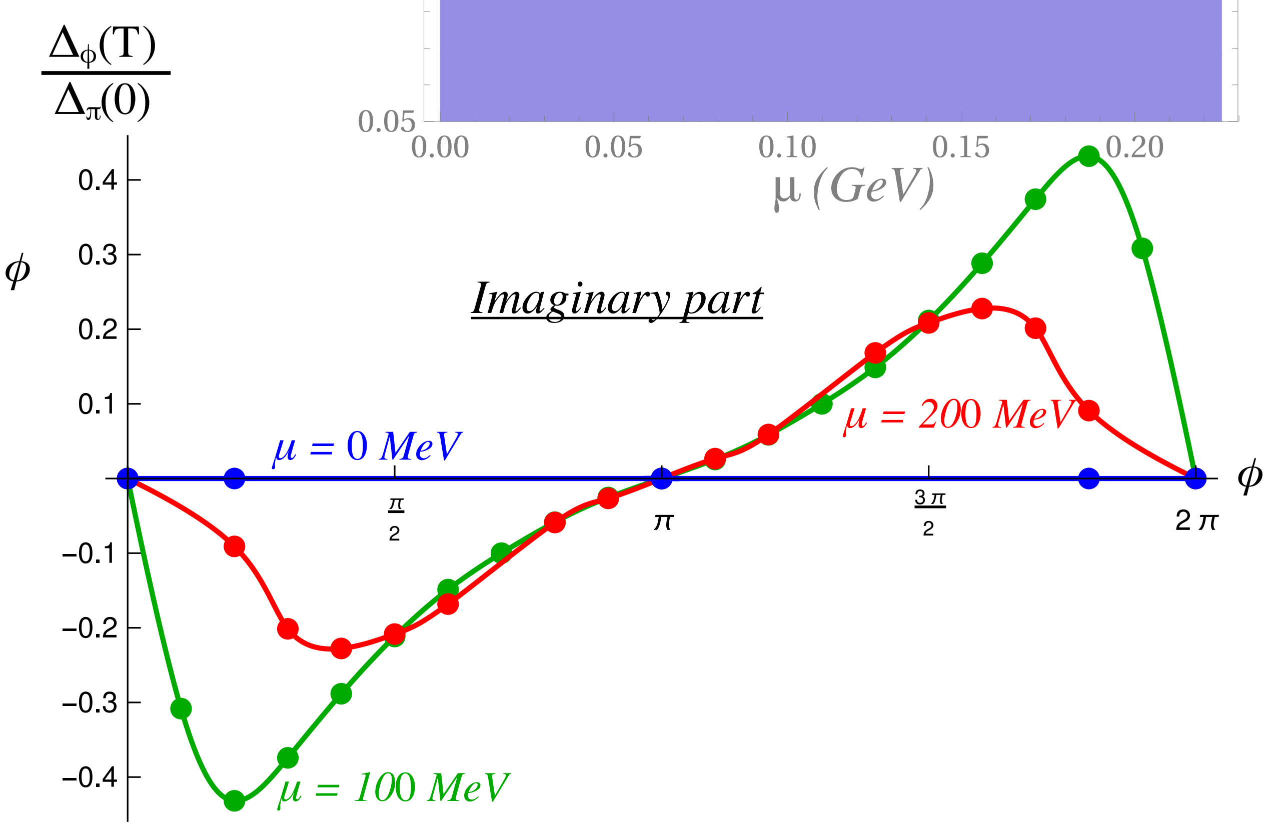
$$\Delta_\phi(T) = Z_2(Z_m) N_c \, T \sum_{\omega_n(\phi)} \int_p \frac{d^3\vec{p}}{(2\pi)^3} \mathrm{Tr}[S(\vec{p},\omega_n(\phi))]$$

$$\omega_n = \pi T \left(2n + \frac{\phi}{\pi}\right)$$

- Chemical potential effects on the dual condensate
  - Follow the line $T = 159\ MeV$ for selected μ

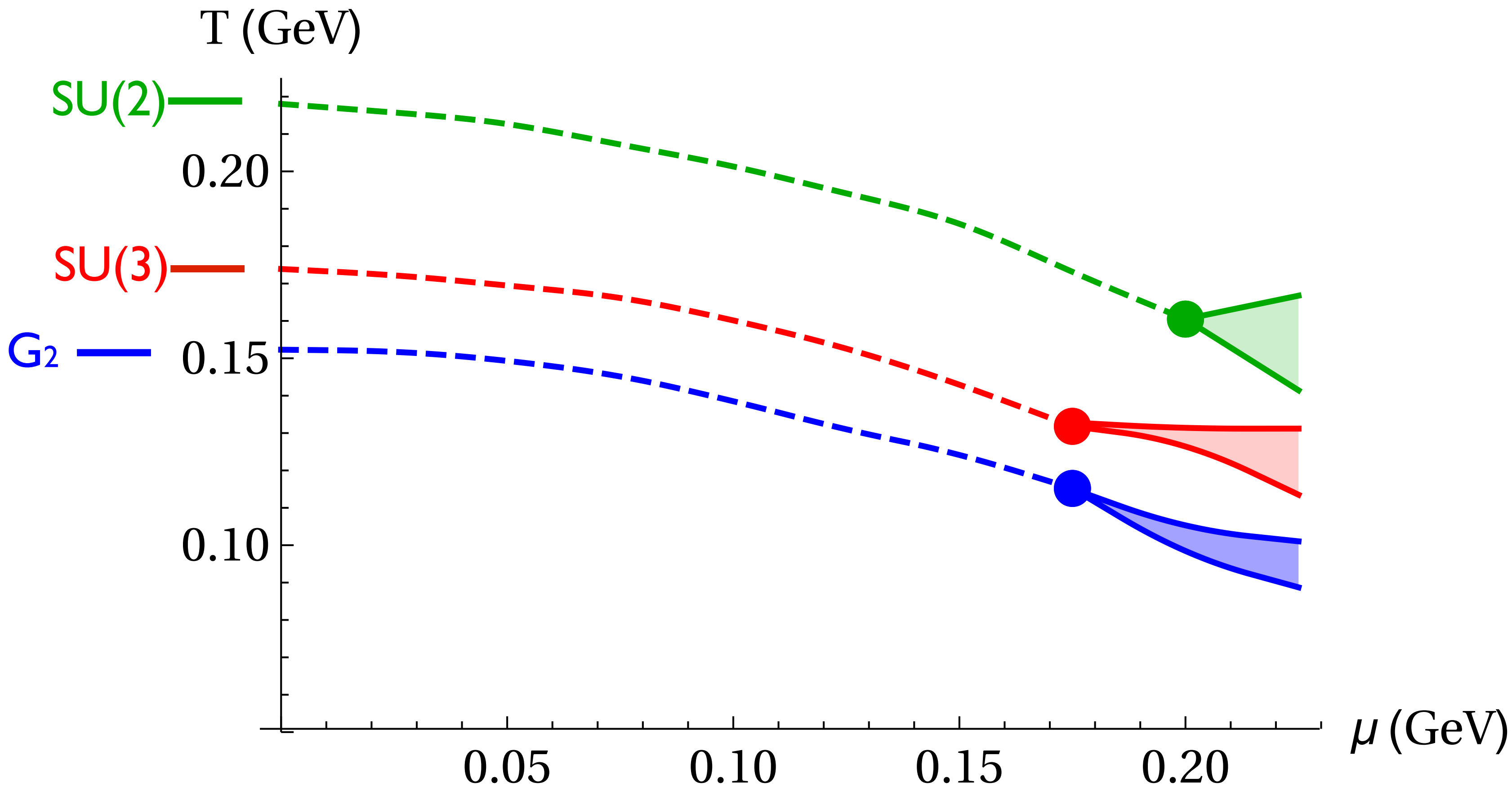






Computation on-going

- Increase the grid resolution
- Scan the confinement properties of different QCD-like theories at finite μ
- Study of the low temperature and large μ behavior
- Diquark condensate



- The bending of the crossover line does not reproduce lattices results for low μ

Summary

- The D dressing function can be neglected in this truncation at $\mu = 0$
- The quenched results show the expected behavior

→ The truncation can be generalized for different gauge-groups

- Ansatz for the gluon dressing

→ G_2 is a good choice for an evaluation of the truncation effects in medium

→ Parameter dependence of our quark-gluon vertex

Summary

- The *D* dressing function can be neglected in this truncation at $\mu = 0$
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→ The truncation can be generalized for different gauge-groups

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→ Parameter dependence of our quark-gluon vertex

- An unquenching procedure is possible

→ The qualitative behavior of the order parameters is respected

- The qualitative behavior remains the same for different quark-gluon vertex parameters
- The (pseudo)-critical temperature for chiral and deconfinement are close to each other

→ The (pseudo)-critical temperature depends on the quark-gluon vertex parameters

Summary

- The *D* dressing function can be neglected in this truncation at $\mu = 0$
- The quenched results show the expected behavior
  - → The truncation can be generalized for different gauge-groups
  - → G_2 is a good choice for an evaluation of the truncation effects in medium
  - → Parameter dependence of our quark-gluon vertex
- An unquenching procedure is possible
  - → The qualitative behavior of the order parameters is respected
  - → The (pseudo)-critical temperature depend on the quark-gluon vertex parameters
- At finite μ
  - → The qualitative behavior of the order parameters is respected
  - → Calculated CEPs remain close for different gauge groups
  - → The bending of the crossover line does not reproduce lattice result

Summary

- The D dressing function can be neglected in this truncation at $\mu = 0$
- The quenched results show the expected behavior

→ The truncation can be generalized for different gauge-groups

→ G_2 is a good choice for an evaluation of the truncation effects in medium

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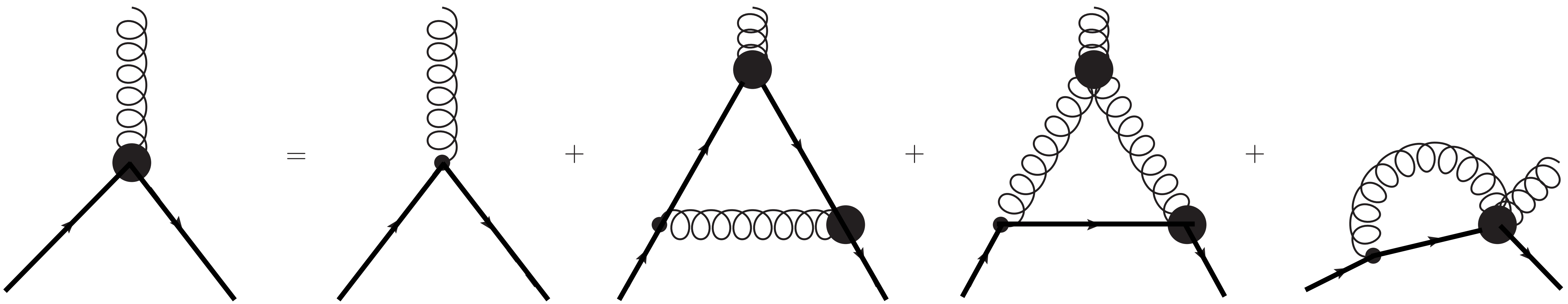
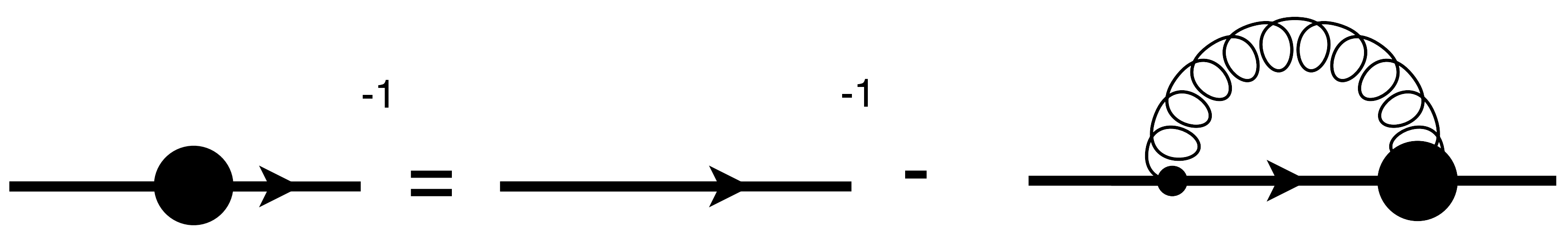
- The quark-gluon vertex

→ New system to solve :





- The quark-gluon vertex

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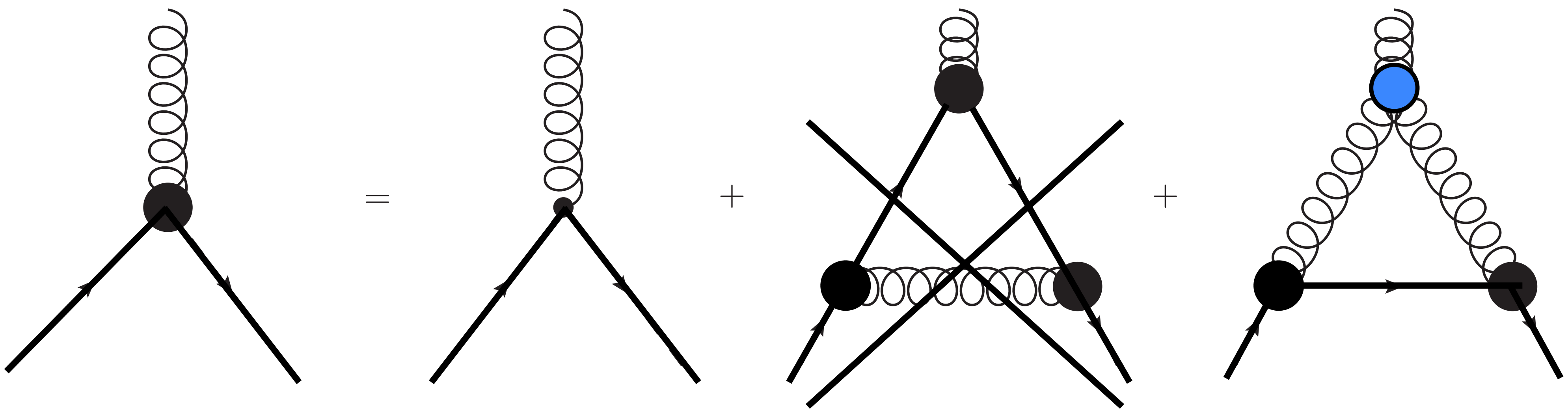


- Follow the approximation used in vacuum study

[R.Williams (2015)]

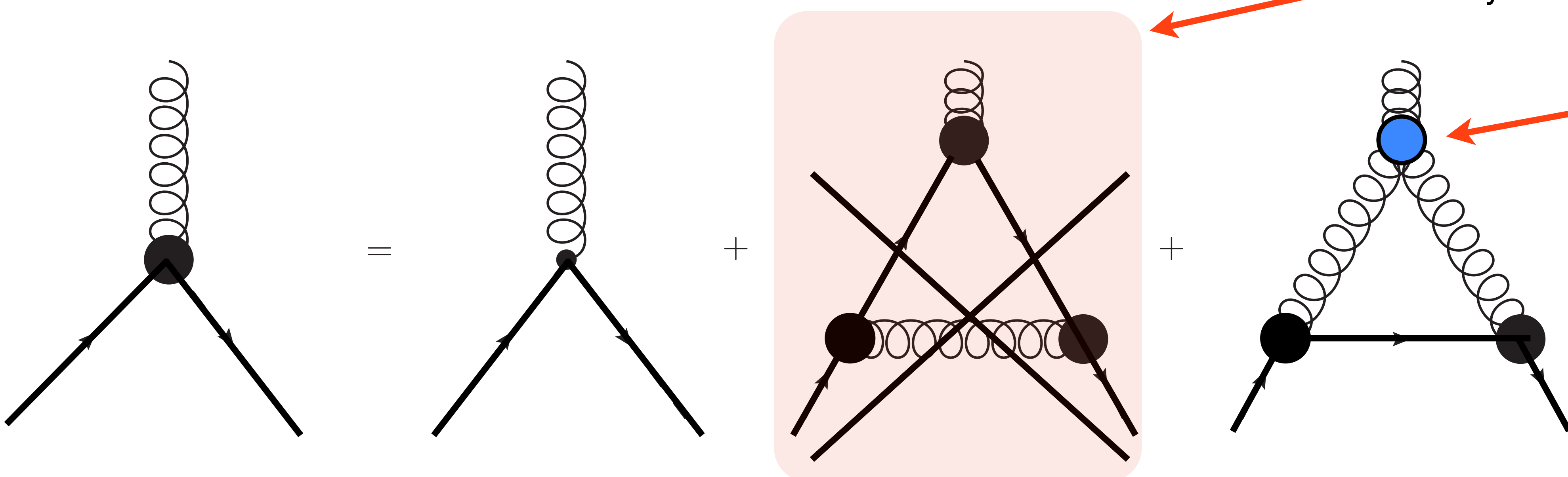
6 Conclusion
Outlook

- The quark-gluon vertex

→ New system to solve :

Relative color factor still negligible ?
Dynamical suppression after Tc ?

New correlation function
to models



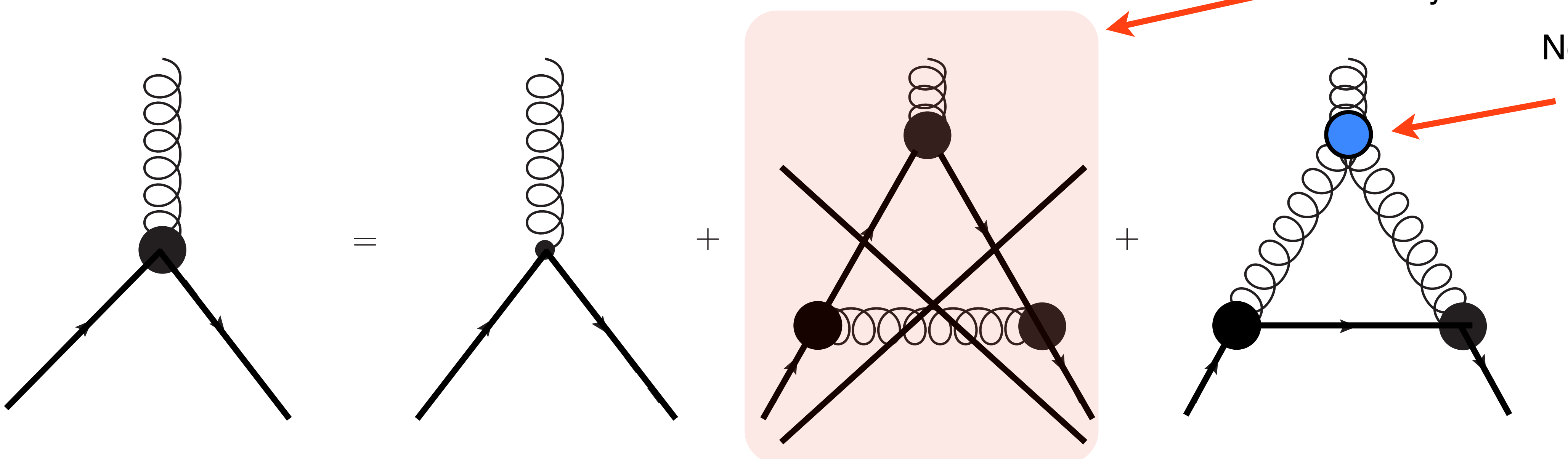
- Follow the approximation used in vacuum study

[R.Williams (2015)]

This approximation is still acceptable : - for QCD-like theory ?
- in medium ?

- The quark-gluon vertex

→ New system to solve :



Relative color factor still negligible ?
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New correlation function
to models

- Follow the approximation used in vacuum study

[R.Williams (2015)]

- In Landau gauge, 24 dressings functions

$$\vec{\gamma} h_1 + u^\mu \gamma^4 h_2 + i\vec{\gamma}\vec{\not{l}} h_3 + ii\vec{\gamma}\vec{\not{k}}_3 h_4 + \vec{\gamma}[\vec{\not{l}},\vec{\not{k}}_3] h_5 + i\vec{l} h_6 + \vec{l}\vec{\not{l}} h_7 + \vec{l}\vec{\not{k}}_3 h_8 + i\vec{l}[\vec{\not{l}},\vec{\not{k}}_3] h_9 + iu^\mu h_{10} + u^\mu\vec{\not{l}} h_{11} + u^\mu \vec{\not{k}}_3 h_{12}$$

$$+iu^\mu[\vec{\not{l}},\vec{\not{k}}_3]h_{13} + i\vec{\gamma}\gamma^4 h_{14} + \vec{l}\gamma^4 h_{15} + \vec{\gamma}[\vec{\not{l}},\not{u}]h_{16} + \vec{\gamma}[\vec{\not{k}}_3,\not{u}]h_{17} + i\vec{l}[\vec{\not{l}},\not{u}]h_{18} + i\vec{l}[\vec{\not{k}}_3,\not{u}]h_{19}$$

$$+iu^\mu[\vec{\not{l}},\not{u}]h_{20} + iu^\mu[\vec{\not{k}}_3,\not{u}]h_{21} + i\vec{\gamma}\vec{\not{l}}\vec{\not{k}}_3\not{u}h_{22} + \vec{l}\vec{\not{l}}\vec{\not{k}}_3\not{u}h_{23} + u^\mu\vec{\not{l}}\vec{\not{k}}_3\not{u}h_{24}$$

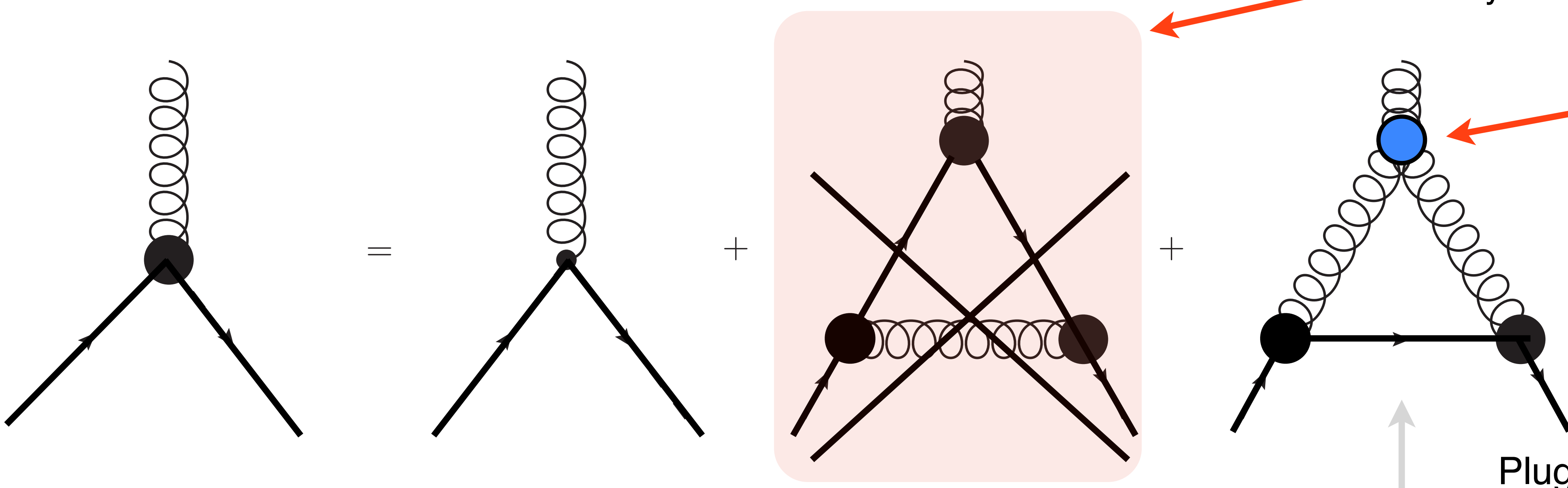
Generalization of
[M. Mitter , J.M. Pawlowski, N. Strodthoff (2014)]

Outlook

Contant Romain

- The quark-gluon vertex

→ New system to solve :



Relative color factor still negligible ?
Dynamical suppression after Tc ?

New correlation function to models

Plug in the fully dressed quark gluon vertex

↕

13 824 Terms

- Follow the approximation used in vacuum study

[R.Williams (2015)]

- In Landau gauge, 24 dressings functions

$$\vec\gamma h_1 + u^\mu\gamma^4 h_2 + i\vec\gamma\vec{\not l} h_3 + ii\vec\gamma\vec{\not k}_3 h_4 + \vec\gamma[\vec{\not l},\vec{\not k}_3]h_5 + i\vec l h_6 + \vec l\vec{\not l} h_7 + \vec l\vec{\not k}_3 h_8 + i\vec l[\vec{\not l},\vec{\not k}_3]h_9 + iu^\mu h_{10} + u^\mu\vec{\not l}h_{11} + u^\mu\vec{\not k}_3 h_{12}$$

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$$+iu^\mu[\vec{\not l},\not u]h_{20} + iu^\mu[\vec{\not k}_3,\not u]h_{21} + i\vec\gamma\vec{\not l}\vec{\not k}_3\not u h_{22} + \vec l\vec{\not l}\vec{\not k}_3\not u h_{23} + u^\mu\vec{\not l}\vec{\not k}_3\not u h_{24}$$

Generalization of
[M. Mitter , J.M. Pawlowski, N. Strodthoff (2014)]

6 Conclusion
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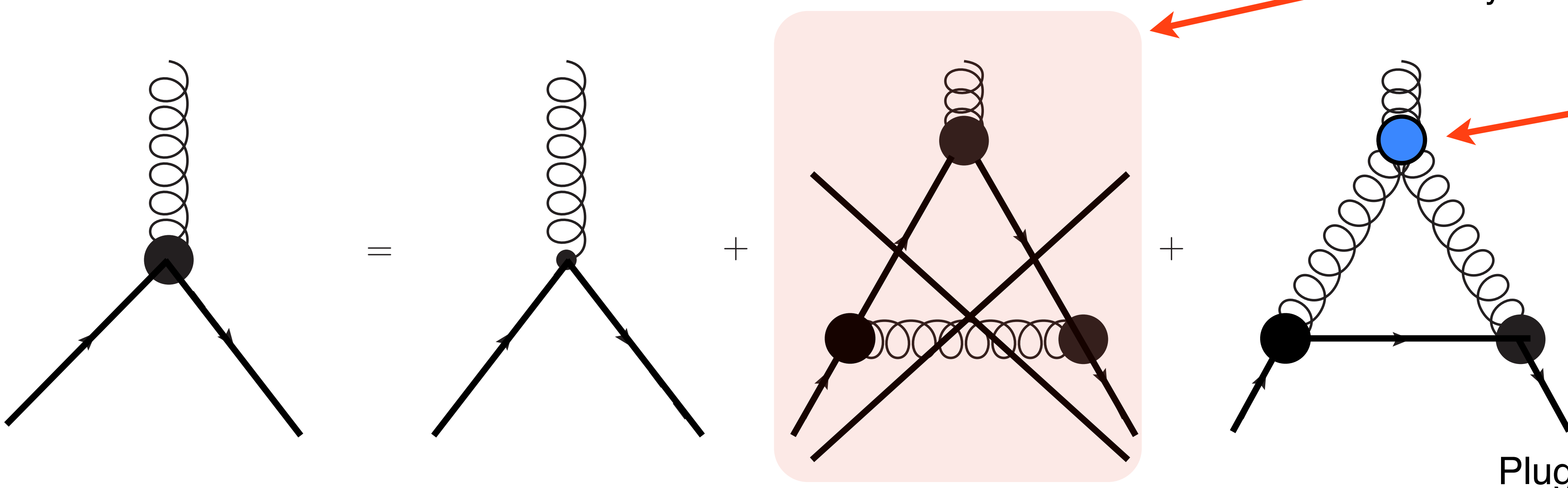

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$$+iu^\mu[\vec{l\!\!/},u\!\!/]h_{20} + iu^\mu[\vec{k\!\!/}_3,u\!\!/]h_{21} + i\vec{\gamma}\vec{l\!\!/}\vec{k\!\!/}_3 u\!\!/ h_{22} + \vec{l}\vec{l\!\!/}\vec{k\!\!/}_3 u\!\!/ h_{23} + u^\mu\vec{l\!\!/}\vec{k\!\!/}_3 u\!\!/ h_{24}$$

Computation in progress

Generalization of
[M. Mitter , J.M. Pawlowski, N. Strodthoff (2014)]

Conclusion

- The employed setup behaves universally
- Qualitative and quantitative comparaison with lattice results at vanishing μ

- Sensitivity to the model parameters
- Low chemical potential results do not reproduce lattices results

- Improvement of the truncation in progress

Thank you