Deconfinement phase transition with heavy quarks

Pok Man Lo

GSI

NeD & TURIC

9-June 2014, Hersonissos, Crete, Greece

pmlo@gsi.de

In collaboration with...

Bengt Friman (*GSI*)

Chihiro Sasaki (*FIAS*)

Krzysztof Redlich (*U. of Wroclaw*)

Olaf Kaczmarek (*U. of Bielefeld*)

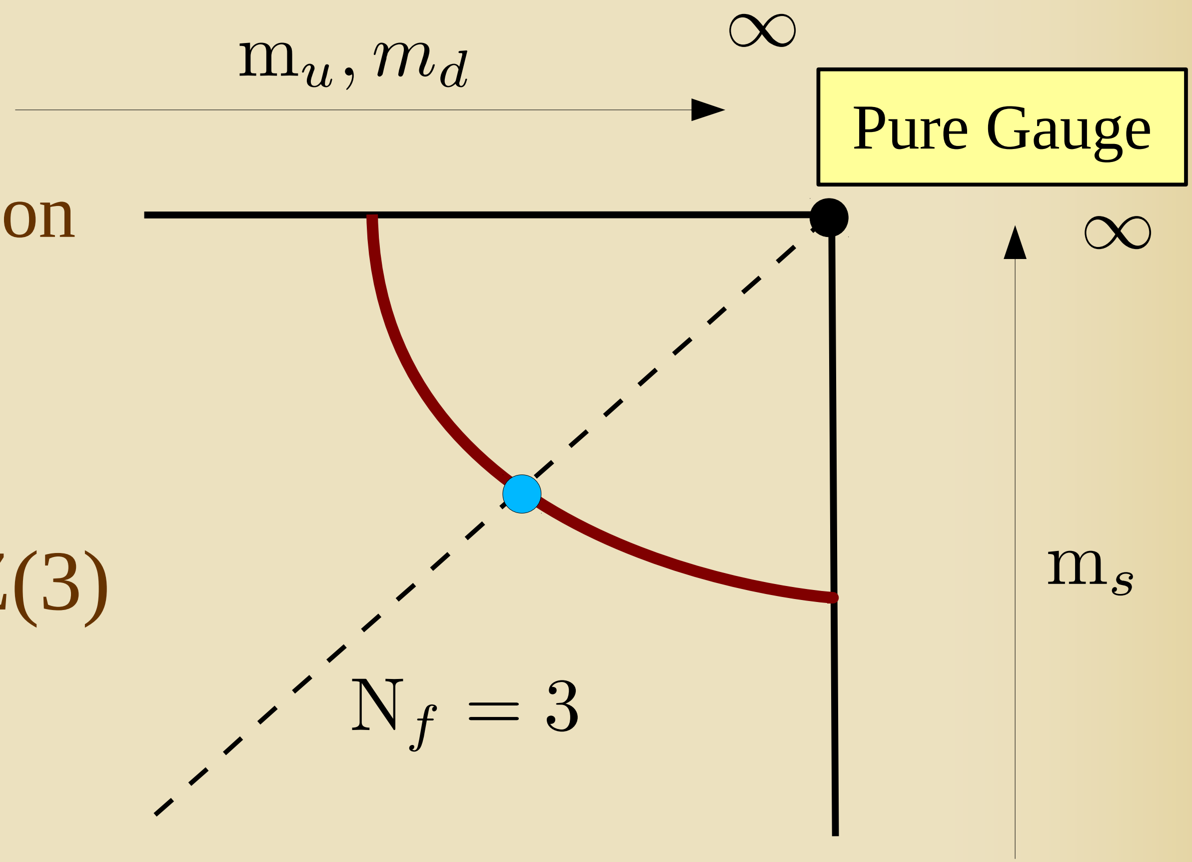
Content

Deconfinement phase transition with heavy quarks

- Effective theory for PL coupled with heavy quarks
- Critical quark mass and phase boundary
- Quark mass dependence of transition temperature

Deconfinement phase transition

- Pure SU(3)
  - 1st order phase transition
  - Stable against small explicit breaking
- Heavy quark breaks Z(3)
  - Strength ↑ as m ↓



1st order → 2nd order (deconfining CEP) → crossover

Polyakov loop

- Order parameter **characterizes** the state of the system

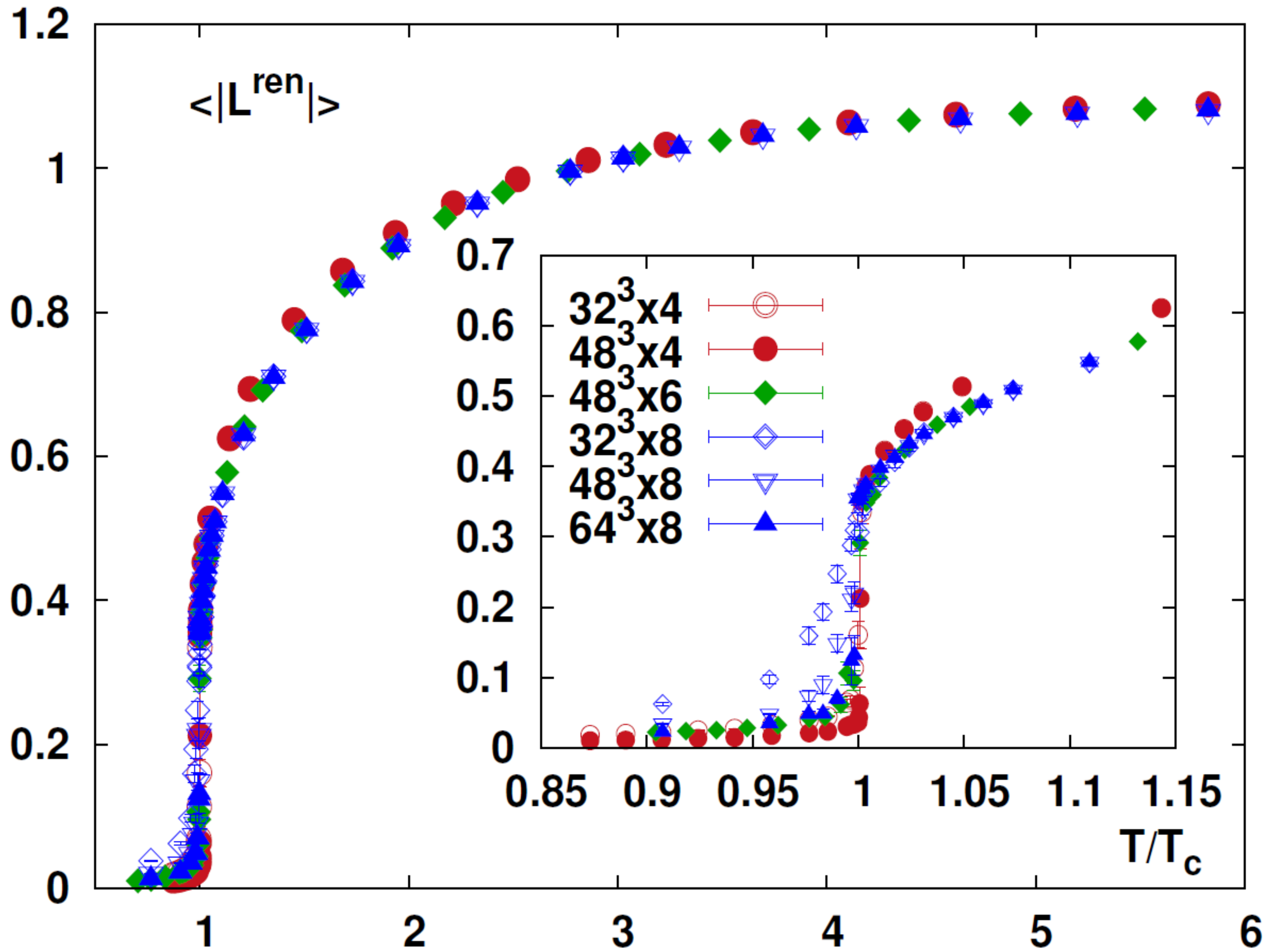
$$< L >$$

Operator does **not** respect the symmetry

$$L \to L\, e^{i2n\pi/3}$$

confined phase: $< L > = 0$

deconfined phase: $< L > \neq 0$



<|L^ren|>
32^3x4
48^3x4
48^3x6
32^3x8
48^3x8
64^3x8
T/T_c

Polyakov loop susceptibilities

- L is complex-valued for SU(3)

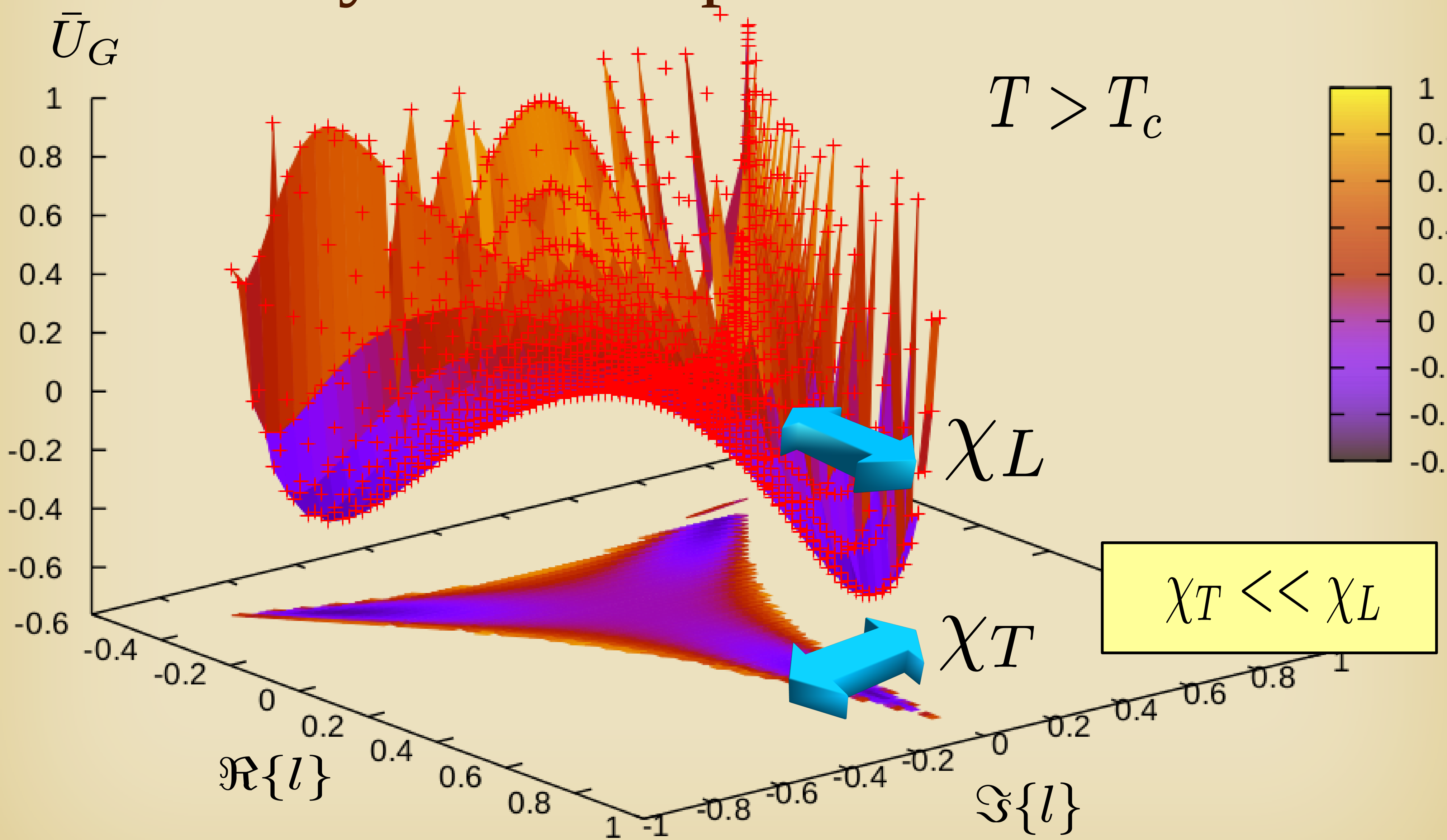
real sector:

$$\mathrm{L} = \mathrm{L}_{\mathrm{L}} + iL_{\mathrm{T}} \longrightarrow \begin{array}{l} \chi_L = V(< L_L L_L > - < L_L >^2) \\ \chi_T = V(< L_T L_T > - < L_T >^2) \end{array}$$

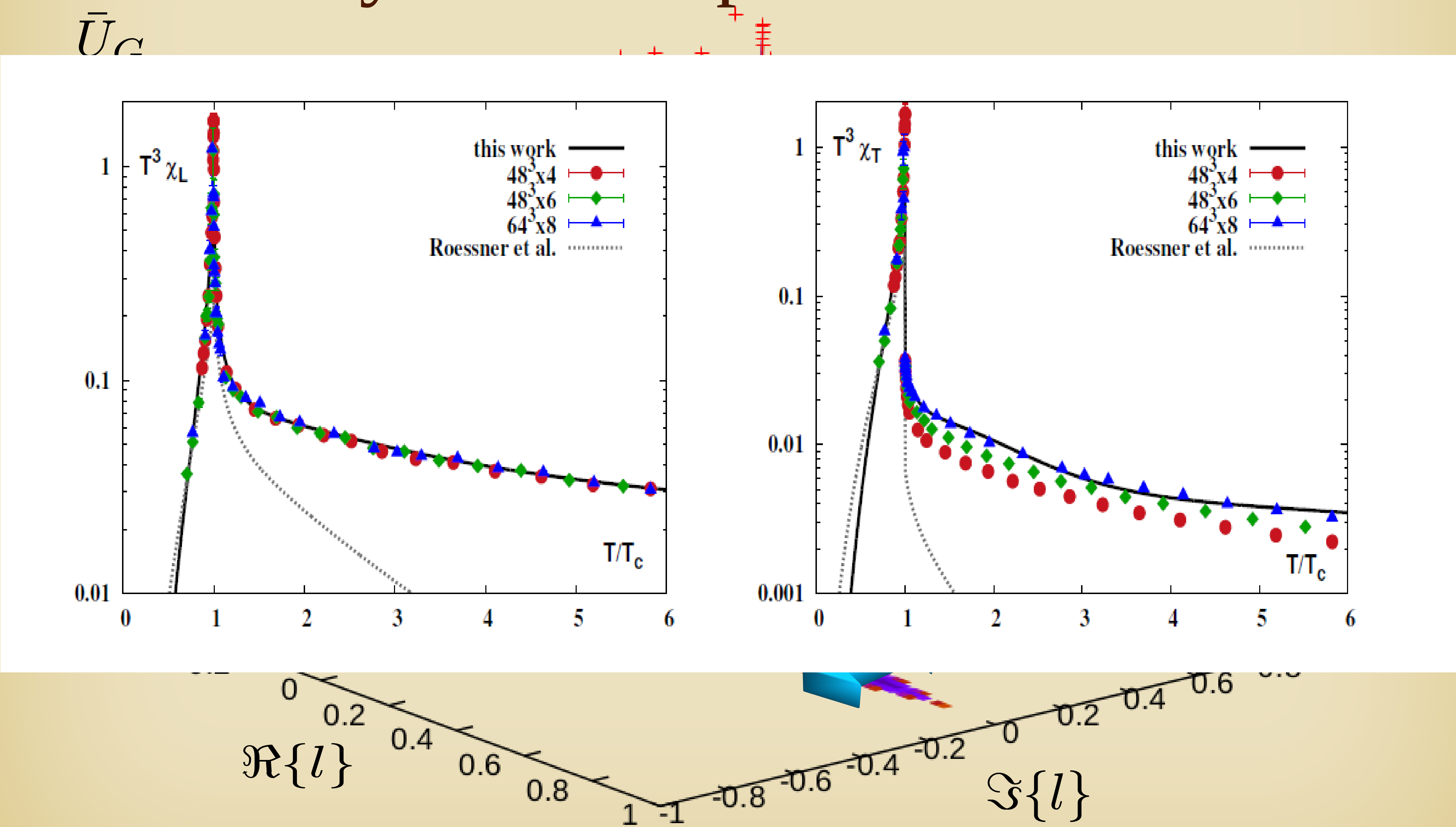
- Sensitive to the **transition** of phases

  features **peak** and **width** near the transition
- Effective potential: inverse of curvature

Polyakov Loop Eff. Potential



Polyakov Loop Eff. Potential



Construction of PL effective model

Z(3) symmetry, Haar measure...

↓

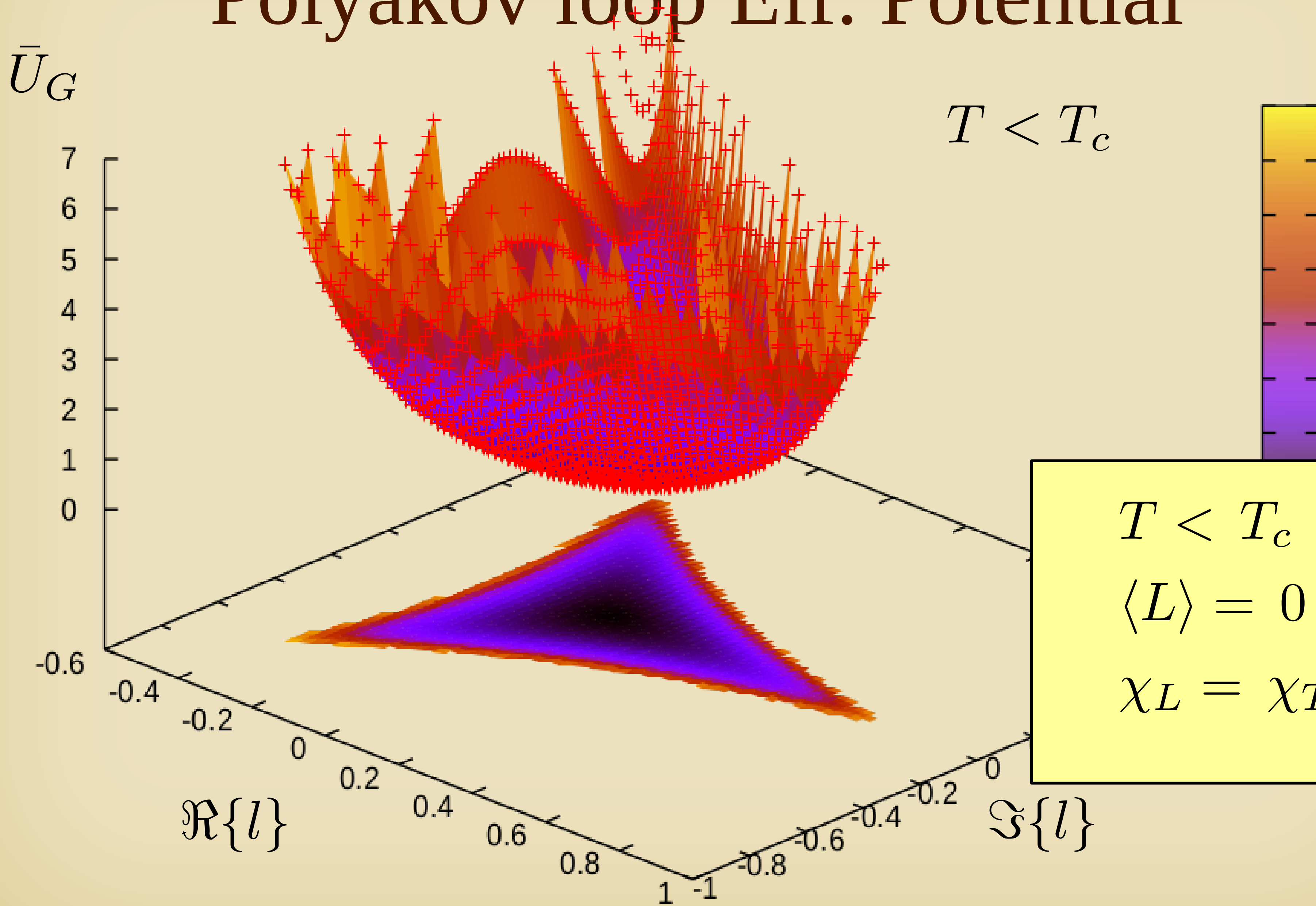
$$U_{eff}[L,\bar{L}] = -\frac{A[T]}{2}\bar{L}L + B[T]\ln M_{Haar} + \frac{1}{2}C[T](L^3+\bar{L}^3) + D[T](\bar{L}L)^2$$

↑

lattice inputs

$P[T], < L >, \chi_L, \chi_T$

Polyakov loop Eff. Potential

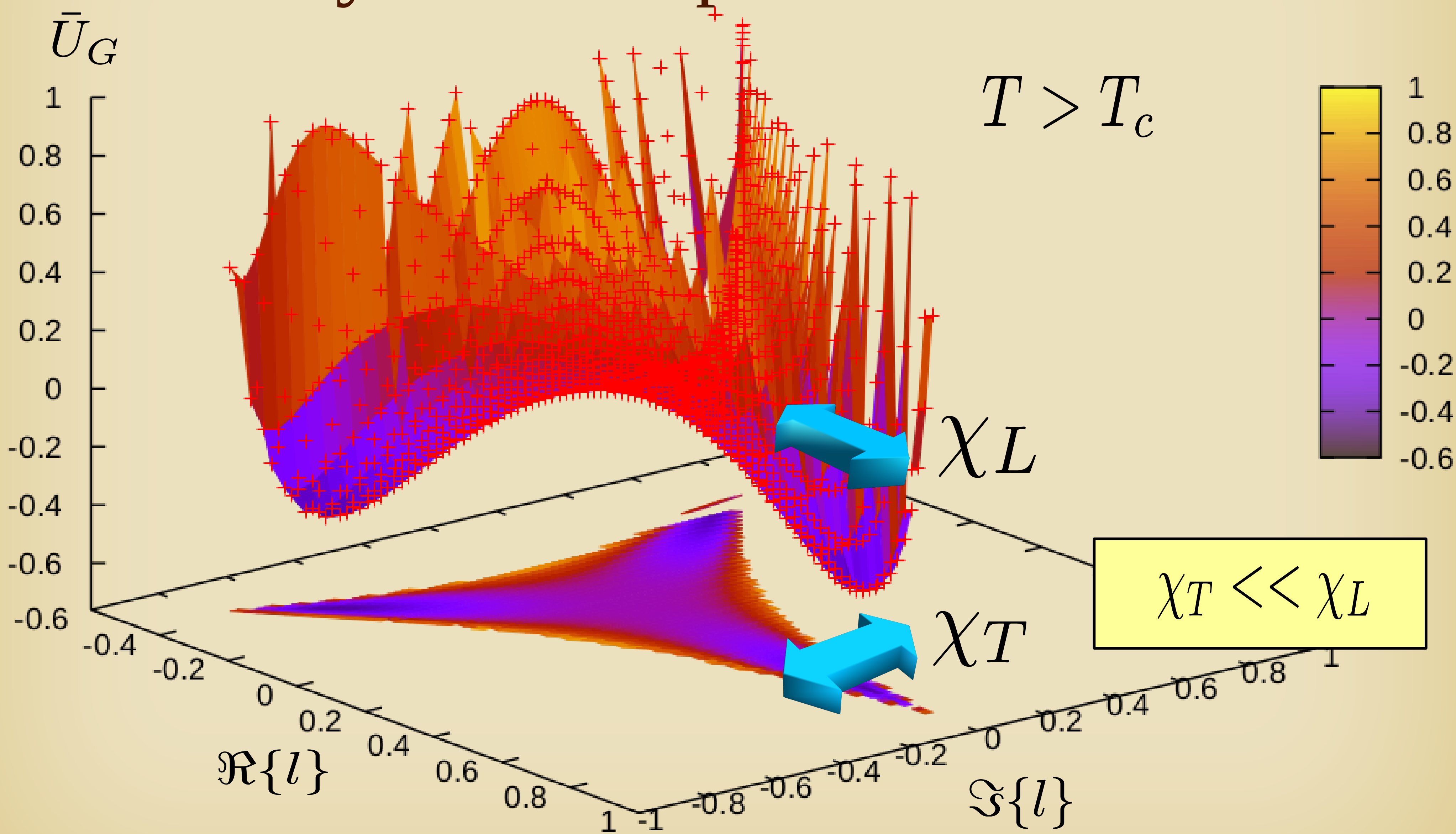


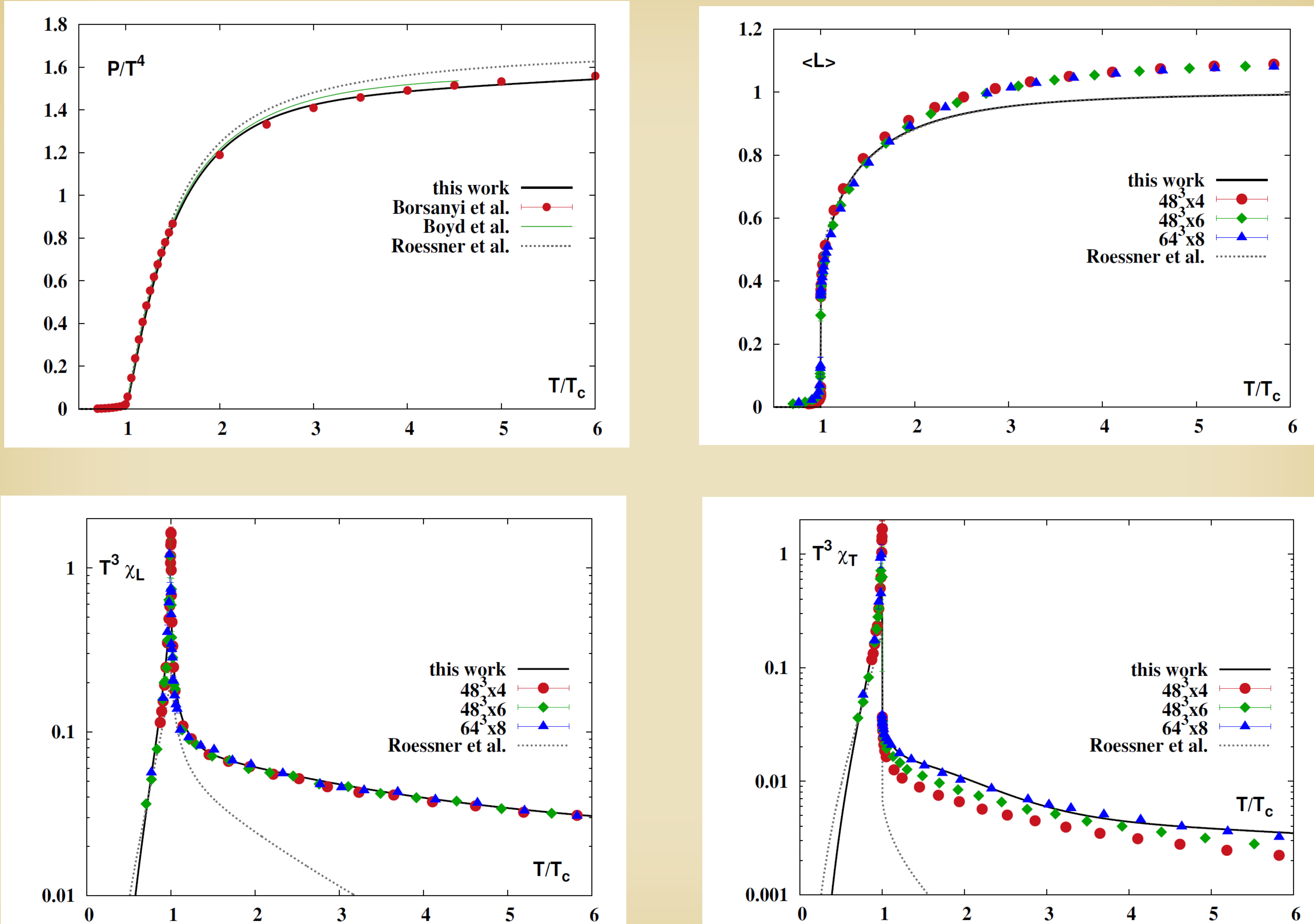
$T < T_c$

$\langle L \rangle = 0$

$\chi_L = \chi_T$

Polyakov Loop Eff. Potential




P/T^4
this work
Borsanyi et al.
Boyd et al.
Roessner et al.
T/T_c
<L>
this work
48^3x4
48^3x6
64^3x8
Roessner et al.
T/T_c
T^3 χ_L
this work
48^3x4
48^3x6
64^3x8
Roessner et al.
T/T_c
T^3 χ_T
this work
48^3x4
48^3x6
64^3x8
Roessner et al.
T/T_c

PL-heavy quark coupling

- Fermionic determinant

$$Z = \int DLD\bar{L}\, \det[\hat{Q}_F]\, e^{-\beta V U_G[L,\bar{L}]}.$$

- Background field approach

$$\hat{Q}_F = (-\partial_\tau + \mu + igA_4)\gamma^0 + i\vec{\gamma}\cdot\nabla - M_Q$$

$$\hat{L} = e^{i\beta g A_4^a T^a}$$

$$L = \frac{1}{N_c} Tr_c \hat{L}$$

PL-heavy quark coupling

- Fermionic determinant (1 loop)

$$\ln \det[\hat{Q}_F] = V 2 N_f \int \frac{d^3k}{(2\pi)^3} [3\beta E[k] + \ln g^+ + \ln g^-]$$

$$g^{\pm} = 1 + 3 \begin{pmatrix} L \\ \bar{L} \end{pmatrix} e^{-\beta E^{\pm}} + 3 \begin{pmatrix} \bar{L} \\ L \end{pmatrix} e^{-2\beta E^{\pm}} + e^{-3\beta E^{\pm}}$$

$$E^{\pm} = E[k] \mp \mu$$

$$E[k] = (k^2 + M_Q^2)^{1/2}$$

Sasaki et al. Phys.Rev. D75 (2007) 074013

PL-heavy quark coupling

- Effective potential

$$\ln\det[\hat{Q}_F] = -VT^3 \bar{U}_Q[L, \bar{L}; M_Q]$$

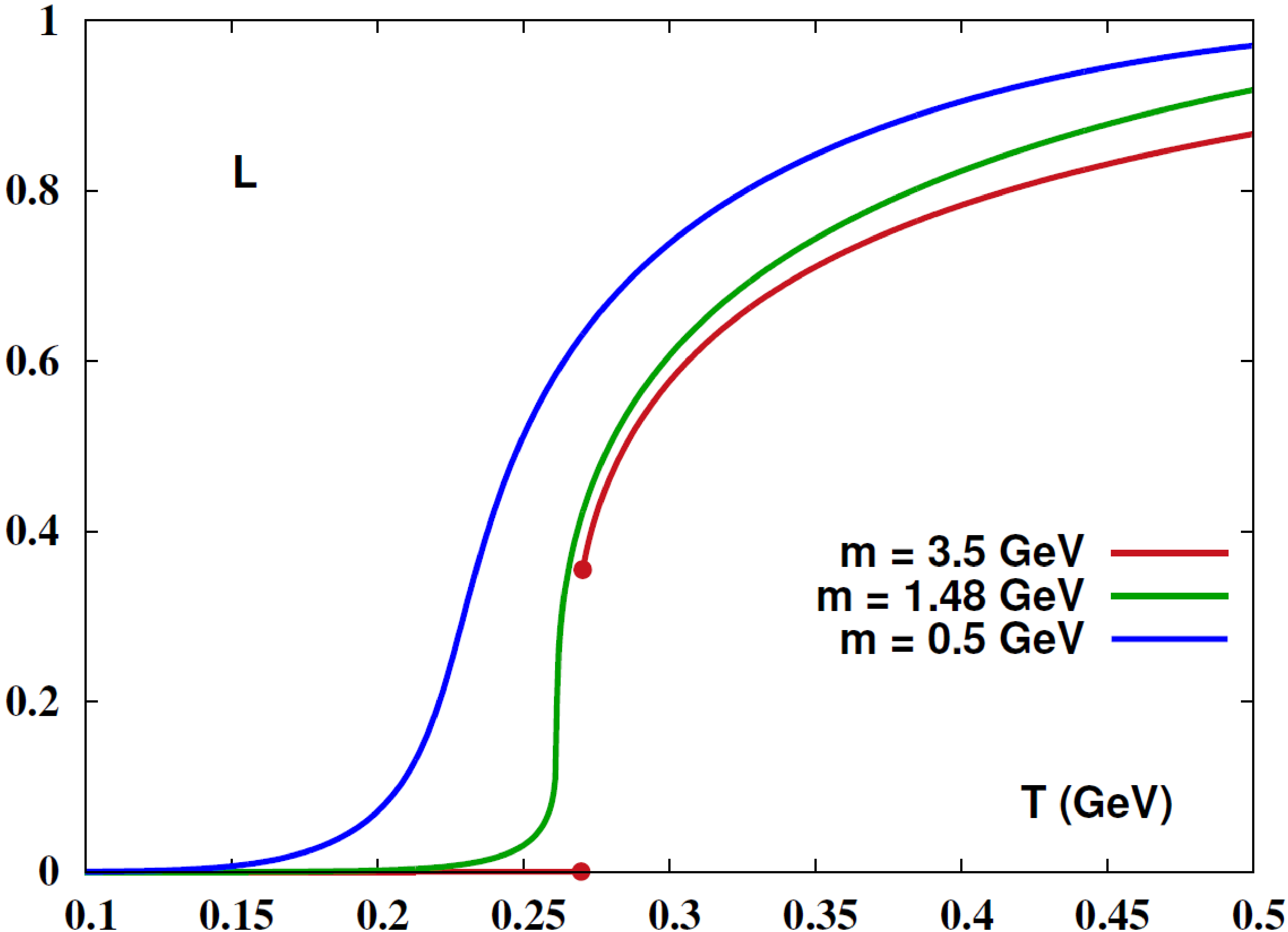
- Heavy quark limit $(\mathrm{M}_Q/T \gg 1)$

$$\bar{U}_Q[L, \bar{L}; M_Q] \approx -h_{\rm eff}[M_Q/T]\, L_{\rm L} + ...$$

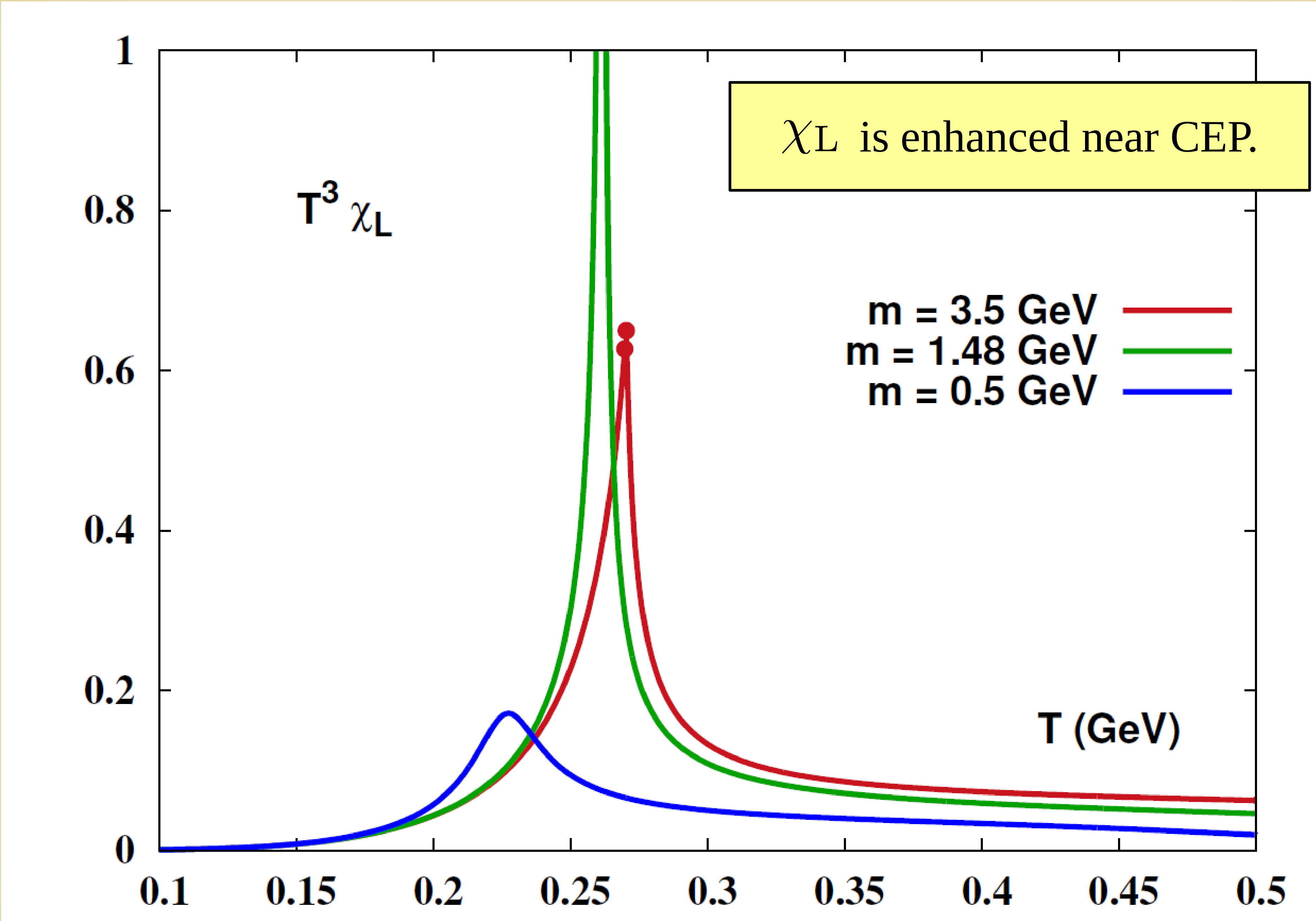
$$\bar{U}_G \longrightarrow \bar{U}_G - h_{\rm eff} L_{\rm L}$$

$$h_{\rm eff}[M_Q/T; N_f] = \frac{6N_f}{\pi^2 T^3} \int dk\, k^2 e^{-\beta\sqrt{k^2+M_Q^2}}$$

$$h_{\rm eff} \to 0 \quad \text{as} \quad M_Q/T \to \infty$$

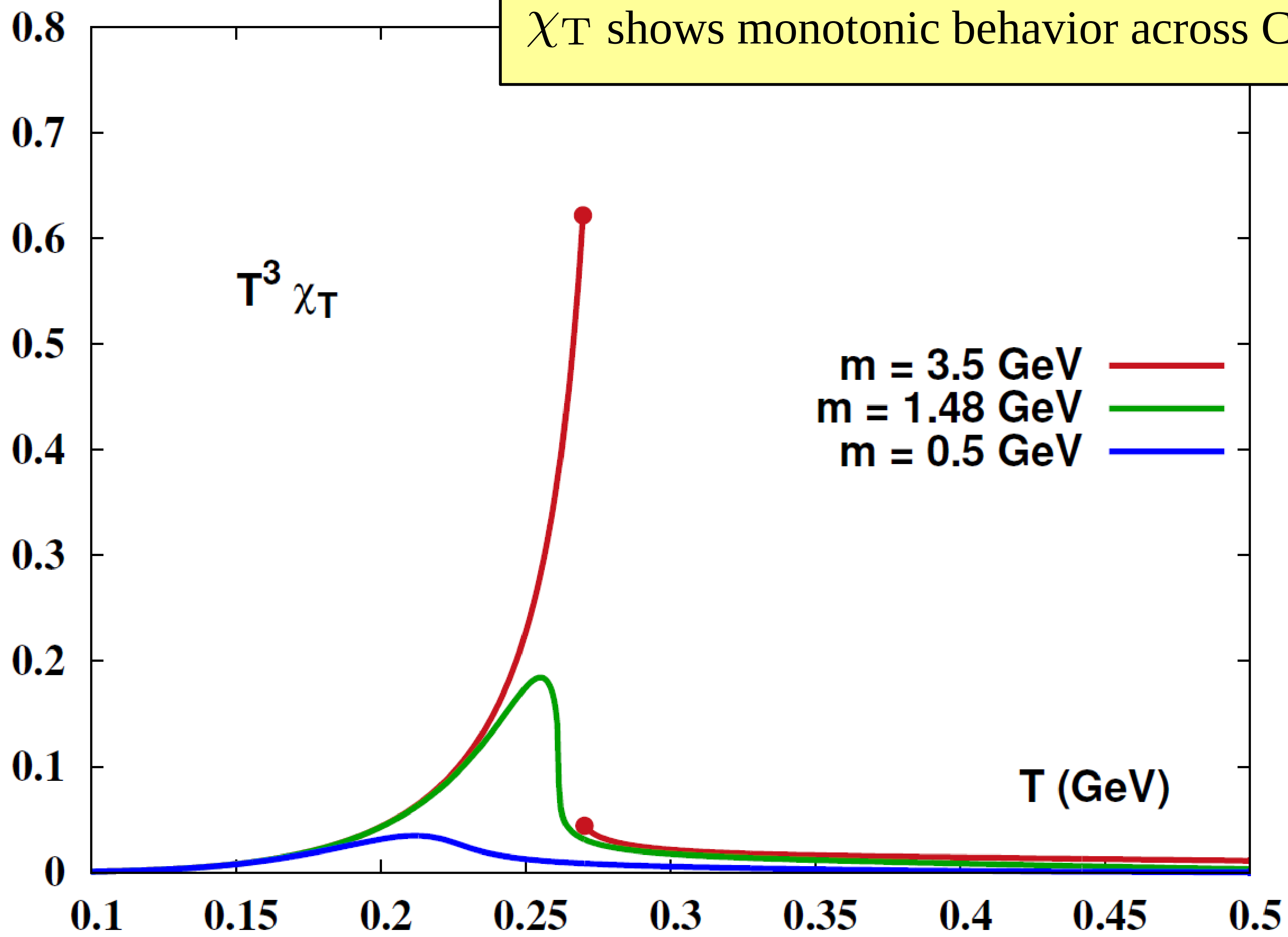


L
m = 3.5 GeV
m = 1.48 GeV
m = 0.5 GeV
T (GeV)
0
0.2
0.4
0.6
0.8
1
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5



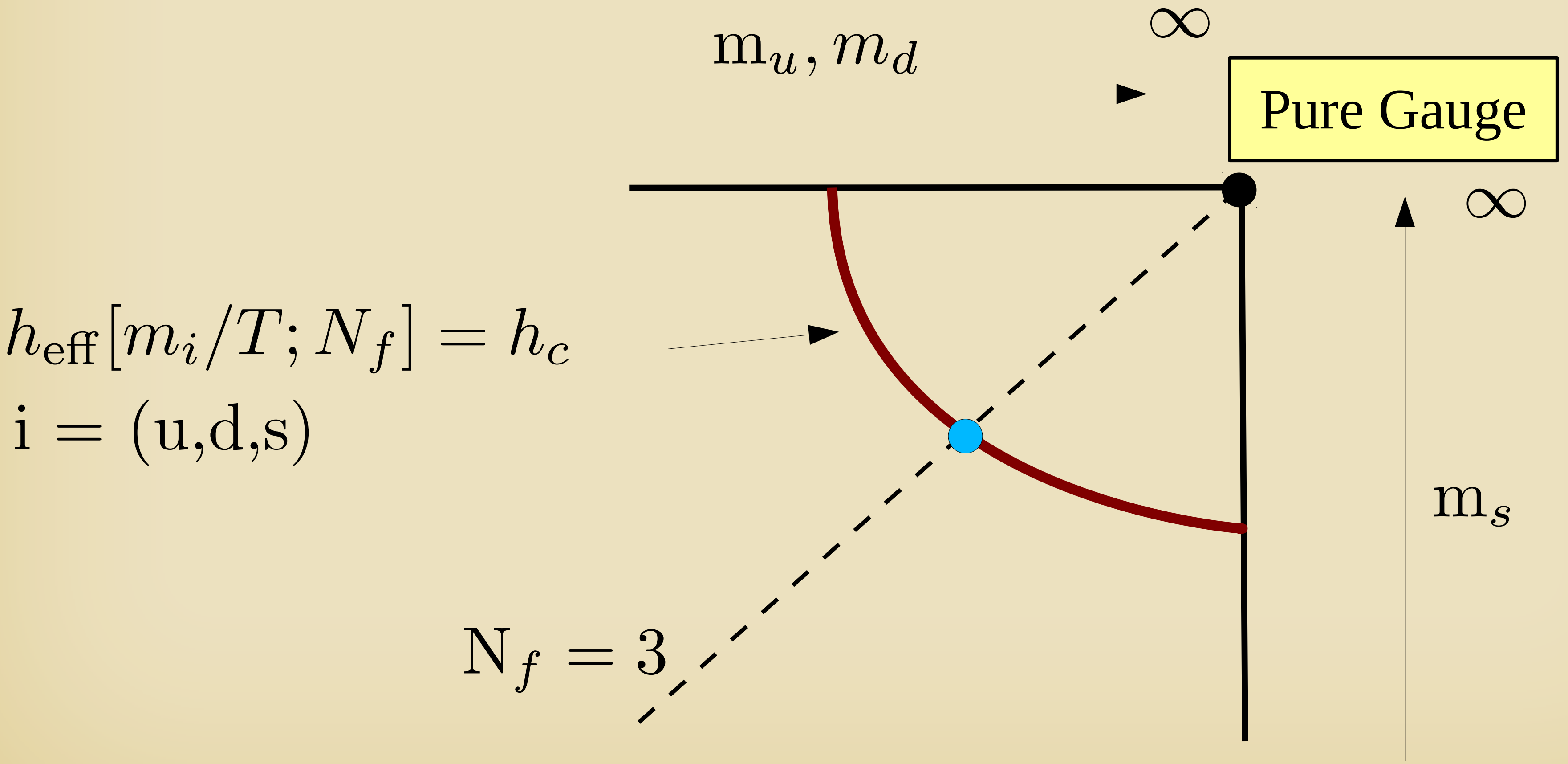
χL is enhanced near CEP.
T^3 χL
m = 3.5 GeV
m = 1.48 GeV
m = 0.5 GeV
T (GeV)
0
0.2
0.4
0.6
0.8
1
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5

χ_T shows monotonic behavior across CEP.



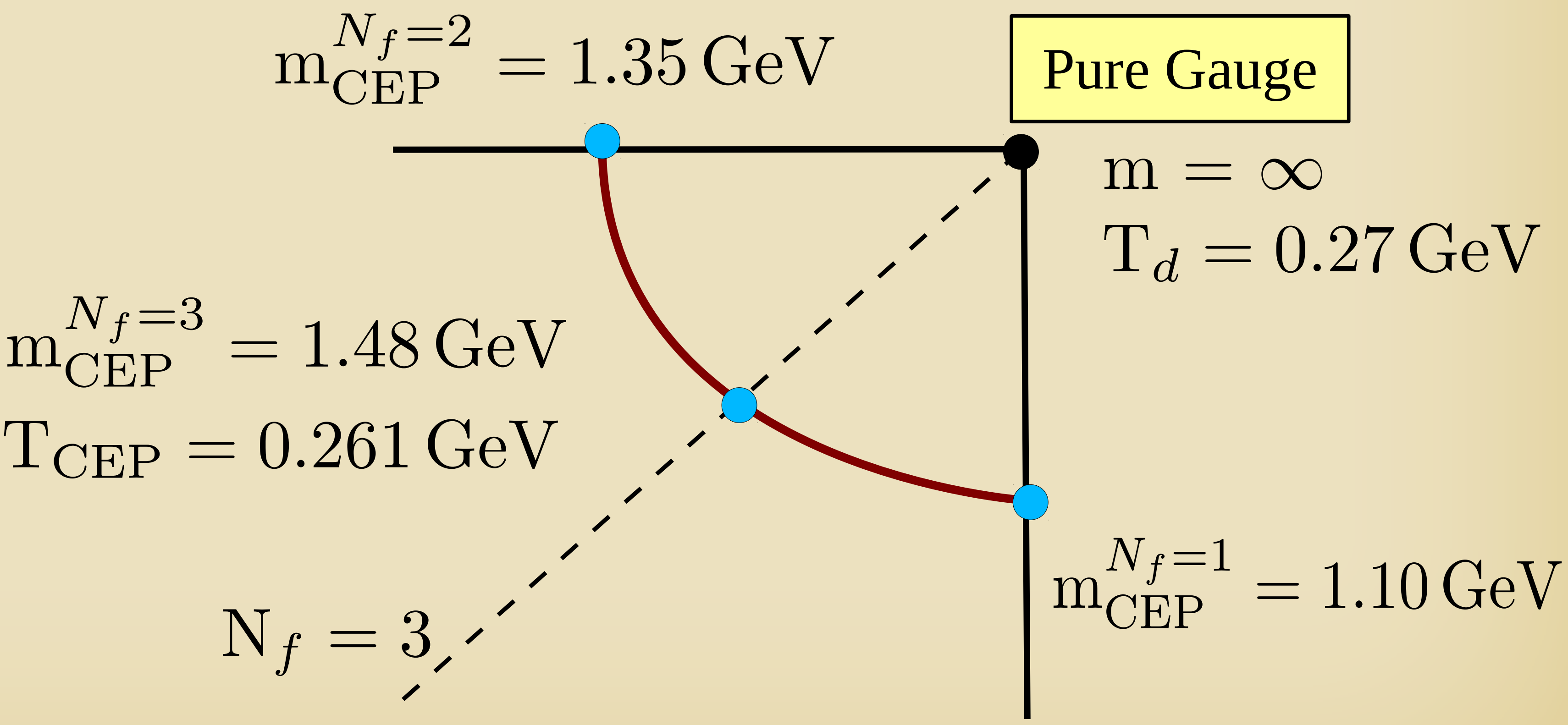
Critical quark mass

- Phase boundary of deconfinement phase transition



Critical quark mass

- Critical end point results from effective potential



Critical quark mass

- N_f dependence of critical quark mass

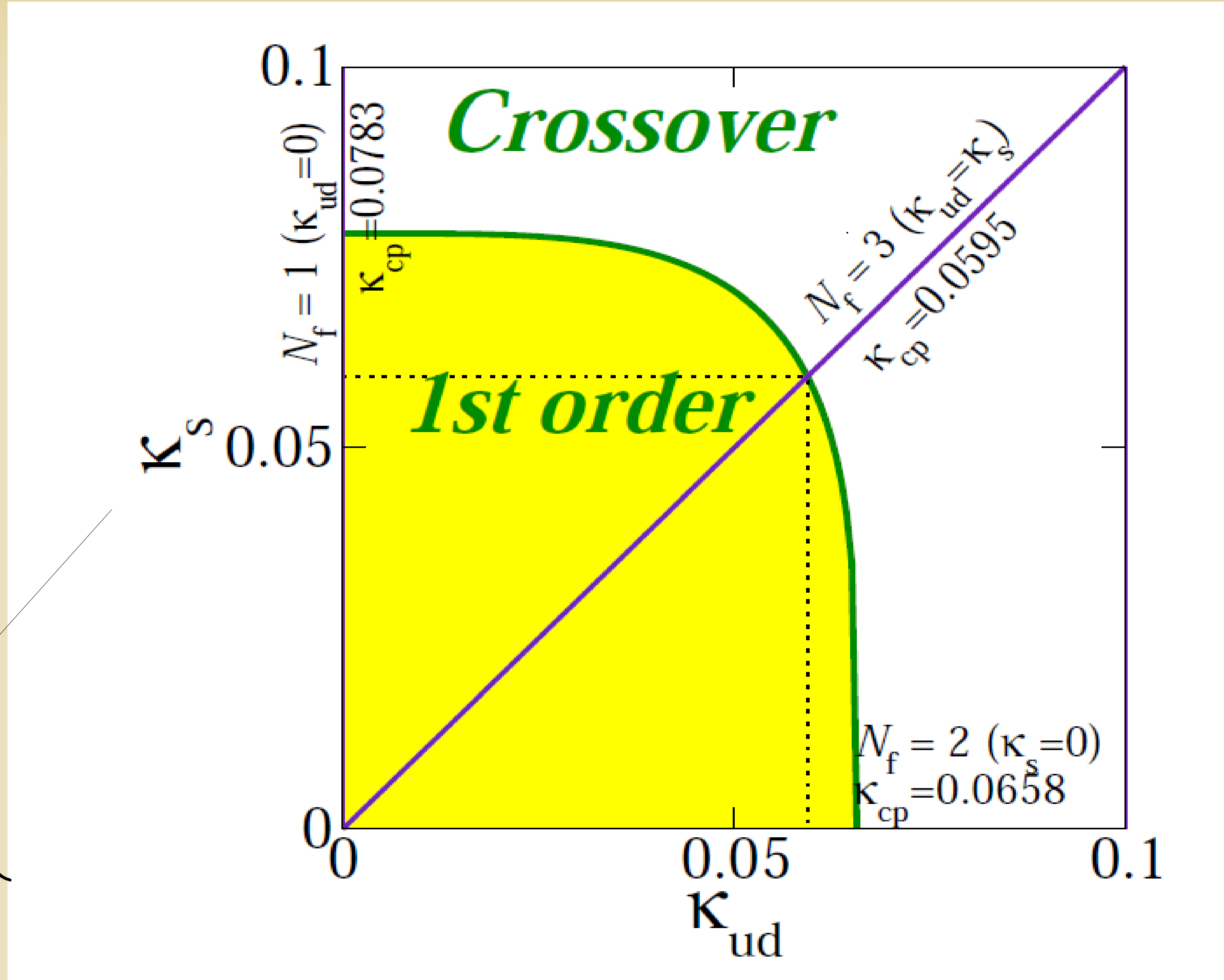
$$h_{\rm eff}[M_Q/T;N_f] = \frac{6N_f}{\pi^2 T^3}\int dk\, k^2 e^{-\beta\sqrt{k^2+M_Q^2}}$$

$$\boxed{\mathrm{h}_{eff}[M_Q/T;N_f] = h_c}$$ ←→ Deconfining CEP

$$\mathrm{h}_{eff}\uparrow N_f \uparrow$$

$$\mathrm{h}_{eff}\downarrow M_Q \uparrow$$

$$\mathrm{m}_{\rm CEP}^{N_f=3} > m_{\rm CEP}^{N_f=2} > m_{\rm CEP}^{N_f=1}$$

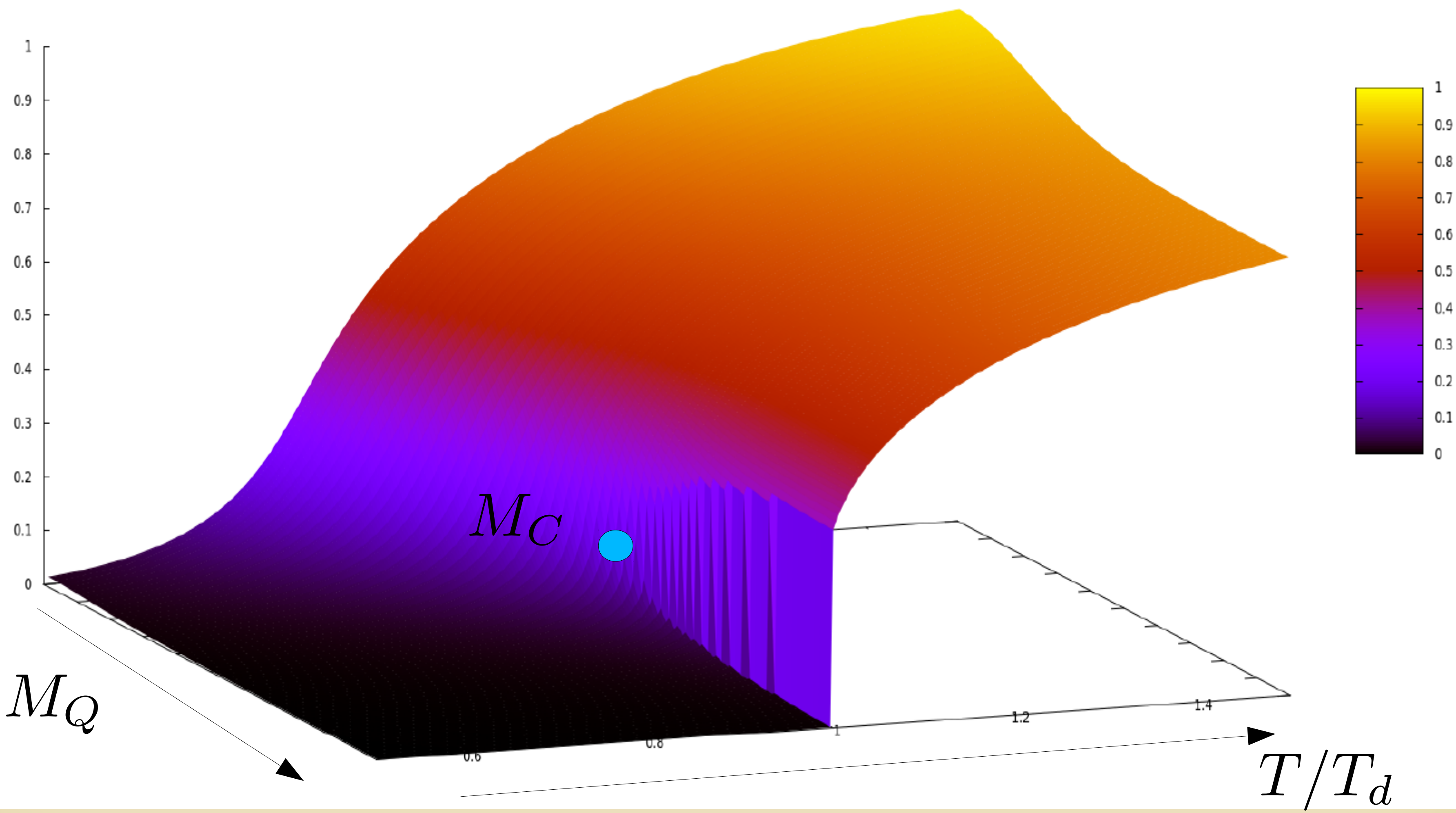


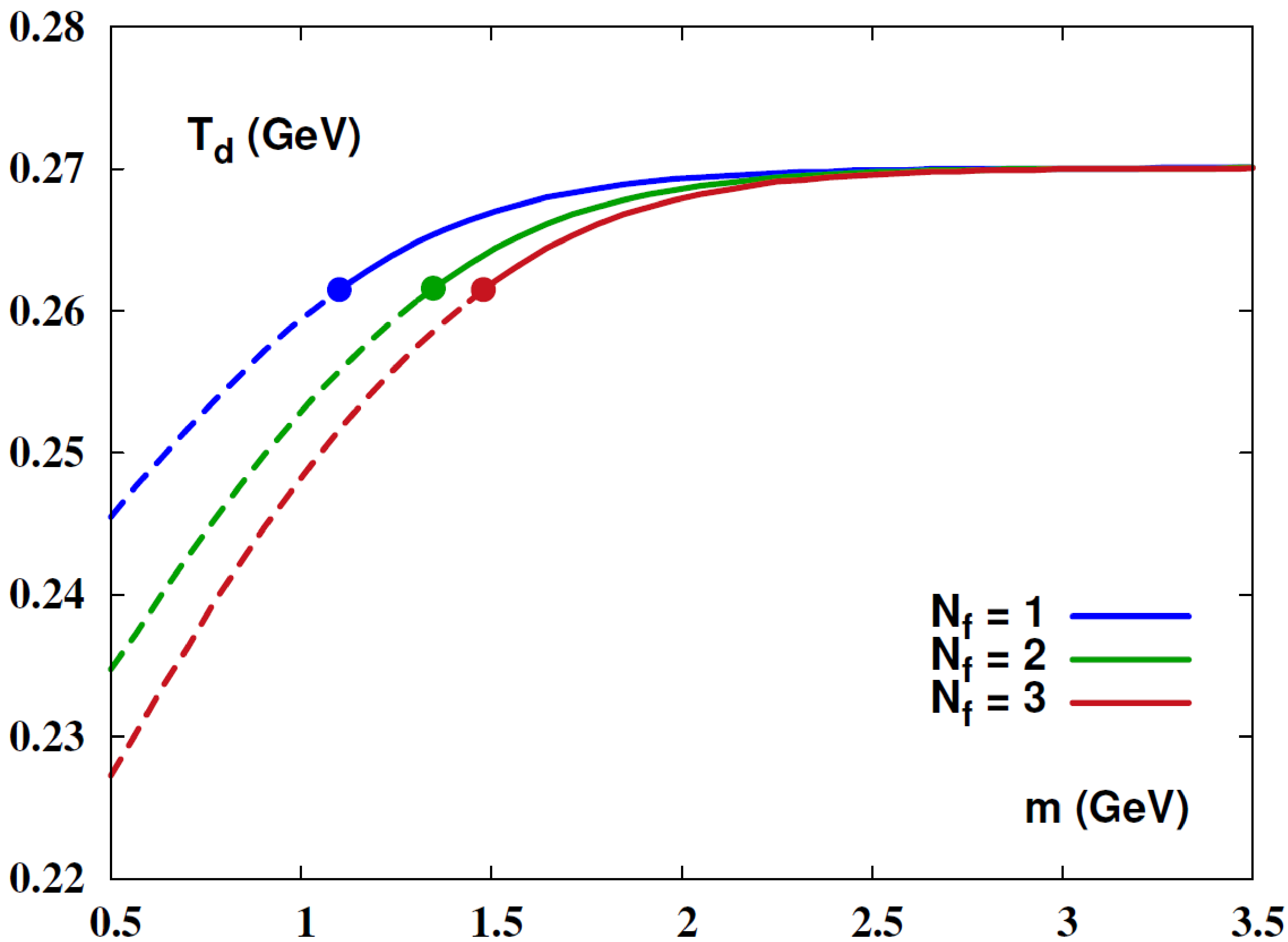
$\kappa \downarrow M_Q \uparrow$

$$\kappa_c^{N_f=3} < \kappa_c^{N_f=2} < \kappa_c^{N_f=1}$$

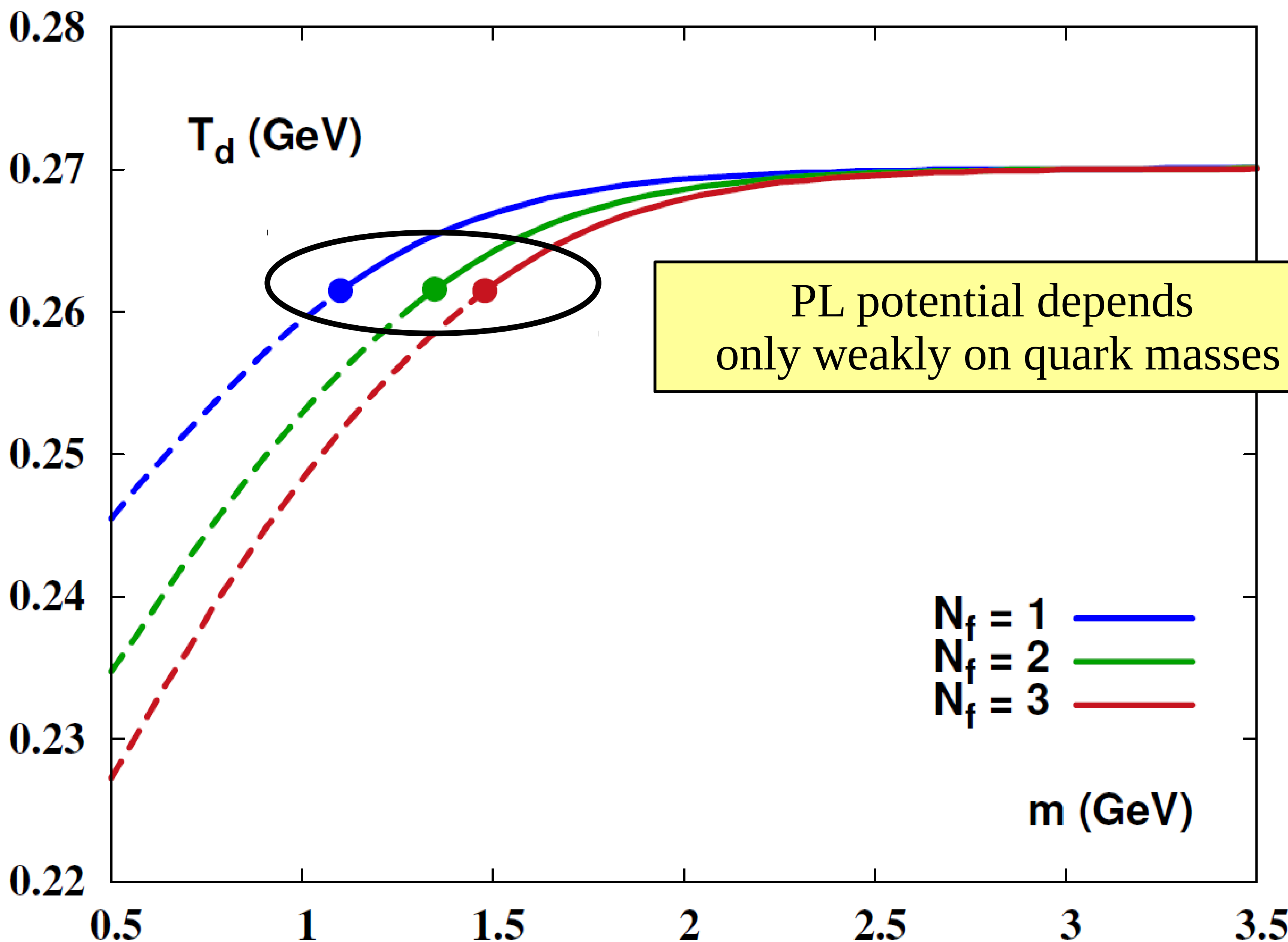
WHOT-QCD Collaboration (Saito, H. et al.)

$< L > [T, M_Q]$

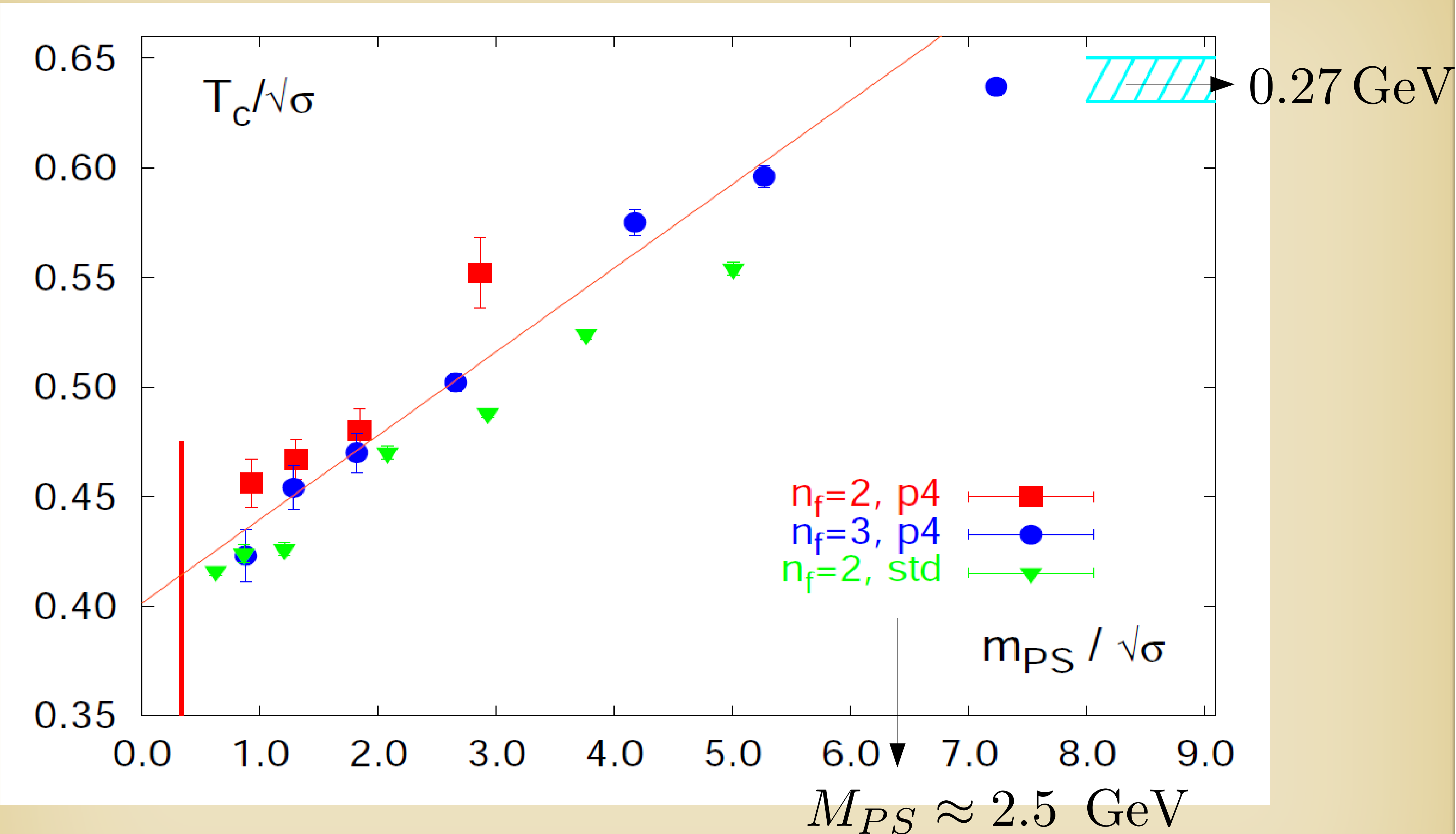




0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.5
1
1.5
2
2.5
3
3.5
T_d (GeV)
N_f = 1
N_f = 2
N_f = 3
m (GeV)



PL potential depends
only weakly on quark masses



F. Karsch, Lattice QCD at high temperature and density

Heavy quark scale

- Typical heavy quarkonium mass scale:

$$\mathrm{m}_c = 1.3\,\mathrm{GeV}$$
$$\mathrm{m}_{J/\psi} = 3.097\,\mathrm{GeV}$$
$$\mathrm{m}_{\eta_c} = 2.98\,\mathrm{GeV}$$
$$\mathrm{m}_{PS}/m_V = 0.96$$

$$\mathrm{m}_b = 4.2\,\mathrm{GeV}$$
$$\mathrm{m}_{\Upsilon} = 9.460\,\mathrm{GeV}$$
$$\mathrm{m}_{\eta_b} = 9.391\,\mathrm{GeV}$$
$$\mathrm{m}_{PS}/m_V = 0.99$$

Model dependence of CEP

- Current model:

$$\mathrm{m}_{\mathrm{CEP}}^{N_f=3} \approx 1.48\,\mathrm{GeV}$$

$$\mathrm{T}_{\mathrm{CEP}} \approx 0.26\,\mathrm{GeV}$$

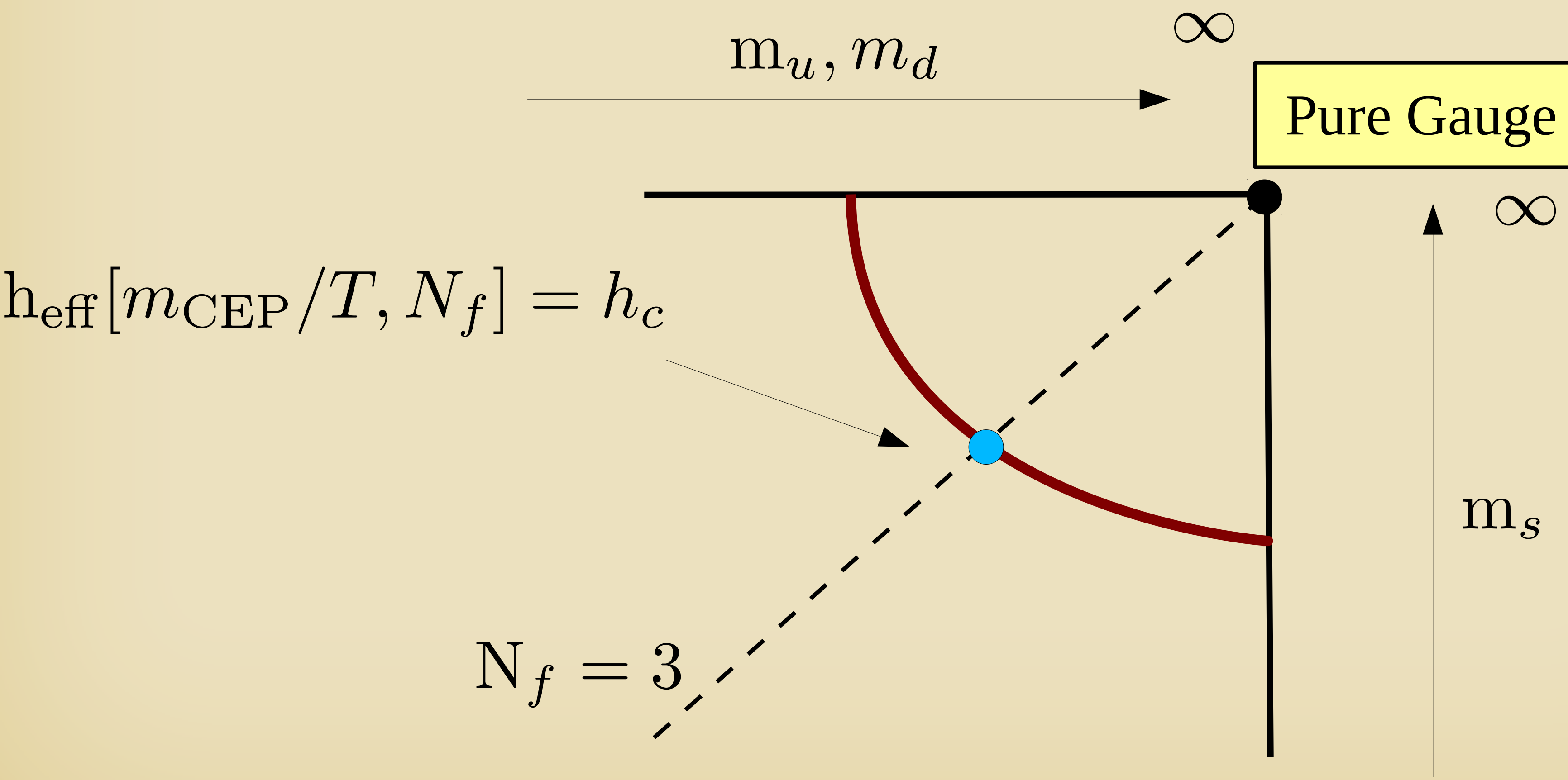
- Matrix model:

$$\mathrm{m}_{\mathrm{CEP}}^{N_f=3} \approx 2.5\,\mathrm{GeV}$$

$$\mathrm{T}_{\mathrm{CEP}} \approx 0.27\,\mathrm{GeV}$$

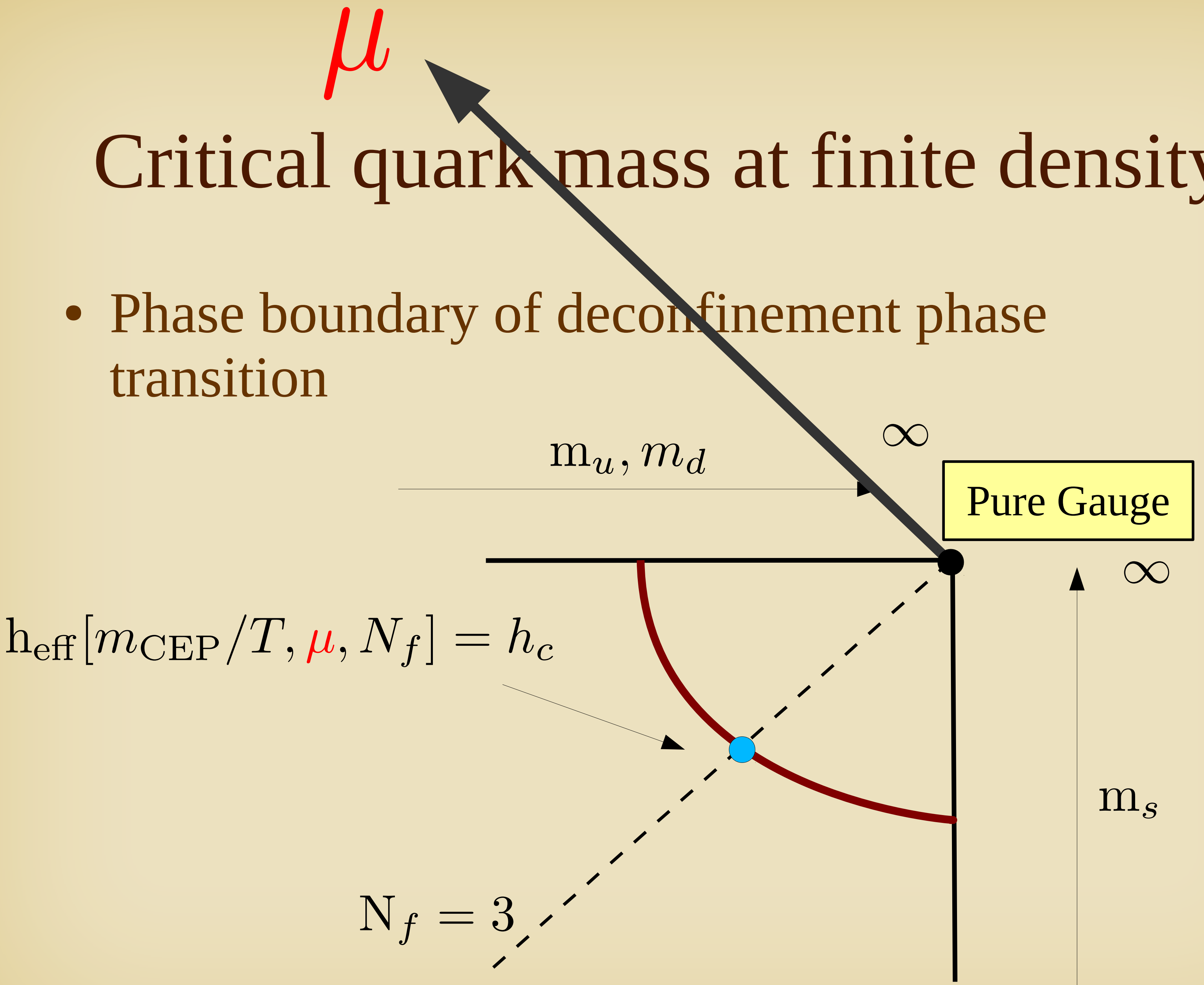
Critical quark mass at finite density

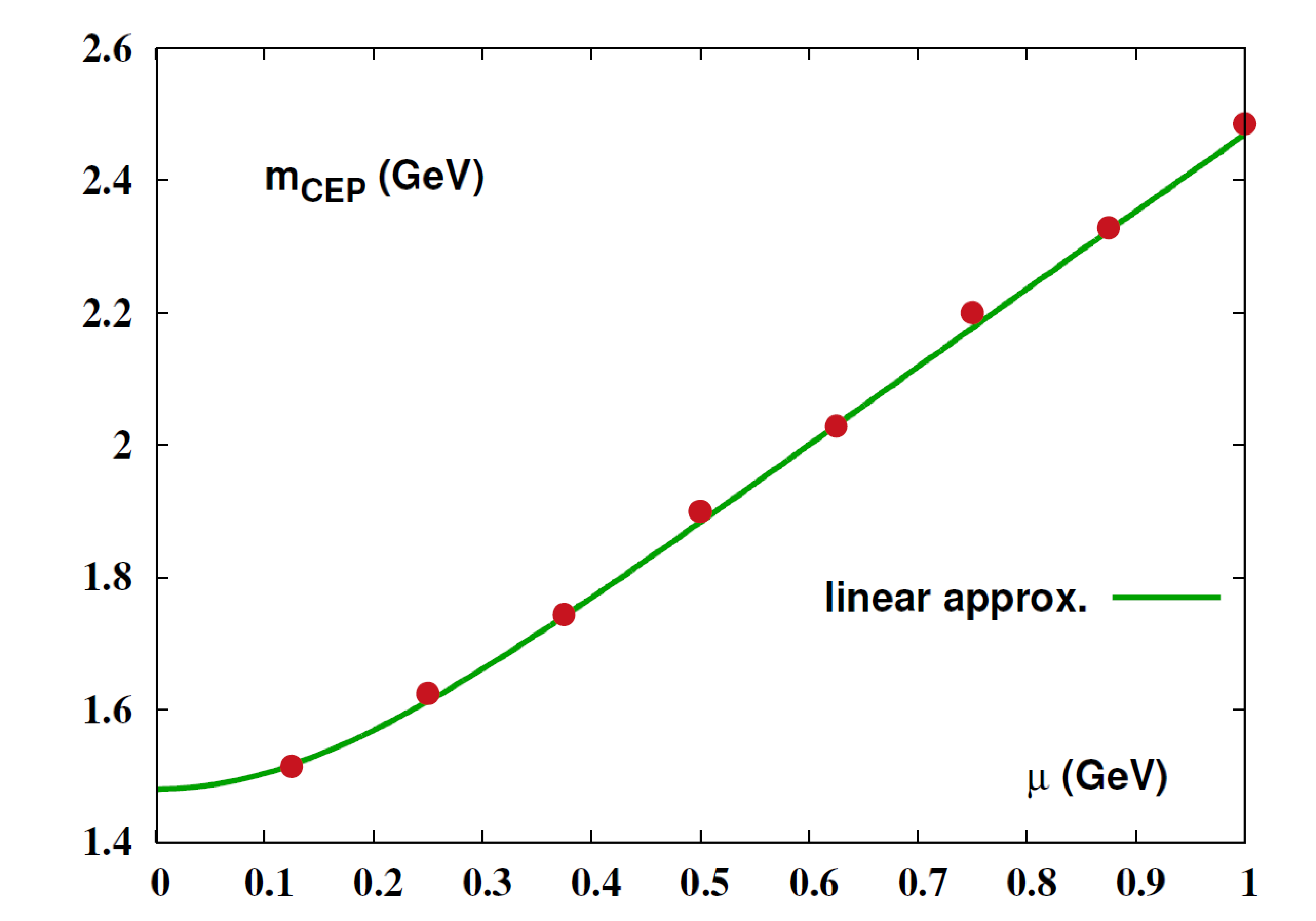
- Phase boundary of deconfinement phase transition



Critical quark mass at finite density

- Phase boundary of deconfinement phase transition





2.6
2.4
2.2
2
1.8
1.6
1.4
m_{CEP} (GeV)
linear approx.
μ (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Summary of part 1

- χ_L is strongly enhanced in the critical region
  $\longrightarrow$ probe the location of CEP
- χ_T is insensitive to criticality
  $\longrightarrow$ shows only monotonic behaviors

- Deconfining CEP: $m_{CEP}^{N_f=3} \approx 1.48\,\mathrm{GeV}$
  - lattice estimate: $\approx 1 - 1.5\,\mathrm{GeV}$
  - $T_{CEP} \approx 0.26\,\mathrm{GeV}$

Summary of part 1

- m_{CEP} increases with μ

  $\longrightarrow$ first order region shrinks!

- Results of the CEP are model dependent

  $\longrightarrow$ mandatory to take fluctuations of order parameter into account in constructing the effective potential

Studying QCD medium with Polyakov loop correlators

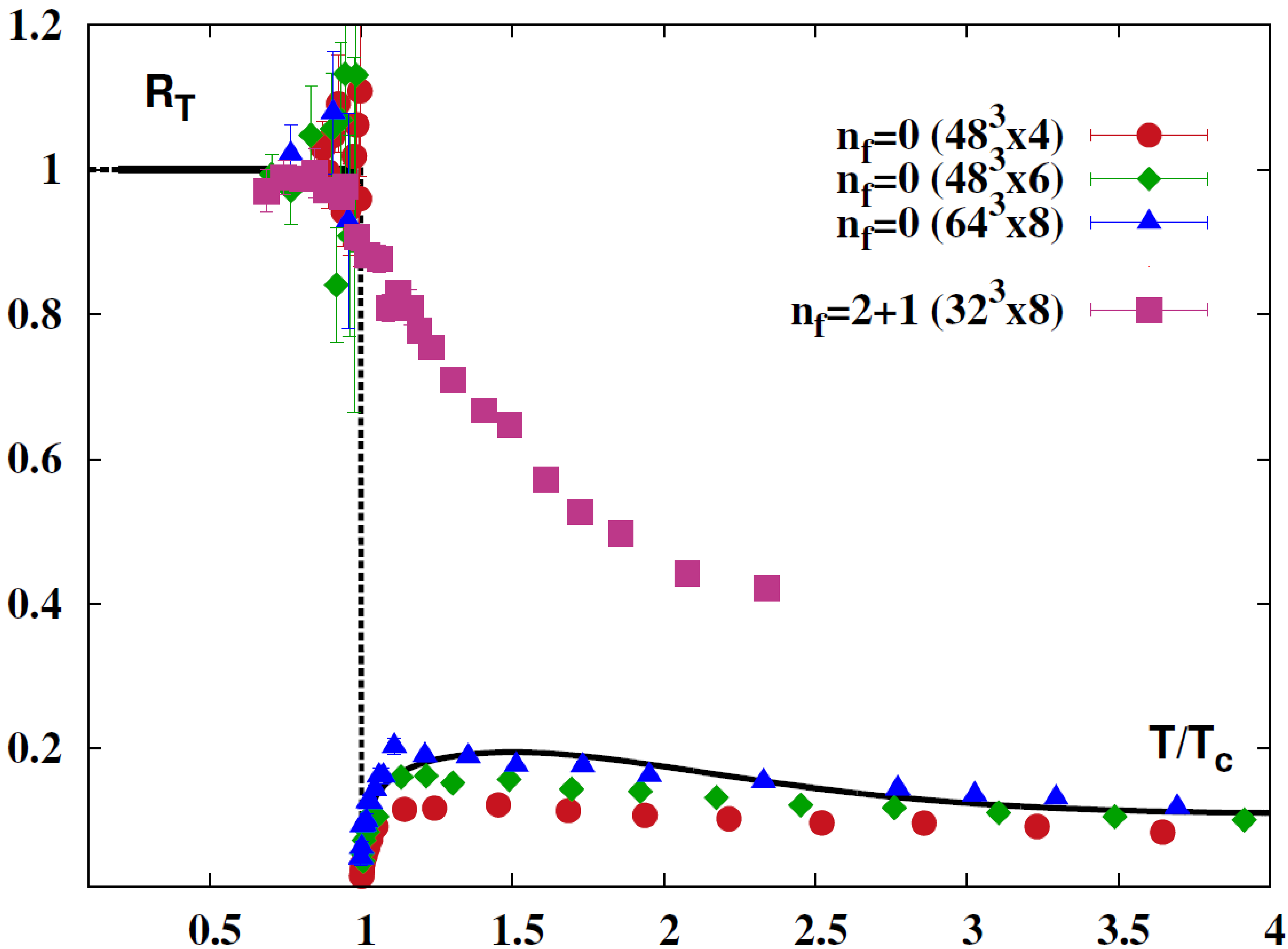
Polyakov line correlators

- The Polyakov loop susceptibilities can be understood as **integrated correlation functions**

$$\mathrm{L}_{\vec{x}} =< \frac{1}{N_c} Tr\, \mathcal{P} e^{ig \int_0^\beta d\tau\, A^4[\tau,\vec{x}]} >$$

$$\chi_{\mathrm{L}} = \int d^3x \, \langle L_{\mathrm{L}}(x) L_{\mathrm{L}}(0) \rangle_c$$

$$\chi_{\mathrm{T}} = \int d^3x \, \langle L_{\mathrm{T}}(x) L_{\mathrm{T}}(0) \rangle_c$$



P. M. Lo, B. Friman, O. Kaczmarek, K. Redlich and C. Sasaki, Phys. Rev. D 88, 074502 (2013)

Polyakov line correlators

- Below T_c , from Z(3) symmetry

$$\longrightarrow \quad \chi_{\mathrm{T}}/\chi_{\mathrm{L}} = 1$$

$$\langle LL \rangle = 0 = \langle L_{\mathrm{L}} L_{\mathrm{L}} \rangle - \langle L_{\mathrm{T}} L_{\mathrm{T}} \rangle$$

- Above T_c, Z(3) is spontaneously broken

$$\longrightarrow \quad \chi_{\mathrm{T}} \neq \chi_{\mathrm{L}}$$

Polyakov line correlators

- Below T_c , from Z(3) symmetry

$$\longrightarrow \chi_{\mathrm{T}}/\chi_{\mathrm{L}} = 1$$

$$\langle LL \rangle = 0 = \langle L_{\mathrm{L}} L_{\mathrm{L}} \rangle - \langle L_{\mathrm{T}} L_{\mathrm{T}} \rangle$$

- Above T_c , Z(3) is spontaneously broken

$$\longrightarrow \chi_{\mathrm{T}} \neq \chi_{\mathrm{L}}$$

$$\chi_{\mathrm{T}} \ll \chi_{\mathrm{L}}$$

Magnitudes of χ's reflect screening properties of QCD medium!

Screening masses of the Polyakov line correlators

- The screening masses for these gauge invariant correlators have been extracted

$$\mathrm{m}_{\mathrm{L,T}} = \lim_{r\to\infty} -\frac{d}{dr}\ln C_{\mathrm{L,T}}(r)$$

Screening masses of the Polyakov line correlators

- The screening masses for these gauge invariant correlators are extracted

$$\mathrm{m}_{\mathrm{L,T}} = \lim_{r\to\infty} -\frac{d}{dr} \ln C_{\mathrm{L,T}}(r)$$

$$\langle L_{\mathrm{L}}(x) L_{\mathrm{L}}(0)\rangle_c$$

$$\langle L_{\mathrm{T}}(x) L_{\mathrm{T}}(0)\rangle_c$$

$$\mathrm{L}_{\vec{x}} =< \frac{1}{N_c} Tr\,\mathcal{P} e^{ig\int_0^\beta d\tau\, A^4[\tau,\vec{x}]} >$$

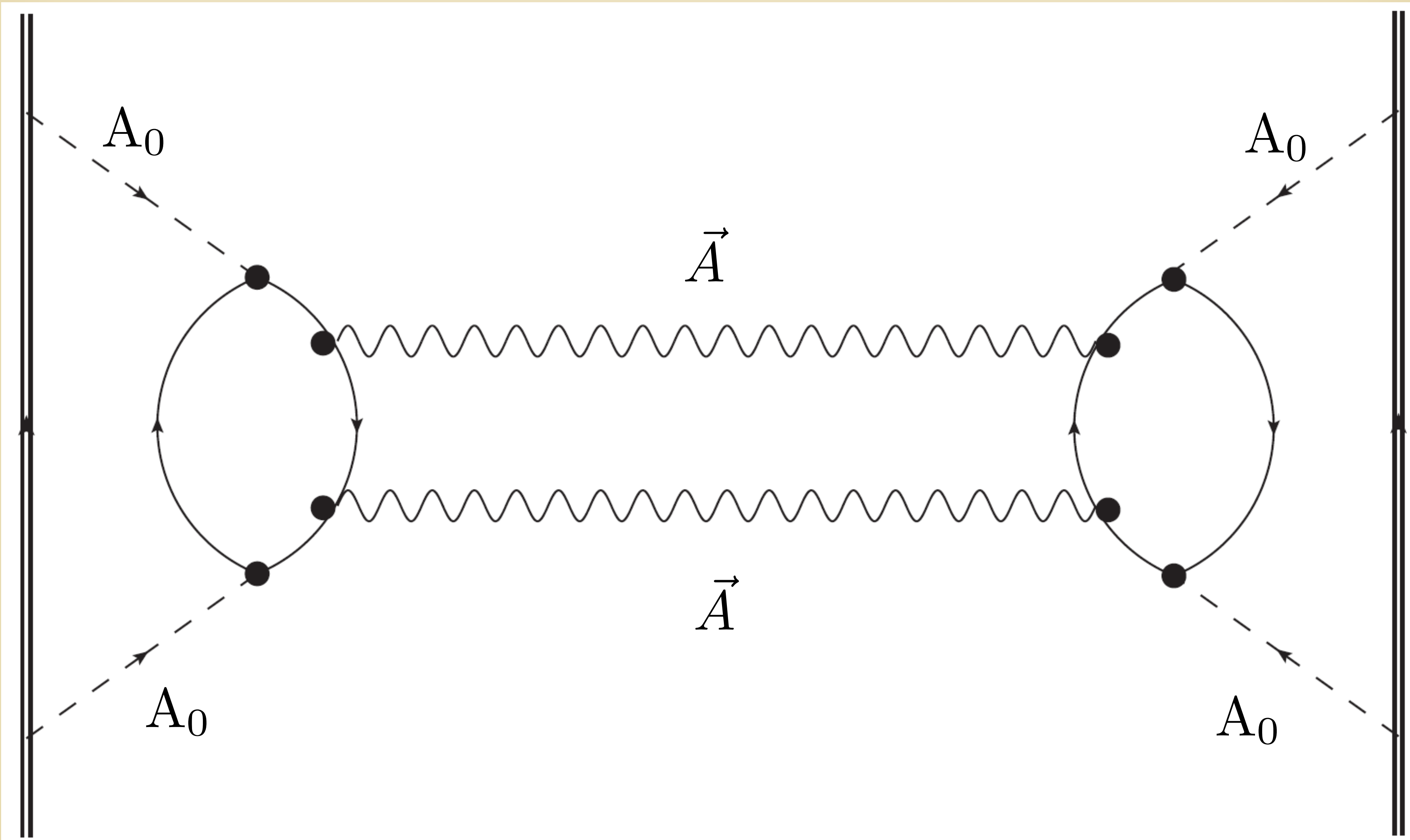
??

Perturbatively:
starts with 2 and 3 gluons exchange
(S. Nadkarni, Phys. Rev. D 33, 3738 (1986))

Effective field theory:
glueball exchange
(E. Braaten and A. Nieto, Phys. Rev. Lett. 74, 3530 (1995))

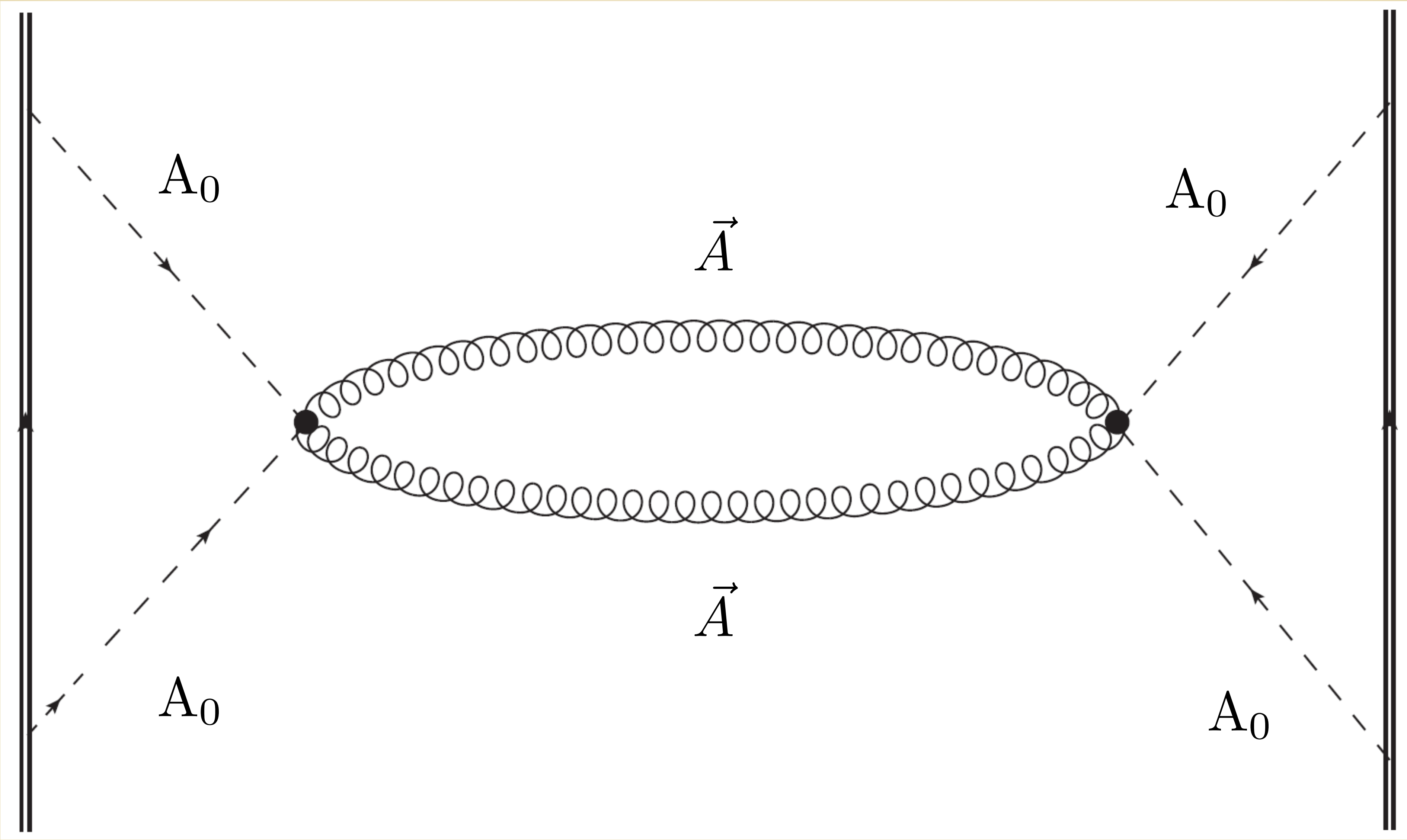
QED

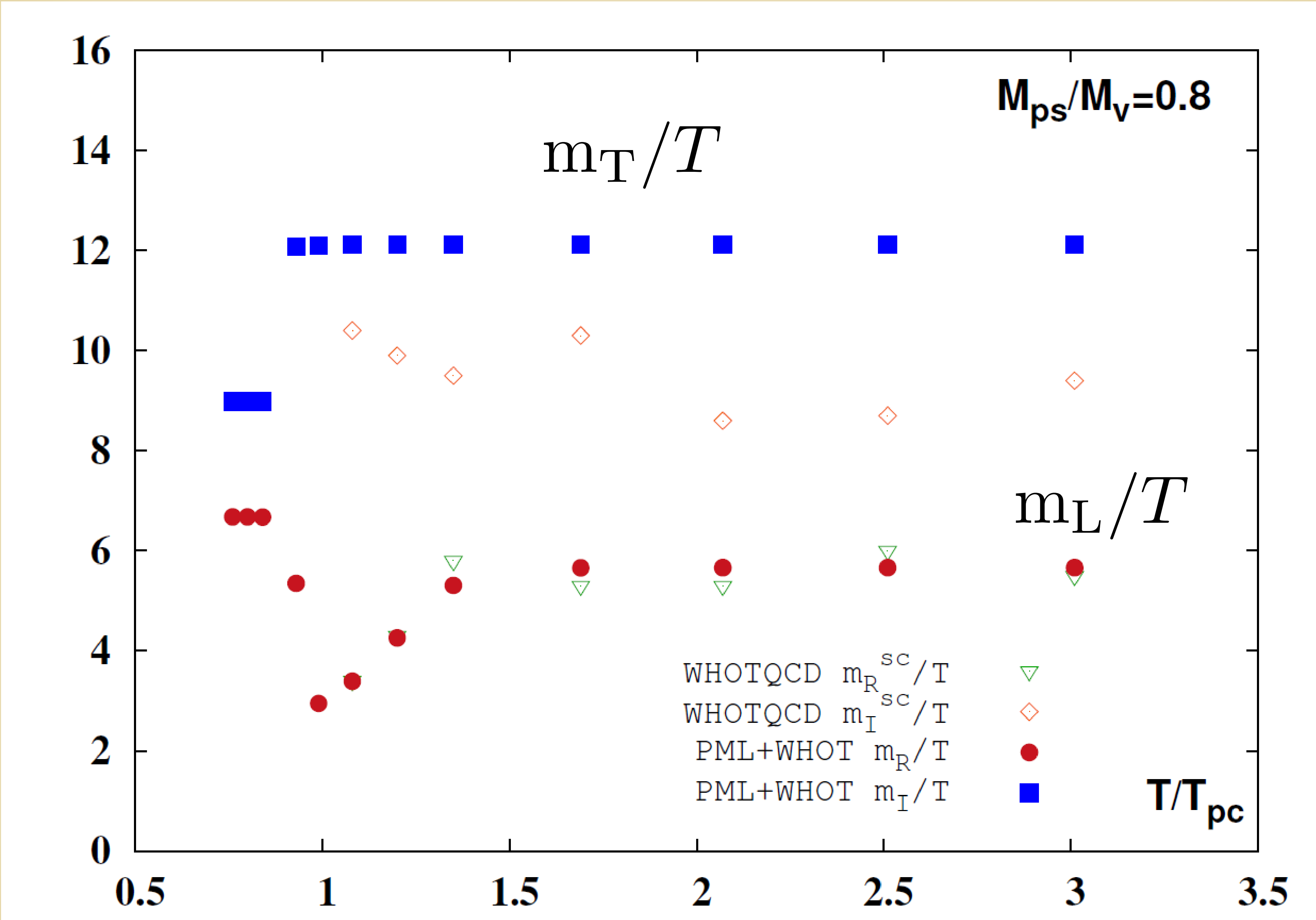
$\langle L_{\rm L}(x) L_{\rm L}(0)\rangle_c$ contains the exchange of magnetic photons!



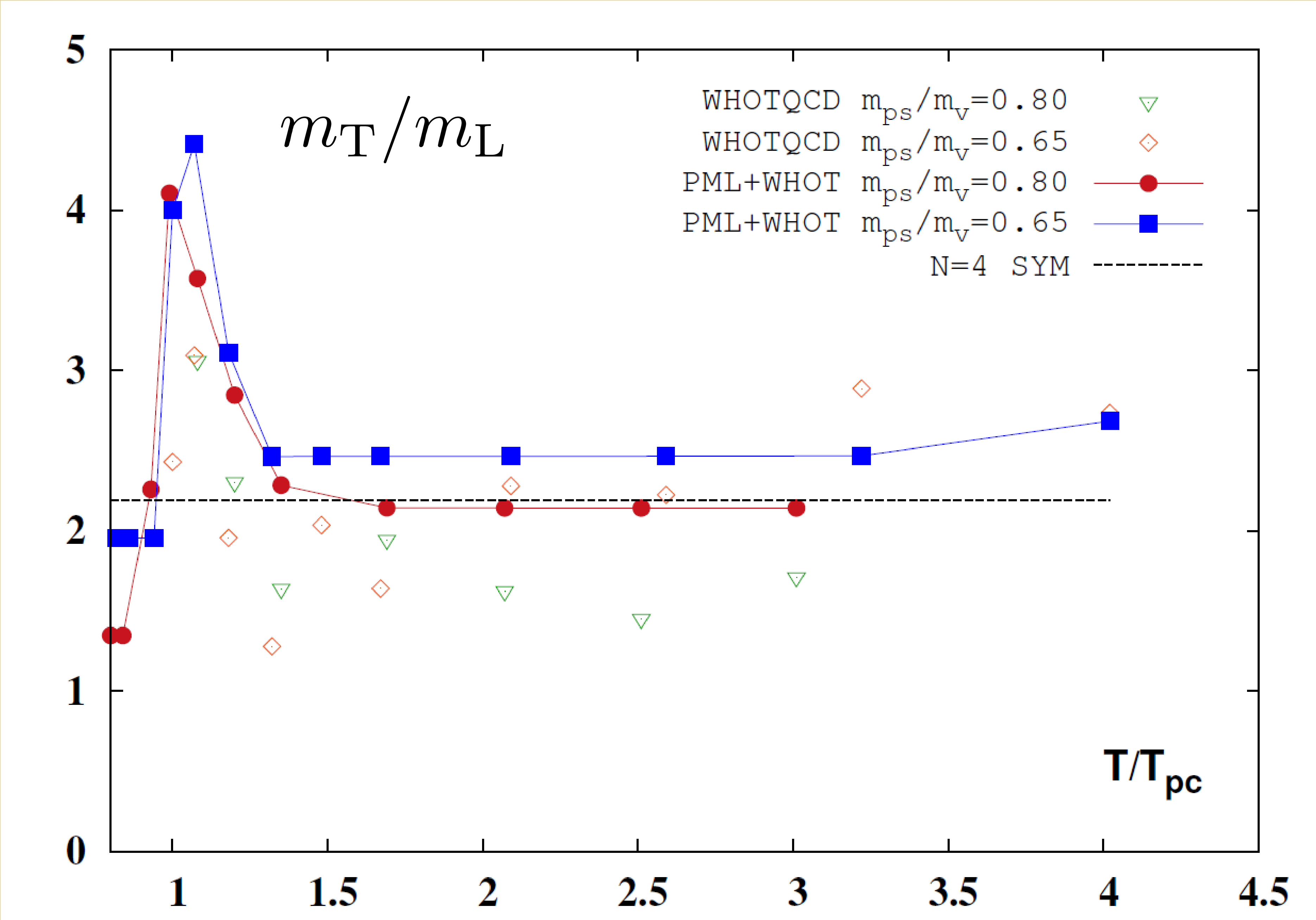
QCD

$\langle L_{\mathrm{L}}(x) L_{\mathrm{L}}(0)\rangle_c$ contains the exchange of magnetic gluons and glueballs!

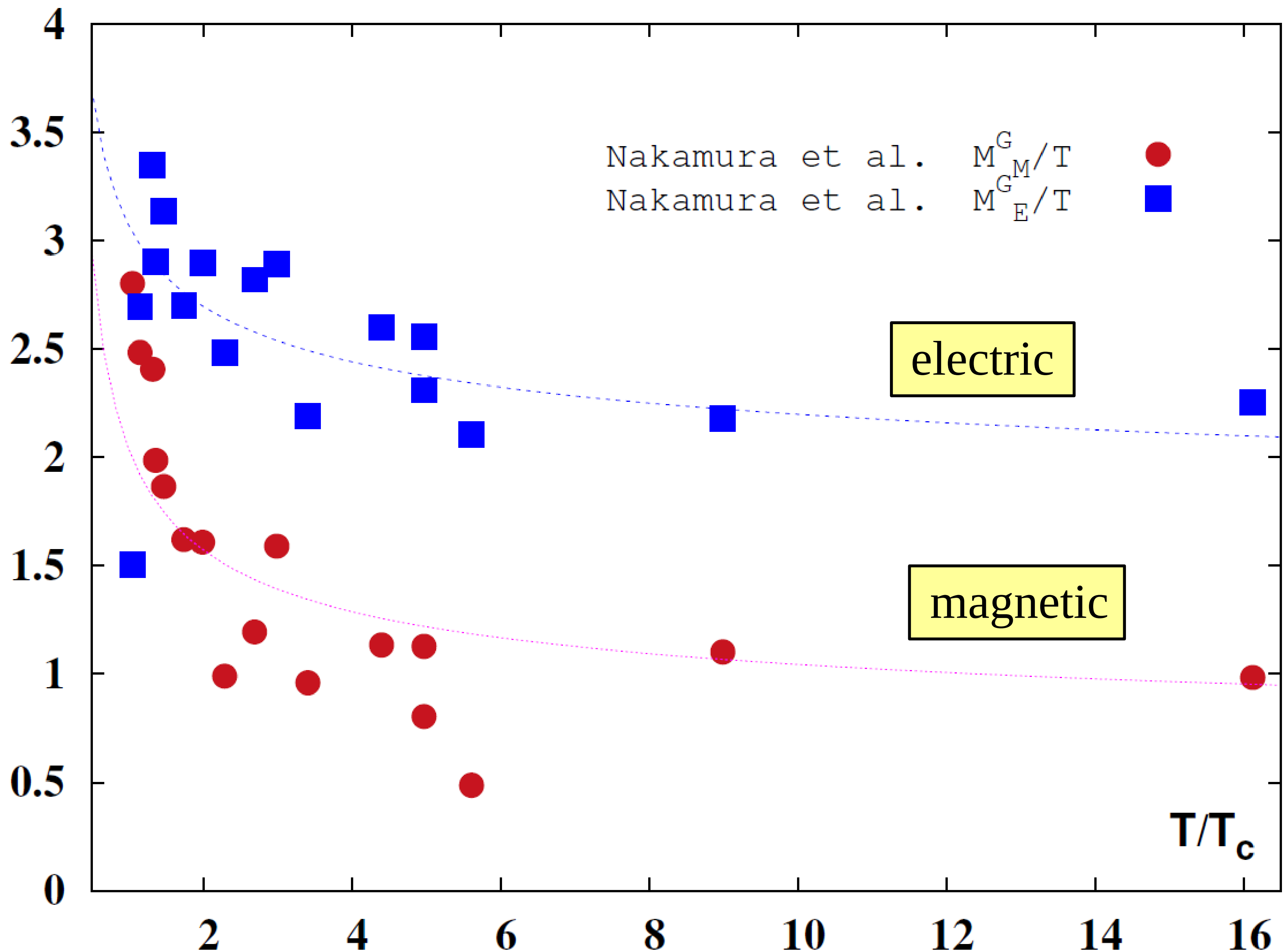




16
14
12
10
8
6
4
2
0
0.5
1
1.5
2
2.5
3
3.5
Mps/Mv=0.8
mT/T
mL/T
WHOTQCD mR sc/T
WHOTQCD mI sc/T
PML+WHOT mR/T
PML+WHOT mI/T
T/Tpc



Y. Maezawa et al. [WHOT-QCD Collaboration], Phys. Rev. D 81, 091501 (2010)



A. Nakamura, T. Saito and S. Sakai, Phys. Rev. D 69, 014506 (2004)

R-parity

$$\mathrm{A}_0 \to -A_0$$

- Longitudinal PL: even, magnetic?
- Transverse PL: odd, electric?

$$\mathrm{m}_{\mathrm{L,T}} = \lim_{r\to\infty} -\frac{d}{dr}\ln C_{\mathrm{L,T}}(r)$$

$$\chi_{\mathrm{L}} = \int d^3x\,\langle L_{\mathrm{L}}(x)L_{\mathrm{L}}(0)\rangle_c$$

$$\chi_{\mathrm{T}} = \int d^3x\,\langle L_{\mathrm{T}}(x)L_{\mathrm{T}}(0)\rangle_c$$

P. B. Arnold and L. G. Yaffe, Phys. Rev. D 52, 7208 (1995)

Y. Maezawa et al. [WHOT-QCD Collaboration], Phys. Rev. D 81, 091501 (2010)

R-parity

$A_0 \rightarrow -A_0$

- Longitudinal PL: even, magnetic?
- Transverse PL: odd, electric? → electric screening > magnetic screening

$$\mathrm{m}_{\mathrm{L,T}} = \lim_{r\to\infty} -\frac{d}{dr}\ln C_{\mathrm{L,T}}(r)$$

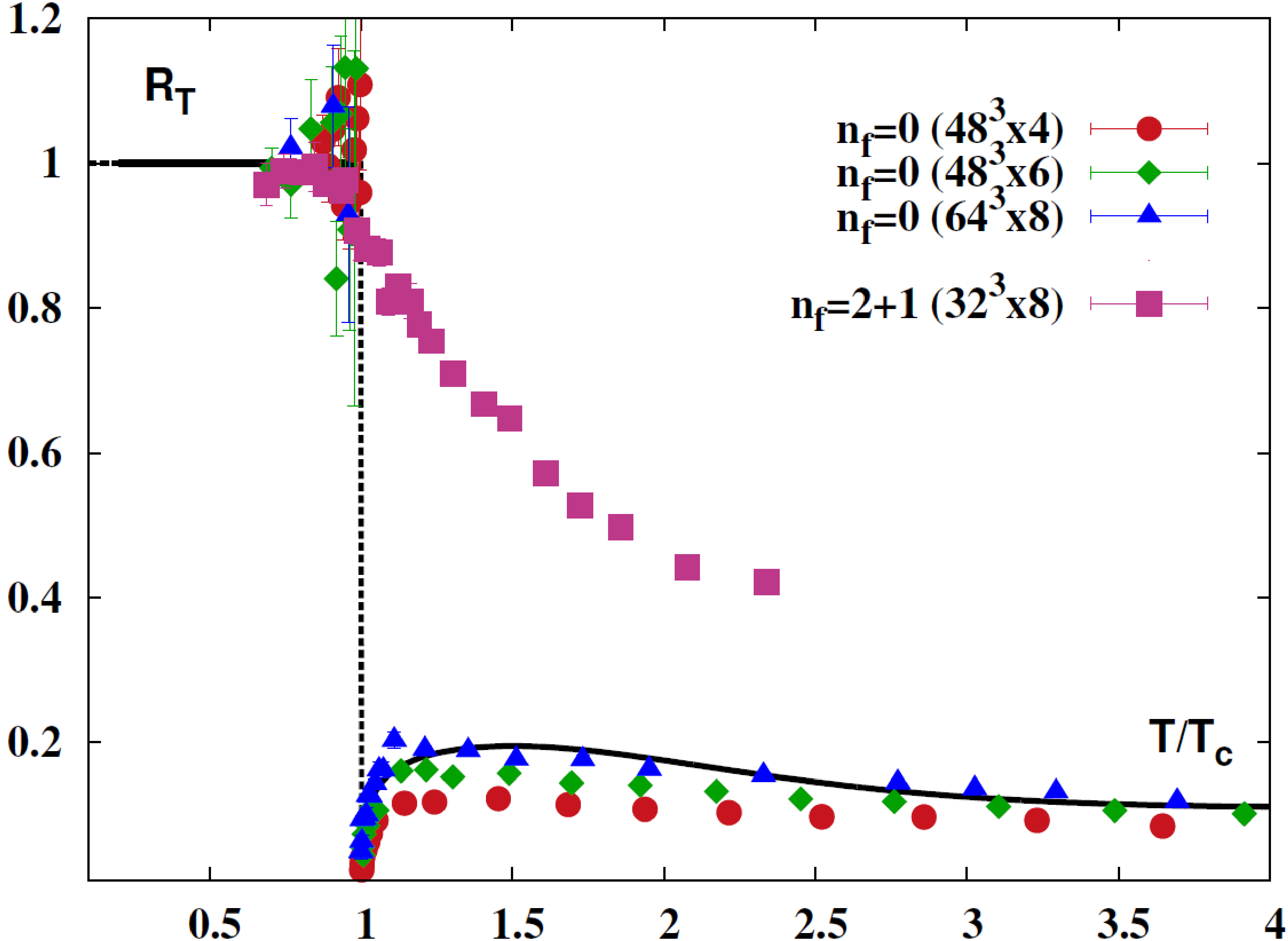
$$\chi_{\mathrm{L}} = \int d^3x \, \langle L_{\mathrm{L}}(x) L_{\mathrm{L}}(0)\rangle_c$$

$$\chi_{\mathrm{T}} = \int d^3x \, \langle L_{\mathrm{T}}(x) L_{\mathrm{T}}(0)\rangle_c$$

above T_c ↓

$\mathrm{m}_{\mathrm{T}} > m_{\mathrm{L}}$

$\chi_{\mathrm{T}} \ll \chi_{\mathrm{L}}$



P. M. Lo, B. Friman, O. Kaczmarek, K. Redlich and C. Sasaki, Phys. Rev. D 88, 074502 (2013)

Summary of part 2

- $\chi_{\mathrm{L,T}}$ can be understood as integrated correlation functions

$$\chi_{\mathrm{L}} = \int d^3x \, \langle L_{\mathrm{L}}(x) L_{\mathrm{L}}(0) \rangle_c$$

$$\chi_{\mathrm{T}} = \int d^3x \, \langle L_{\mathrm{T}}(x) L_{\mathrm{T}}(0) \rangle_c$$

- From R-parity

$\chi_{\mathrm{T}} < \chi_{\mathrm{L}}$

$\mathrm{m_T} > m_{\mathrm{L}}$ ⟷ electric screening > magnetic screening

Summary of part 2

- $\chi_{\mathrm{L,T}}$ link screening properties and deconfinement

Theoretical understanding is still incomplete, perturbative study is still absent.

Thank You!