C and P violations in the PNJL model

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① Deconfinement is a remnat of C violation

② Chiral restoration is a remnant of P restoration

③ D and C happen almost simultaneously in the real world

⇔C and P may happen simultaneously in the θ world

Deconfinement as remnant of C violation

- Deconfinement at zero density can be regarded as a remnat of C violation at $\theta=\pi/3$, where $\mu_I = i\theta T$ is the imaginary chemical potential.

- PNJL model analysis

  H.K., Yuji Sakai , Kouji Kashiwa, Masanobu Yahiro

  Journal of Physics G 36 (2009)

  115010-1-115010-17

PNJL model

- K. Fukushima, Phys. Lett. B591, 277(2004)
  Polyakov loop+NJL

- Chiral symmetry chiral restoration
  extended Z_3symmetry deconfiment
- at imaginary chemical potential,
  there is Roberge-Weiss transition
  as C violation

RW periodicity and extended Z_3 symmetry（EZ_3）

$$\theta = \mu_I/T$$

$$\Omega = -2N_f \int \frac{d^3p}{(2\pi)^3}\Big[3E(p) + \frac{1}{\beta}\ln\ [1+3(\Phi+\Phi^* e^{-\beta E^-(\mathbf{p})})e^{-\beta E^-(\mathbf{p})} + e^{-3\beta E^-(\mathbf{p})}] + \frac{1}{\beta}\ln\ [1+3(\Phi^*+\Phi e^{-\beta E^+(\mathbf{p})})e^{-\beta E^+(\mathbf{p})} + e^{-3\beta E^+(\mathbf{p})}]\Big] + U_{\mathrm{M}} + \mathcal{U}$$

$$E(p) = \sqrt{\mathbf{p}^2+M^2}\,,\ \sigma = \langle\bar{q}q\rangle, \quad \Sigma_{\mathrm{s}} = -2G_{\mathrm{s}}\sigma, \quad U_{\mathrm{M}} = G_{\mathrm{s}}\sigma^2,\ M = m_0 + \Sigma_{\mathrm{s}}.$$

extended Z_3 trans.

$$\theta \to \theta + 2\pi k/3,\ \ \Phi(\theta) \to \Phi(\theta)e^{-i2\pi k/3} \qquad \theta = \mu_I/T$$

修正版Polyakovループ　$\Psi \equiv e^{i\theta}\Phi$

$$\theta \to \theta + 2\pi k/3\ , \quad \Psi(\theta) \to \Psi(\theta), \quad \Psi(\theta)^* \to \Psi(\theta)^*$$

Thermodynamic potential

$$\theta = \mu_I/T$$

$$\Omega = -2N_f \int \frac{d^3p}{(2\pi)^3}\Big[3E(p) + \frac{1}{\beta}\ln\,[1 + 3\Psi e^{-\beta E(\mathbf{p})} + 3\Psi^* e^{-2\beta E(\mathbf{p})} e^{3i\theta} + e^{-3\beta E(\mathbf{p})} e^{3i\theta}]$$
$$+\frac{1}{\beta}\ln\,[1 + 3\Psi^* e^{-\beta E(\mathbf{p})} + 3\Psi e^{-2\beta E(\mathbf{p})} e^{-3i\theta} + e^{-3\beta E(\mathbf{p})} e^{-3i\theta}]\Big] + U_{\mathrm{M}} + \mathcal{U}$$

$$E(p) = \sqrt{\mathbf{p}^2 + M^2}\,,\ \sigma = \langle \bar{q}q \rangle, \qquad \Sigma_{\mathrm{s}} = -2G_{\mathrm{s}}\sigma, \qquad U_{\mathrm{M}} = G_{\mathrm{s}}\sigma^2,\ M = m_0 + \Sigma_{\mathrm{s}}.$$

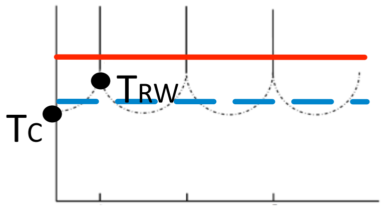
extended Z_3 trans.

$$\theta \to \theta + 2\pi k/3,\ \ \Phi(\theta) \to \Phi(\theta)e^{-i2\pi k/3}$$

修正版Polyakovループ $\Psi \equiv e^{i\theta}\Phi$ $\qquad \theta \to \theta + 2\pi k/3\,, \quad \Psi(\theta) \to \Psi(\theta)$

$$\boxed{\Omega(\theta) = \Omega(\Psi(\theta), \Psi(\theta)^*, e^{3i\theta})}$$

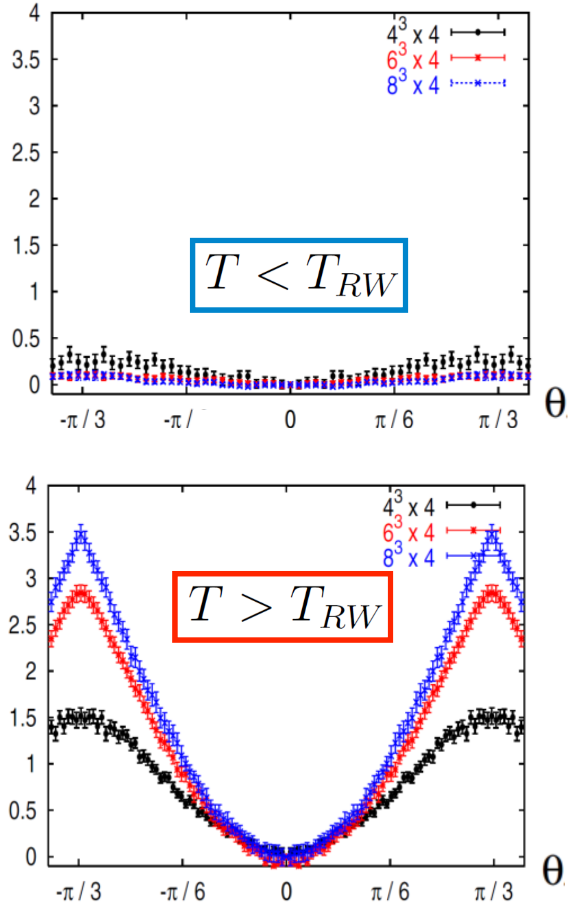
Extended Z_3 inv.

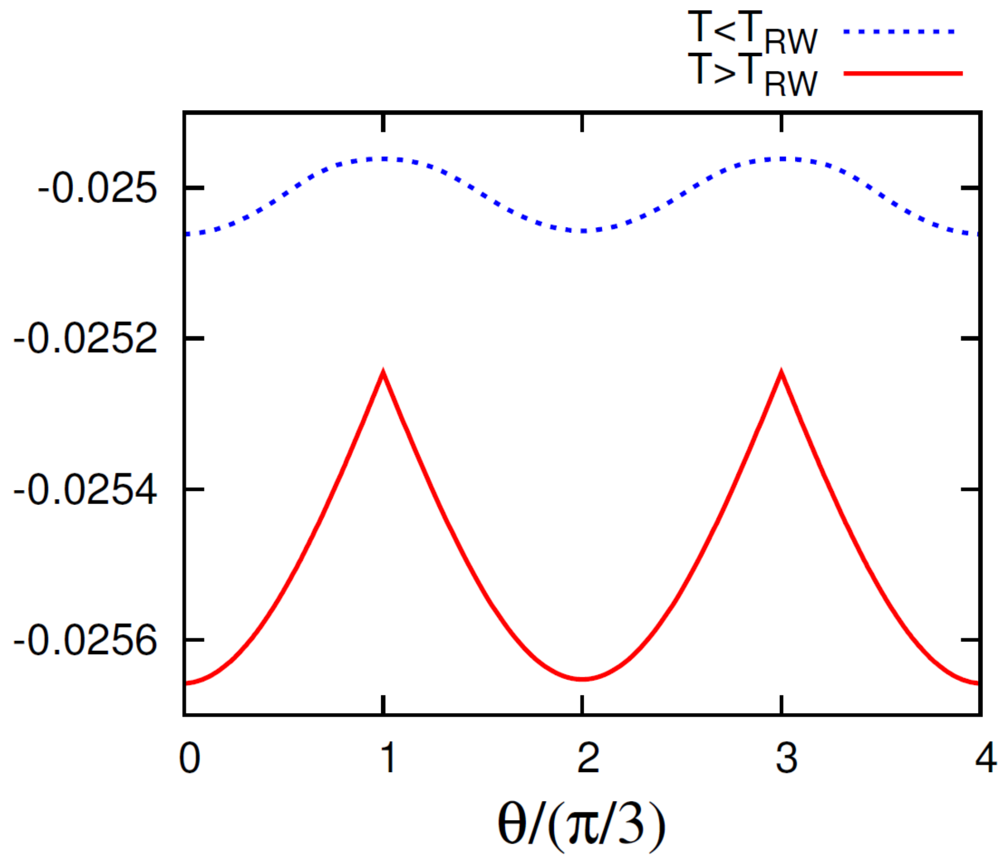


Roberg-Weiss periodicity and transition

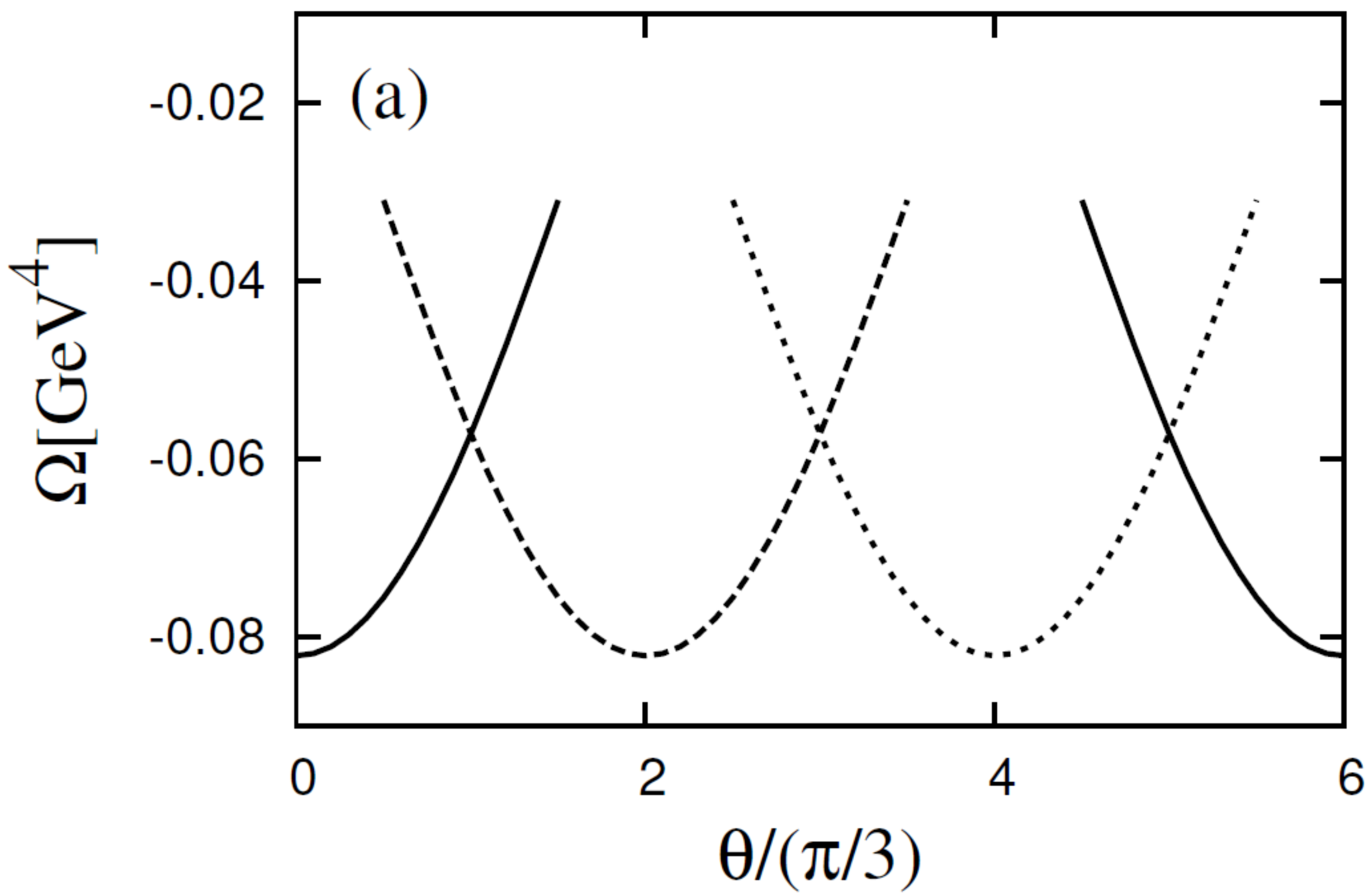
$$\Omega(\theta) = \Omega(\theta + 2\pi k/3) = \Omega(-\theta).$$

Kratochvila, Forcrand PRD**73**,114512(2006)

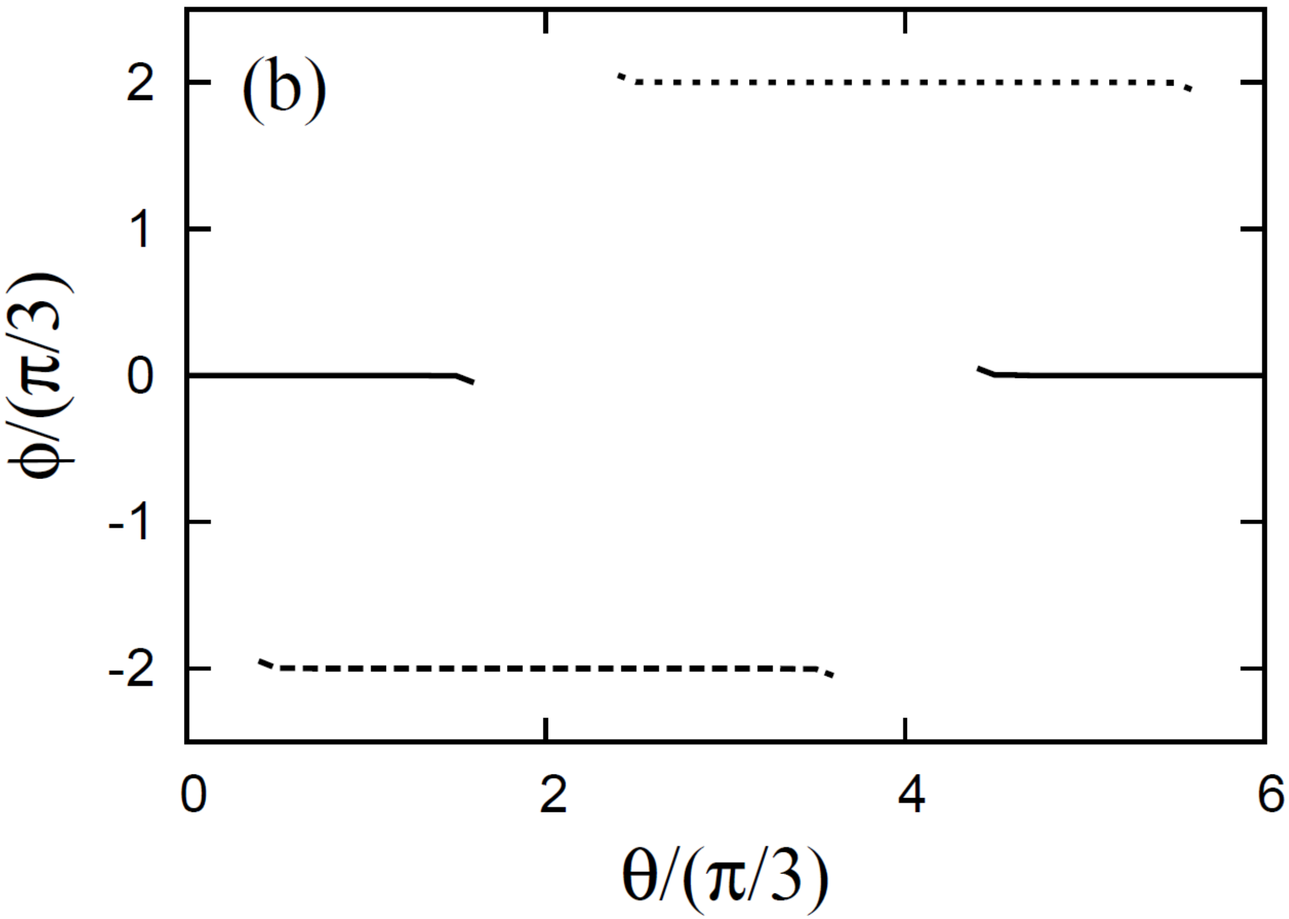




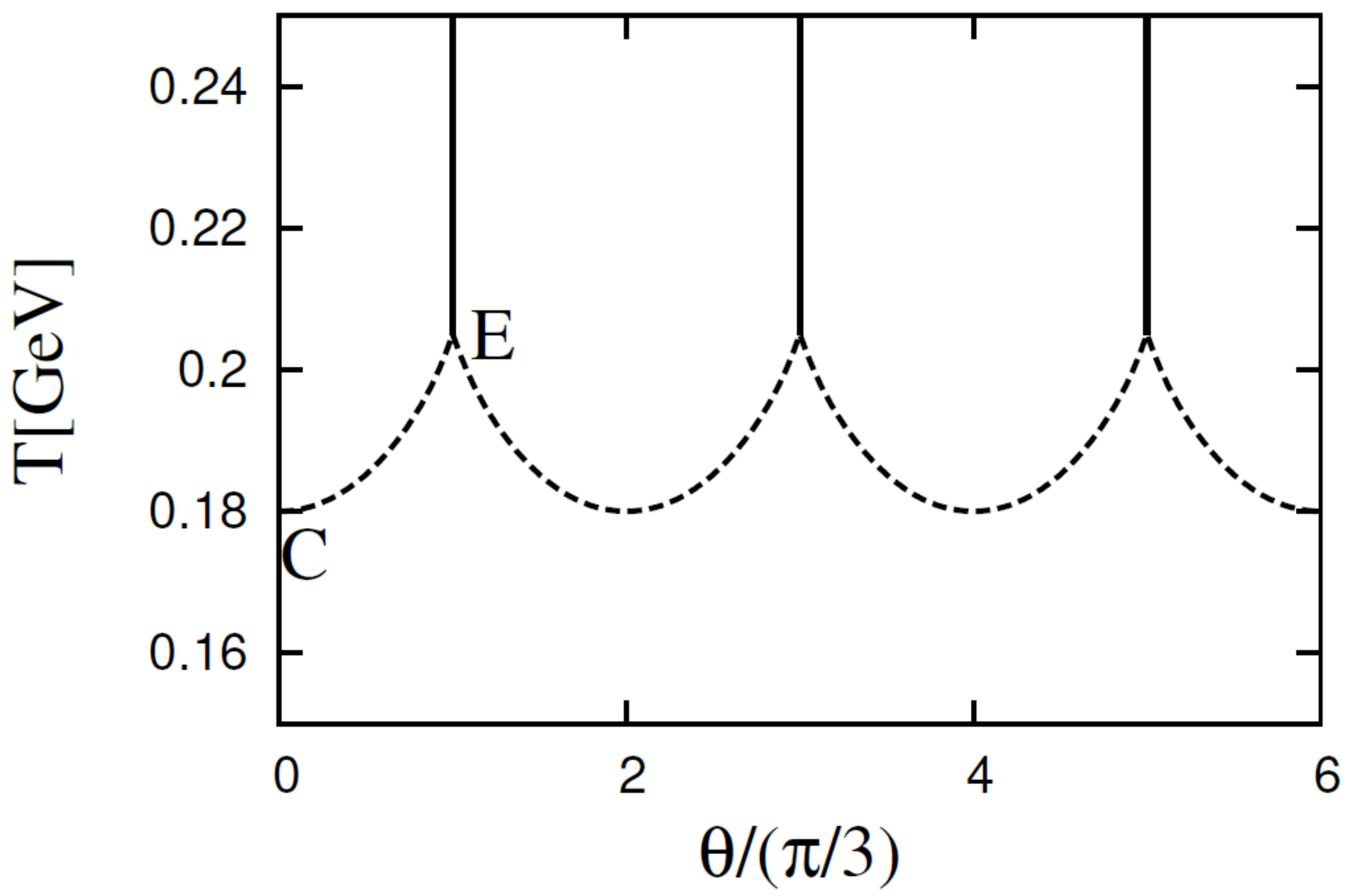
Thermodynamic potential



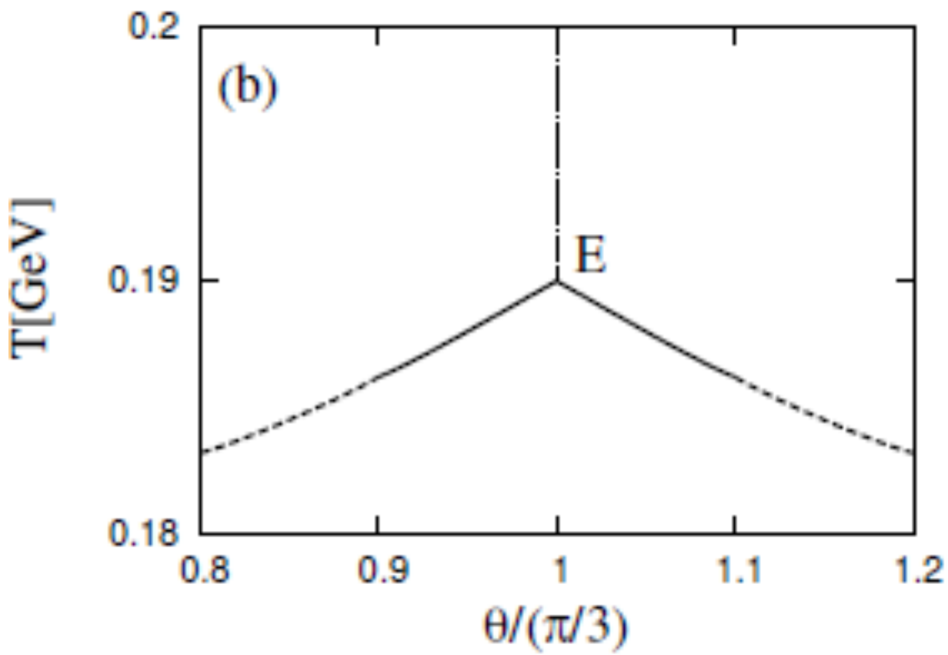
Phase of Polyakov loop



Phase diagram



Nontrivial CEP of deconfinement



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RW transition

- θ-even quantities have cusp when $T>T_{RW}$, $\theta=(2k+1)\pi/3$ (k integer), while θ-odd quantities are discontinuous there.
- At $\theta=(2k+1)\pi/3$ and $T=T_{RW}$, Spontaneous breaking of C symmetry happens as T increases.

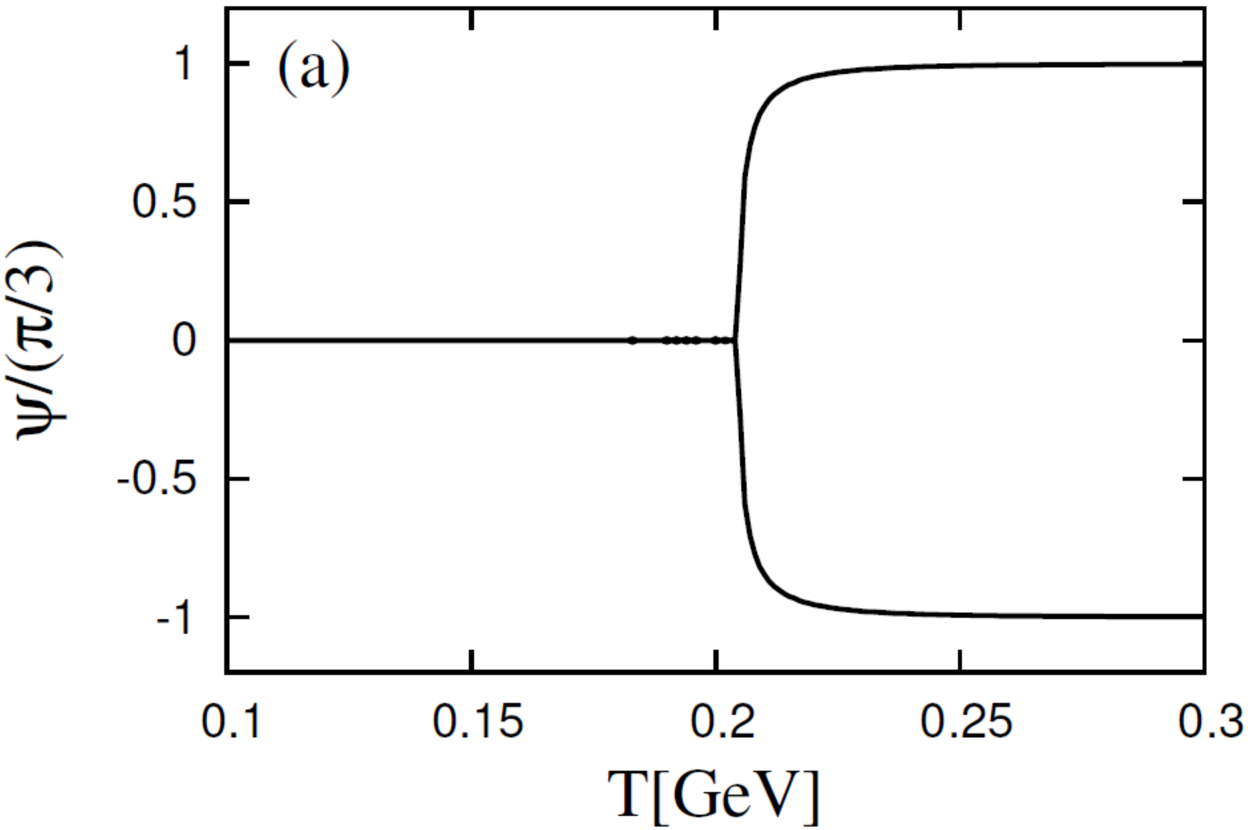
θ-odd quantities are order parameters.

Imaginary part or phase of modified Polyakov loop Ψ

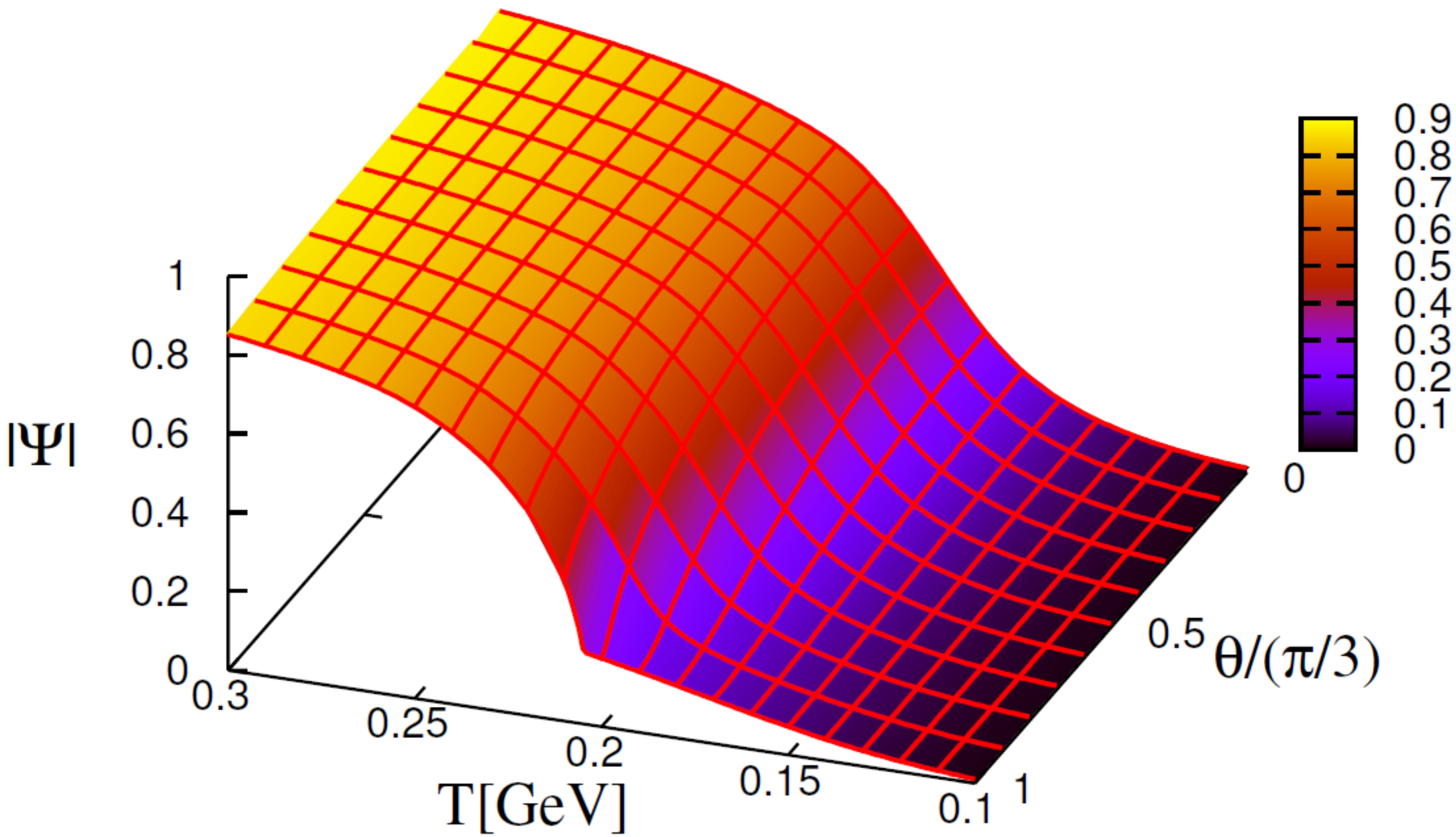
phase $\psi$of modified Polyakov loop Ψ

baryon number density (imaginary)

C violation at θ＝π/3



Deconfinement as remnant of C violation



Dashen mechanism

- CP violation in θvacuum.

Dashen, Phys. Rev. D3, 1879(1971)

NJL version

Boer and Boomsma,

Phys. Rev. D78,054027 (2008)

Θ_v-term in two-flavor NJL

$$L_{NJL} = \overline{\psi}(i\gamma^{\mu}\partial_{\mu} - m_0 + \gamma_0\mu)\psi + L_4 + L_{\theta}$$

$$L_4 = (1-c)G[(\overline{\psi}\tau_a\psi)^2 + (\overline{\psi}\tau_a i\gamma_5\psi)^2]$$

$$L_{\theta} = ce^{i\,\theta_{\mathrm{v}}}\det(\overline{\Psi}_{\mathrm{R}}\Psi_{\mathrm{L}}) + H.C.$$

PNJL model

- Replace derivative by D_μ
- Treat $A_4 = iA_0$ as a back ground field.
- Add Polyakov potential $U(\Phi)$

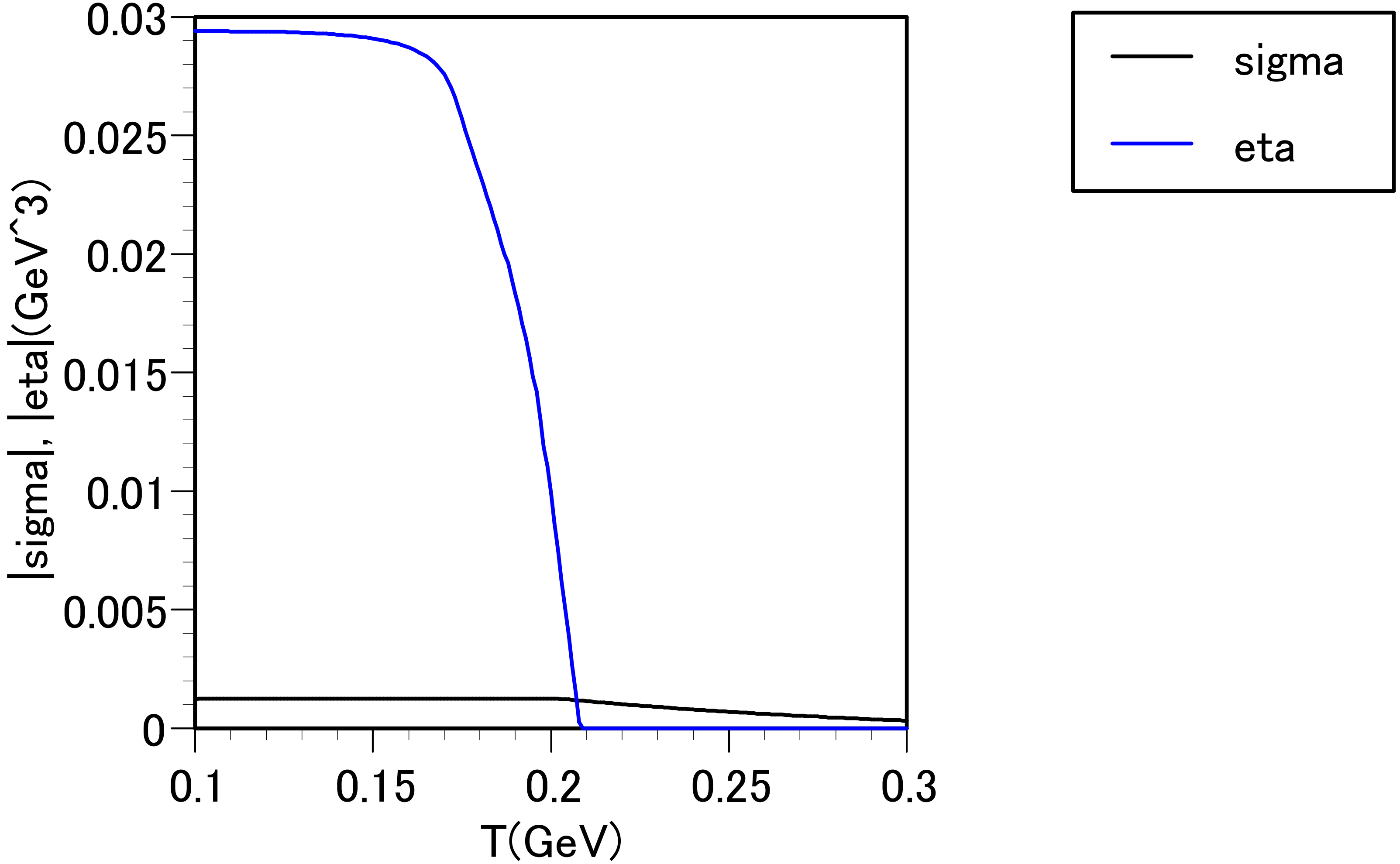
P violation and restoration at $\theta_v = \pi$

- For large c (c > c_{criti}), P symmetry is spontaneously broken at low temperature.
- P is restored at high T.
- P-odd quantities such as η are order parameters.

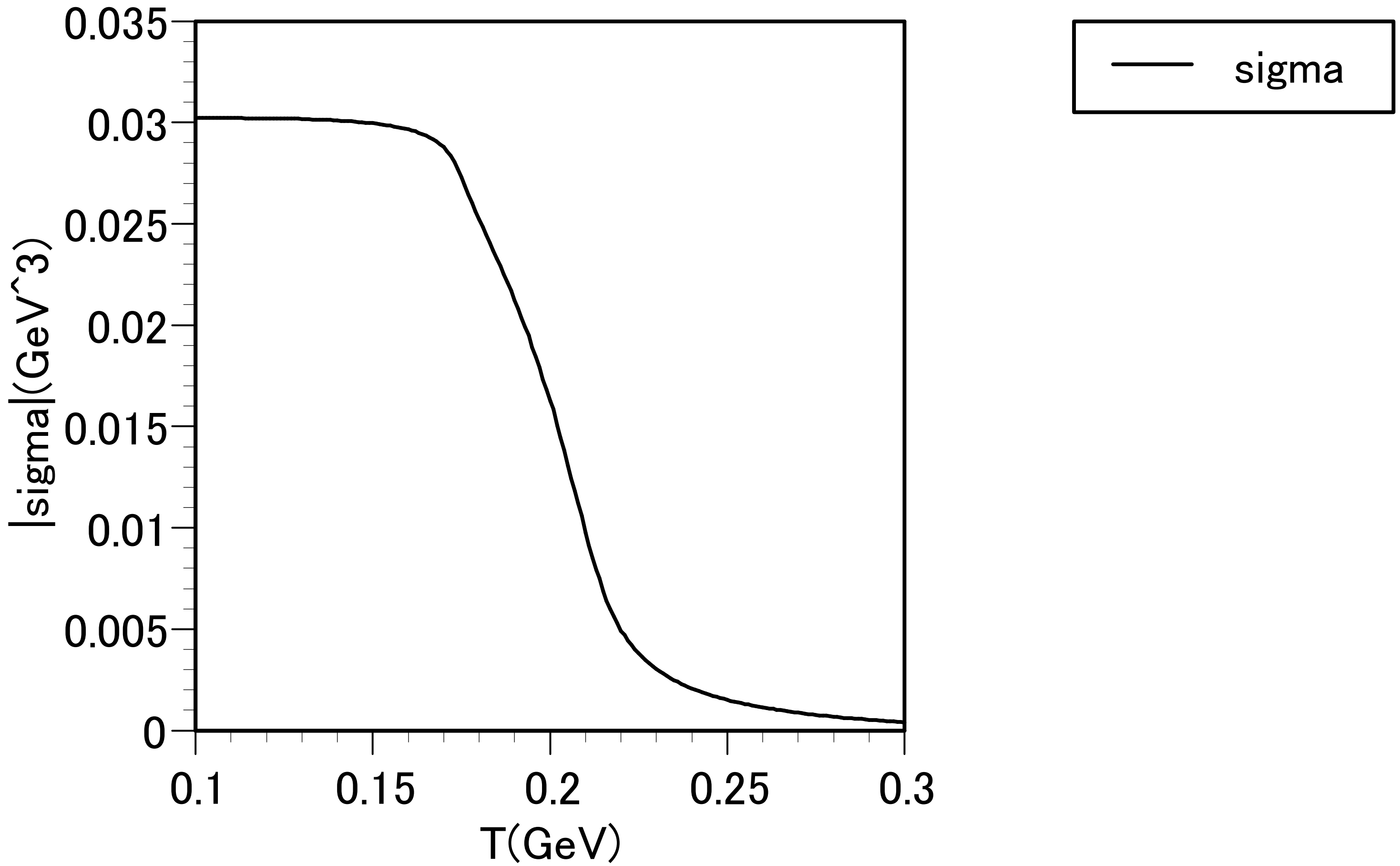
In broken phase,

$$\eta = \langle \bar{\psi} i \gamma_5 \psi \rangle \neq 0$$

P violation and restoration at$\theta_v = \pi$



Chiral breaking and restoration at θ_v=0



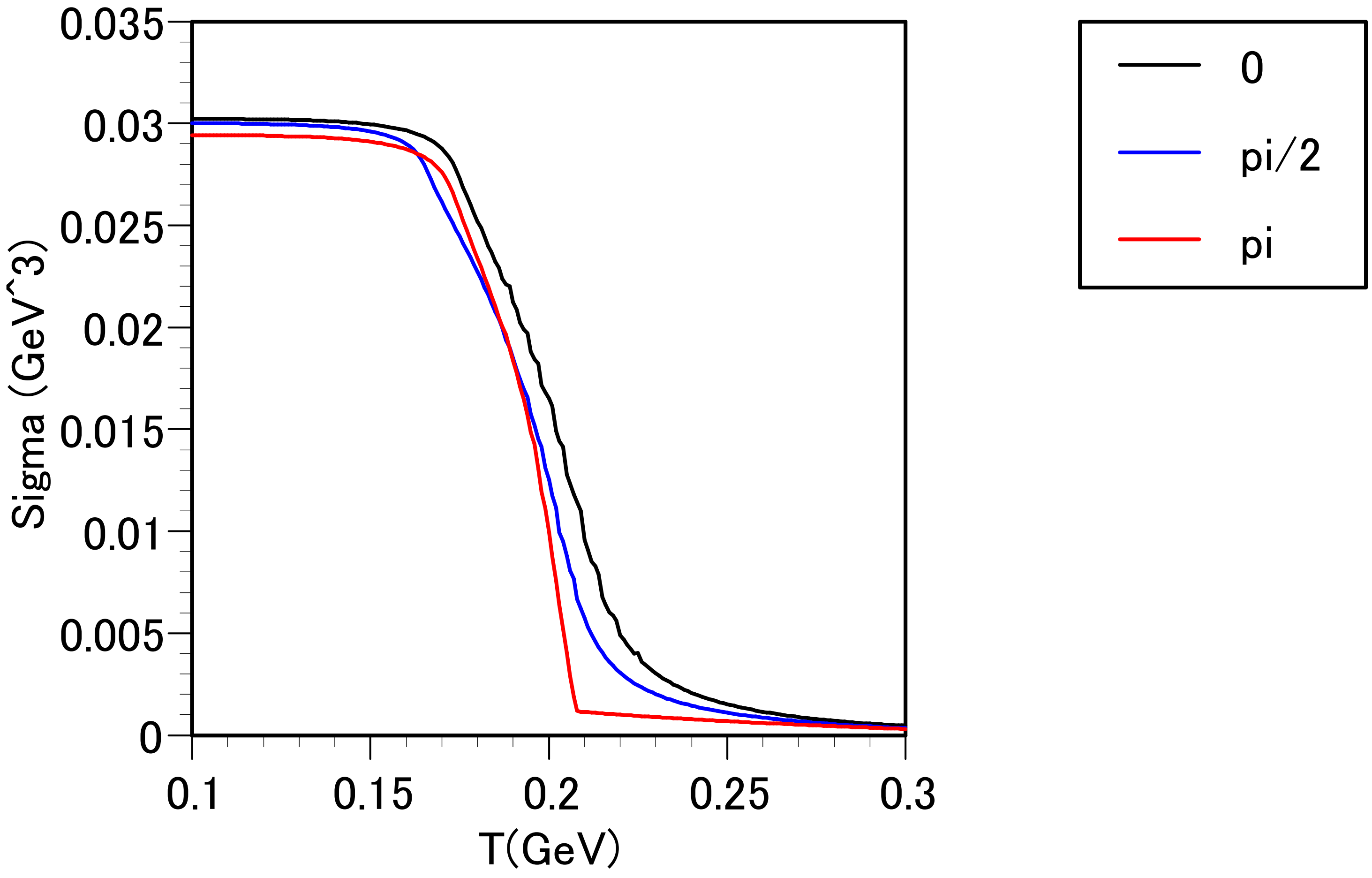
Chiral restoration as remnant of P restoration

Define $\Sigma = (\sigma^2+\eta^2)^{1/2}$

Chiral restoration at $\theta_v=0$ is a remnant of P restoration at $\theta_v=\pi$.

PNJL modde can treat both C and P at the same time!! ($\theta v = \pi$ and $\theta = /3$)

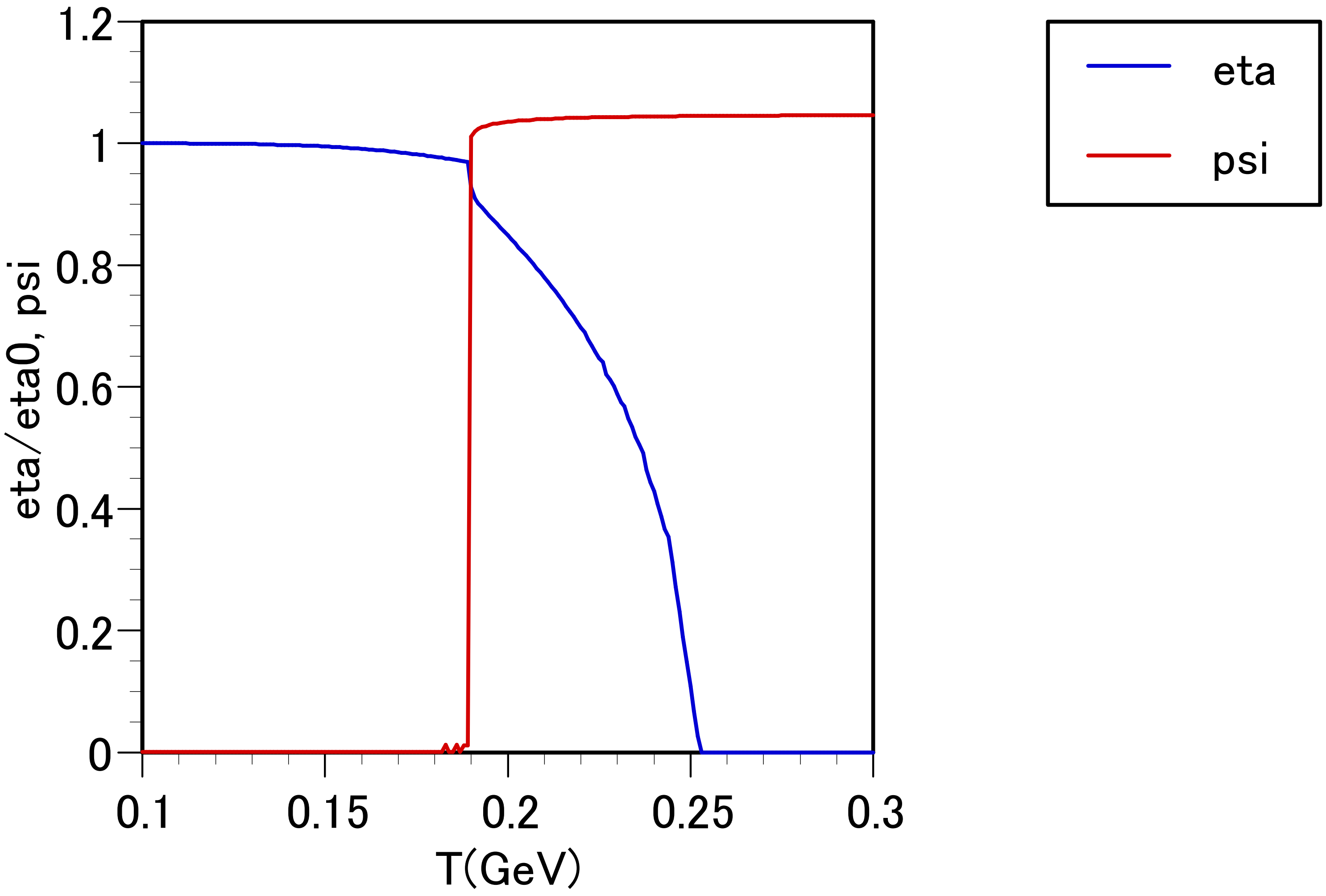
Chiral restoration as remnant of P restoration



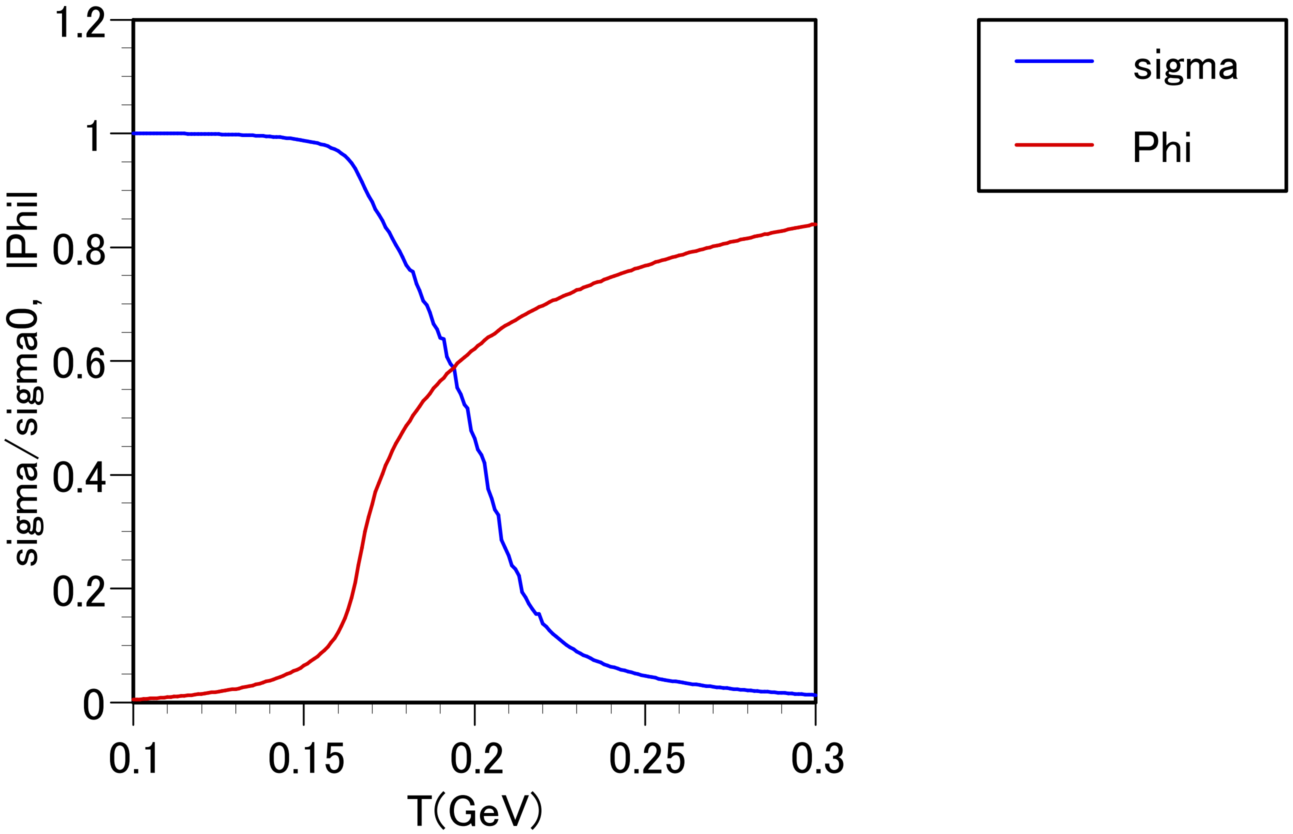
Dashen vs. RW

	Dashen	RW
Symmetry	P	C
Condition	At $\theta_v = \pi$	At $\theta = \pi/3$
Order parameter	η	ψ, n_q
Ω	has a cusp	has a cusp
Broken phase	low T	high T
Origin	anomaly instanton	term with $e^{3i\theta}$

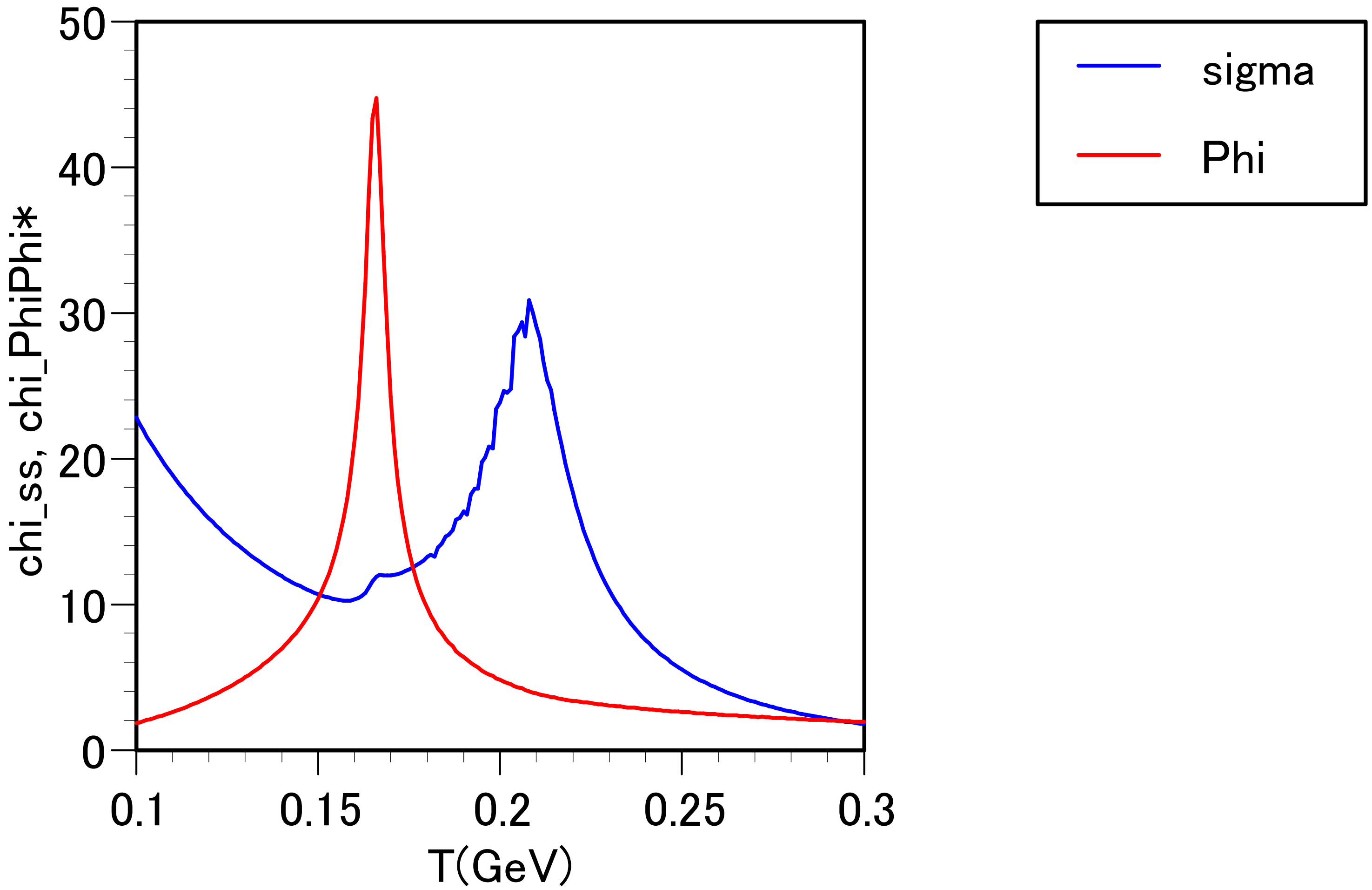
P restoration and C violation at $\theta = \pi/3$ and $\theta_v = \pi$ (θ world)



P restoration and C violation at $\theta = 0$ and $\theta_v = 0$ (Real World)



susceptiblities at $\theta=0$ and $\theta_v=0$ (Real World)



PC and CP

Real World

PC

Polyakov

Chiral

PC and CP

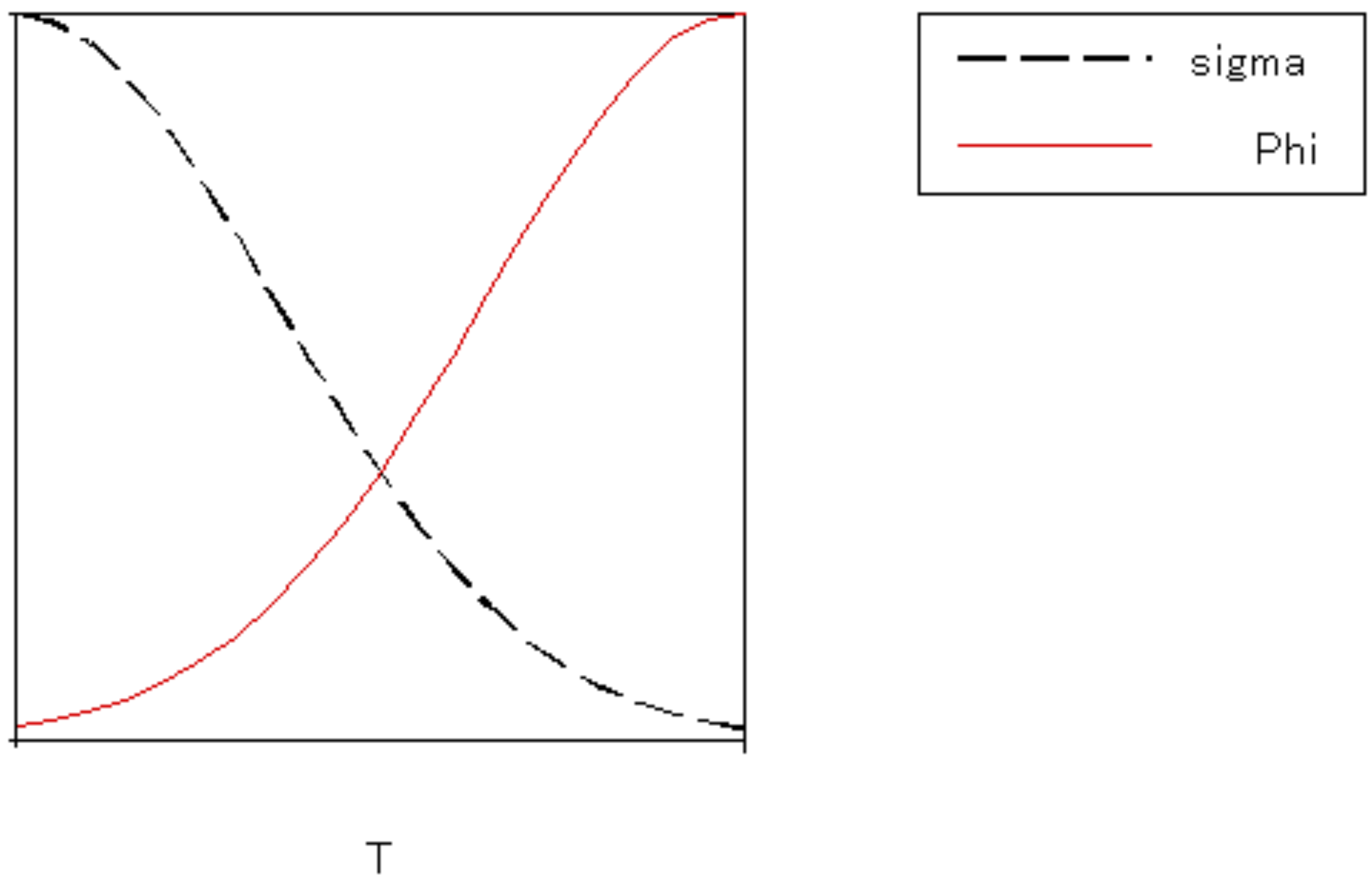
Real World		θ world
PC		CP
Polyakov	⇔	C violation
Chiral		P restoration

Prediction

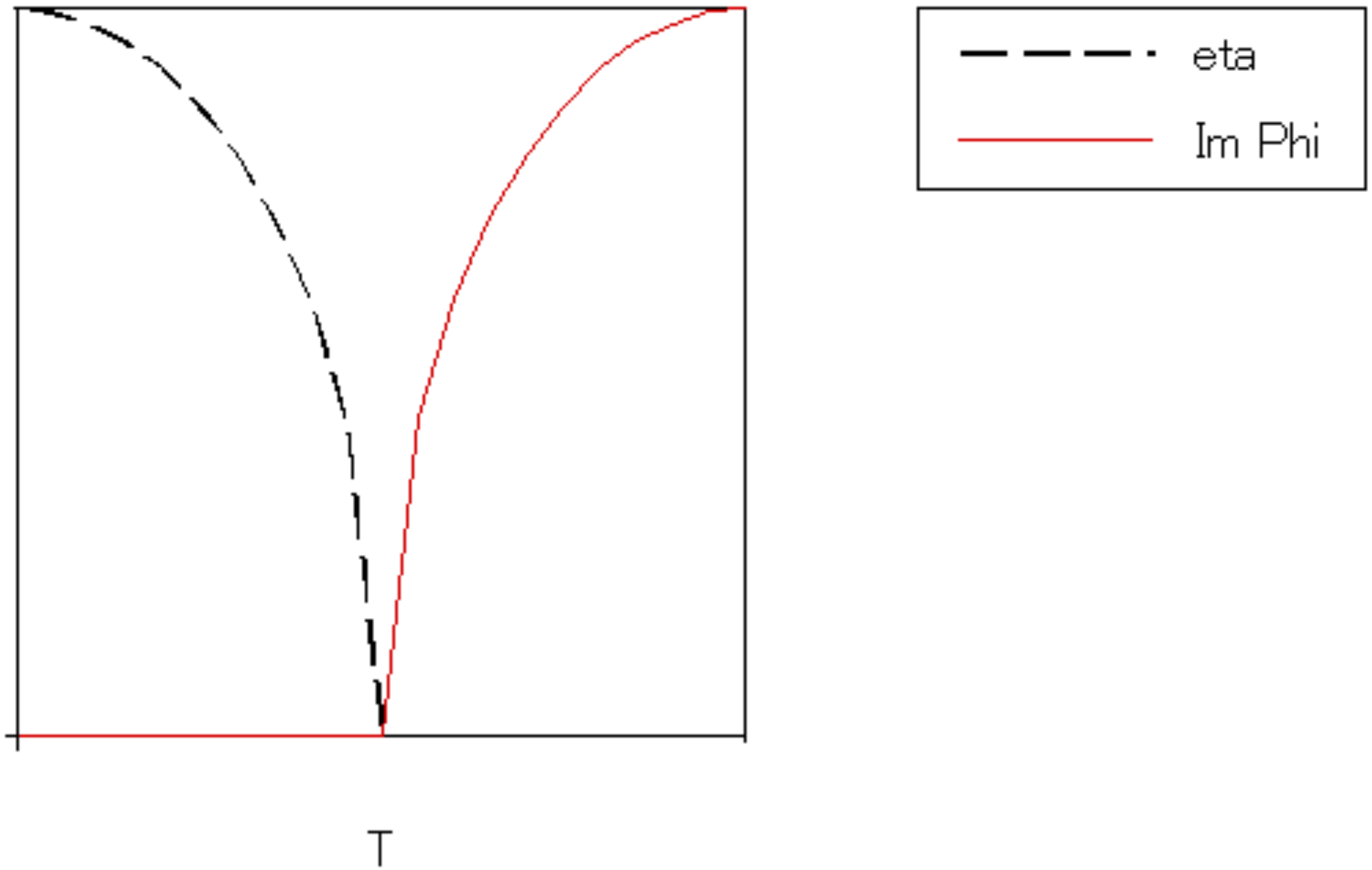
- If P and C happen almost simultaneously at real world,

C and P happen (almost) simultaneously at θworld ! ! ?

Real World

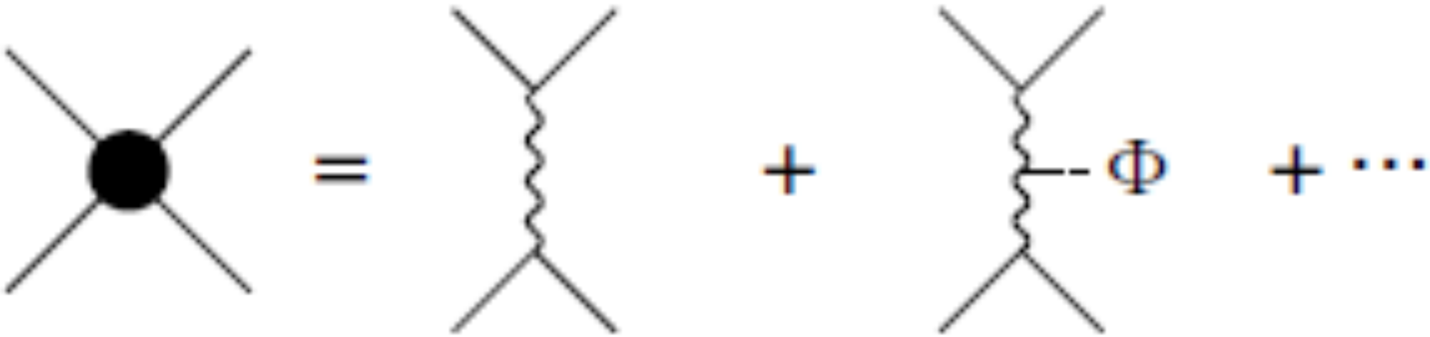


θWorld

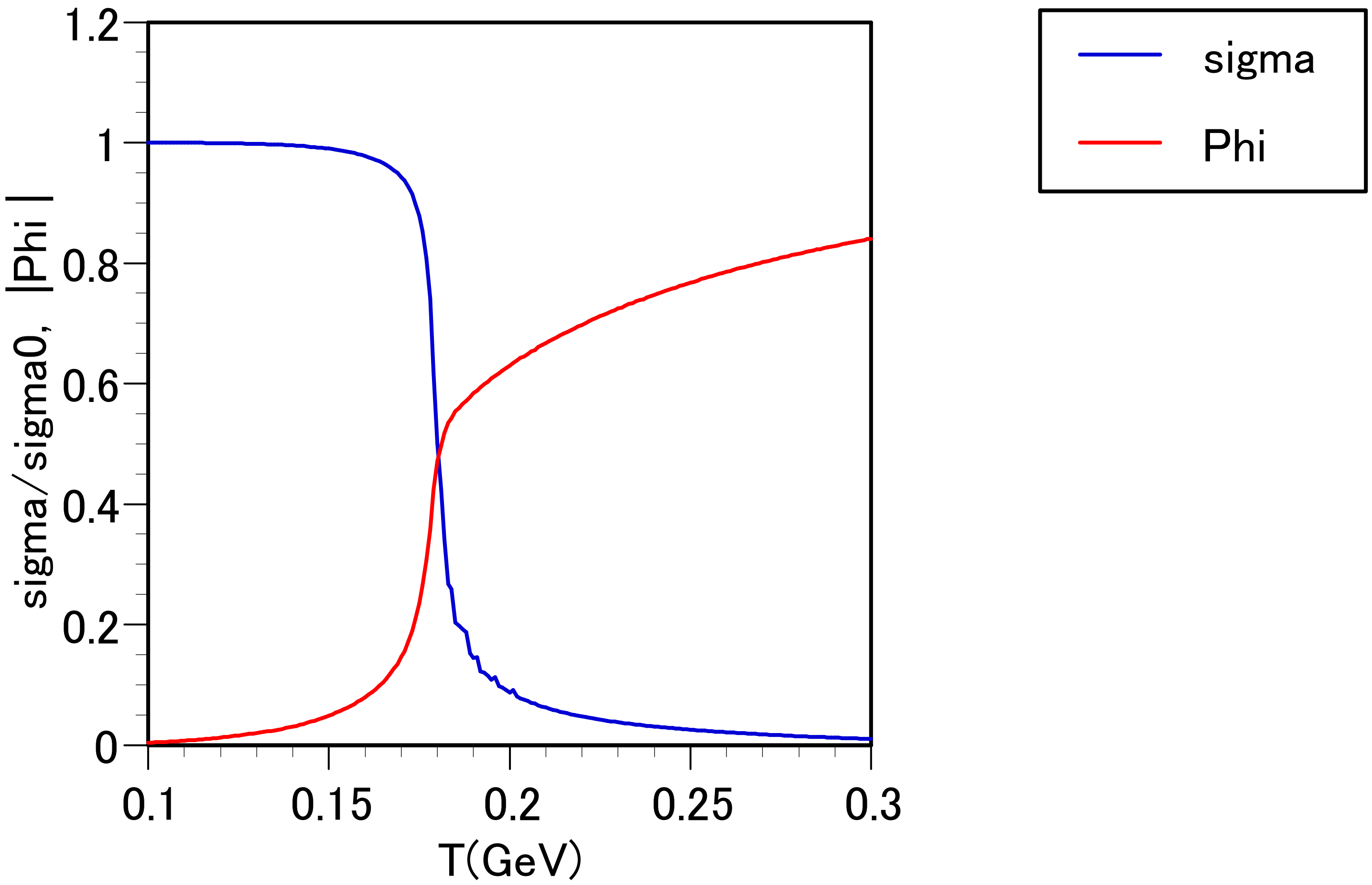


Entanglement PNJL model

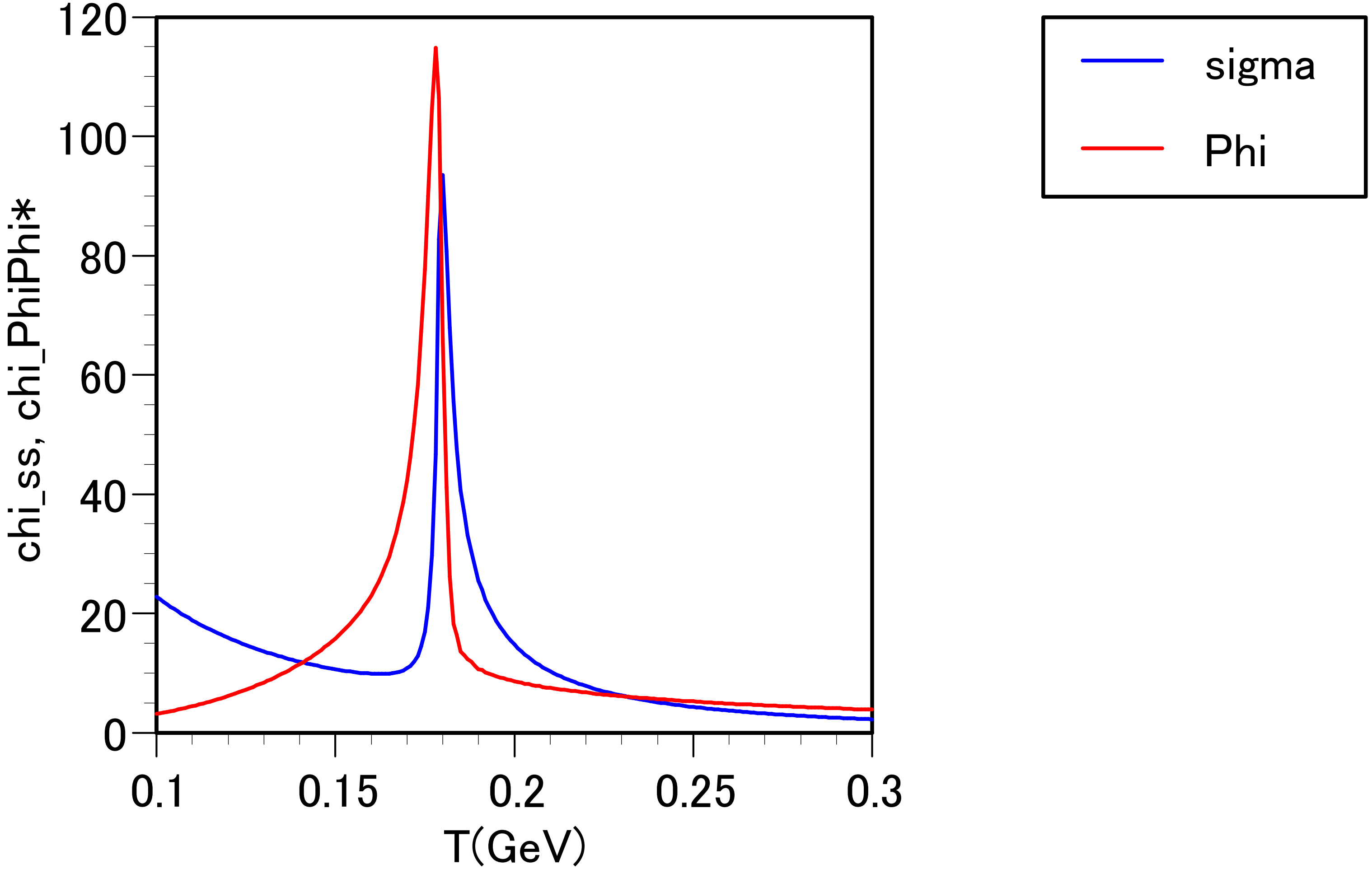
- $G_s \Rightarrow G_s[1-\alpha\Phi\Phi^* - \beta(\Phi^3+\Phi^{*3})]$
- Y. Sakai et al., arXiv:1006.3648[hep-ph]



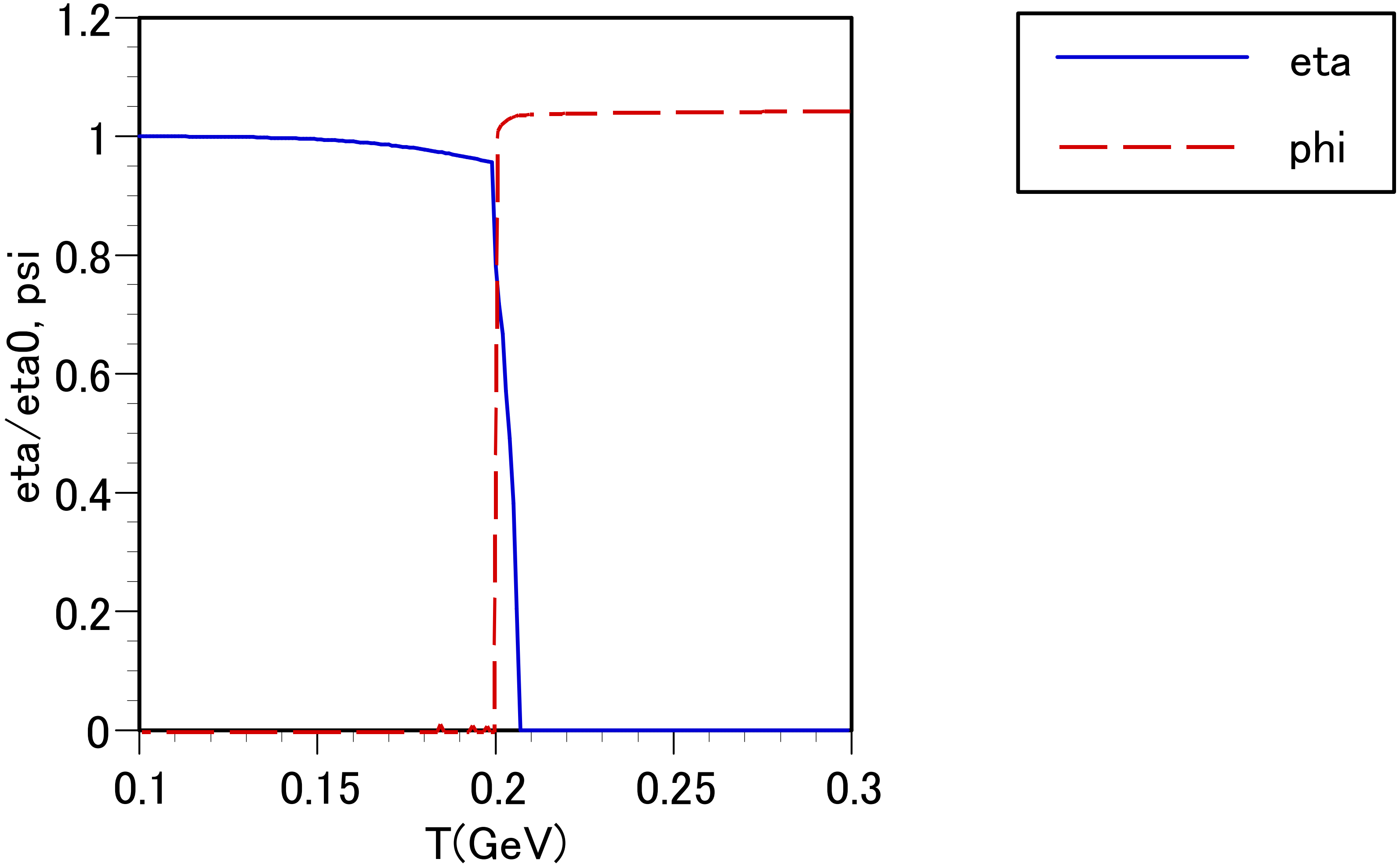
EPNJL at θ＝0 and θ＝0 (Real World)



Susceptibilities at θ=0 and θ=0 (Real World)



EPNJL at θ＝π and Θ＝π/3



Summary

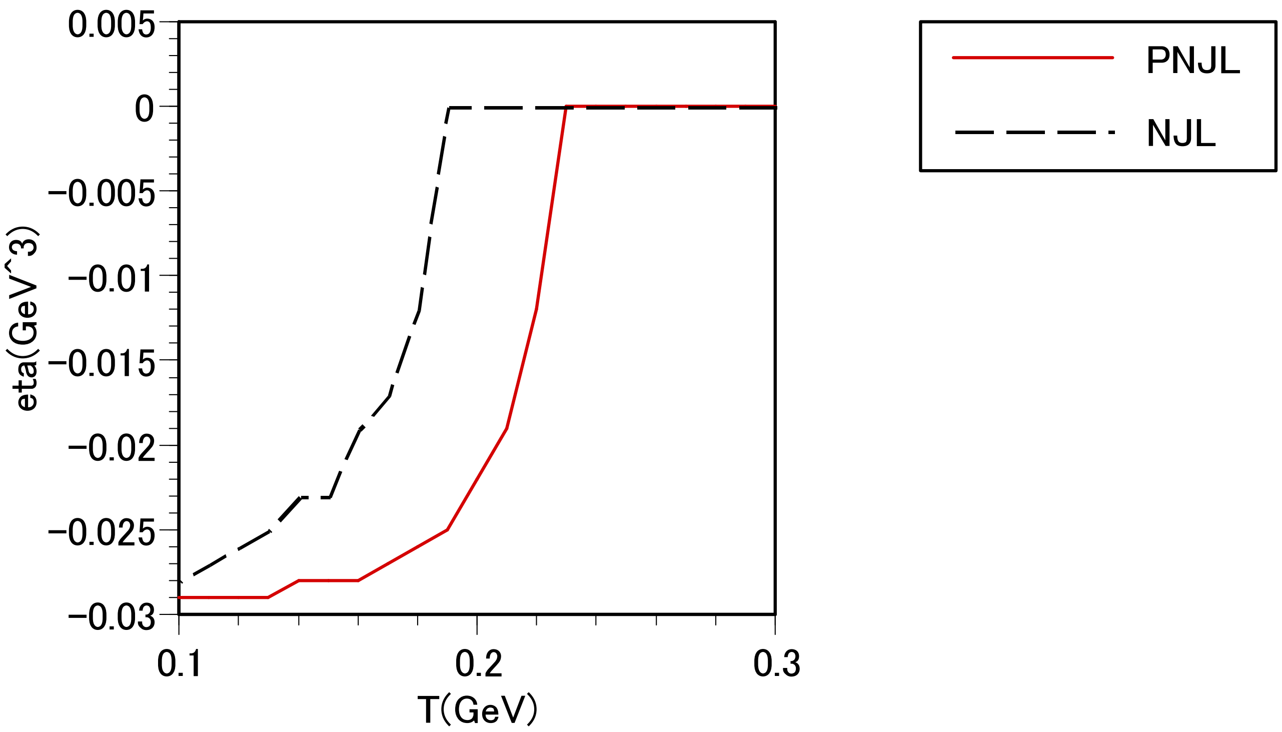
① Deconfinement is a remnat of C violation

② Chiral restoration is a remnant of P restoration

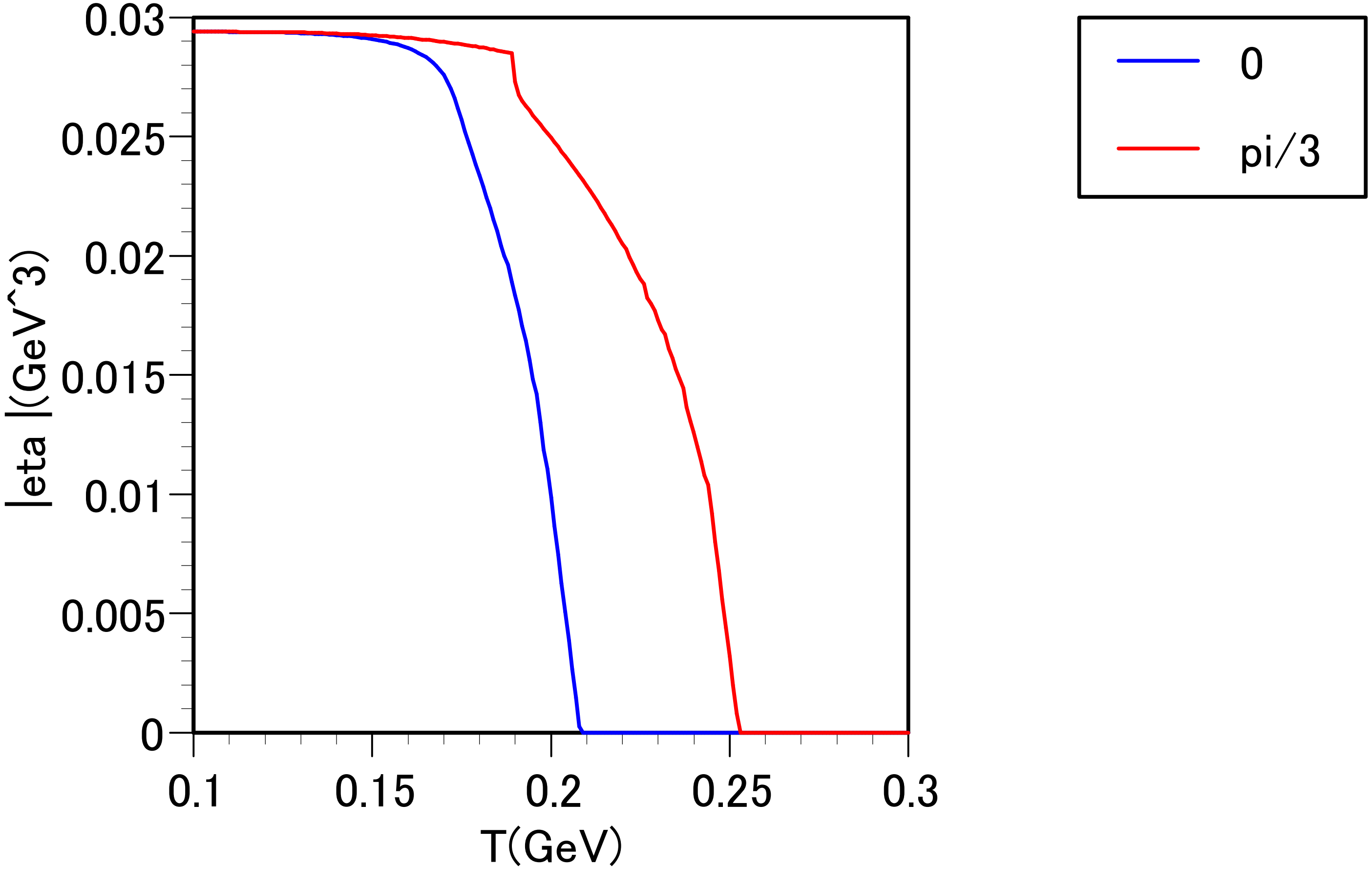
③ P and C happen almost simultaneously in the real world

⇔C and P may happen (almost) simultaneously in the θ world

NJL vs PNJL$(\theta = 0, \theta_v = \pi)$



θ-dependence ($\theta_v=\pi$)



θ_v-dependence ($\theta=\pi/3$)