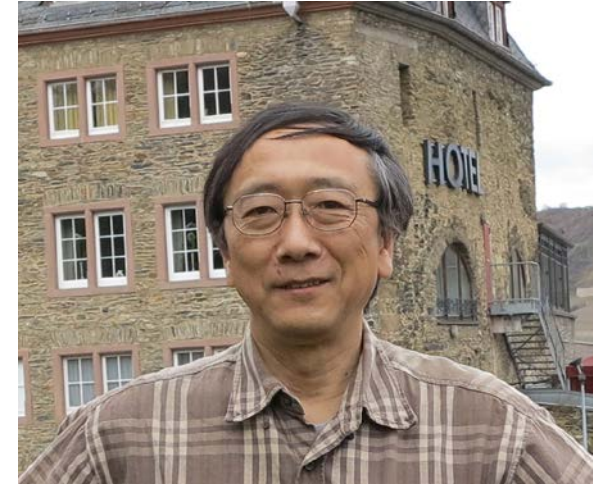


有限温度QCD: 過去・現在・未来

-- 金谷さんとの遭遇 --

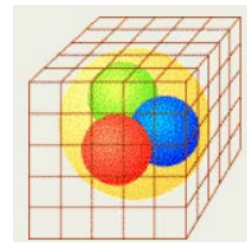
1. 金谷「くりこみ群」レビューの衝撃
2. 金谷-Satzと松井-Satzがもたらした事
3. 筑波大学での事
4. WHOT QCD Collaboration (7編の共著論文)
5. Gradient flow が拓く未来



「有限温度密度系の物理と格子QCDシミュレーション」

2015年9月5日

初田哲男 (理研)



Abstract.

I. Introduction

0. Introduction

1. scaling と hadron 構造の探究

II. くりこみ条件とくりこみ群

2. くりこみ群

2. 1 くりこみ変換

2. 2 regularization independence

2. 3 ふたつのくりこみ群方程式の関係

2. 4 Euler 方程式と scale 変換

2. 5 摂動展開の改良

2. 6 くりこみ群方程式の検証とくりこみ変換の不変部分

2. 7 classical field とくりこみ群

2. 8 anomalous trace identity

2. 9 くりこみ群方程式の利用

2. 10 dimensional transmutation

III. くりこみ群方程式

3. Gell Mann-Low 方程式

3. 1 QEDにおける GML方程式

3. 2 摂動論による計算

3. 3 UV asymptotic region

3. 4 IR asymptotic behavior

3. 5 Lee model における GML方程式

4. Callan-Symanzik 方程式とその周辺

4. 1 Callan-Symanzik 方程式

4. 2 family renormalization

4. 3 Nishijima-Tomozawa 方程式

4. 4 MacDowell 方程式

4. 5 Weinberg の定理と斉次くりこみ群方程式

5. Weinberg のくりこみ群方程式

5. 1 mass independent renormalization

5. 2 Weinberg の方程式と C-S方程式

5. 3 漸近領域と effective mass

5. 4 赤外問題と Weinberg の方程式

6. 'tHooft のくりこみ群方程式

6. 1 unit-of-mass

IV. まとめと問題点

7. まとめと問題点

*) これは79年2月に名古屋大学理学部物理学教室に提出した修士論文に、一部字句の訂正を加えたものです。

Abstract.

I. Introduction

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4.2 family renormalization

7. まとめと問題点

理論に存在する対称性や不定性の研究は、その理論を特徴付ける最小限の情報、いわゆる「本質的なもの」の認識に役立つ。我々はくりこみ群方程式を研究する事により、くりこみ理論を表現する物理的なパラメータの中に余分な自由度を見出した。そして同時に、こうした余分な自由度を使った理論の表現がそれを直観的に表わす上でいかに有用なものであるかを見た。

いずれにせよ我々は理論の exact な姿を知らず、同時に、摂動以外にその近似の程度を予想し得る、あるいはその近似の度合をシステムティックにあげ得る様な実際的計算方法を知らない。そして何より、こうした宗教裁判を考える上で科学として忘れる事の出来ないポイントは、「それでも QED は実験を説明する」という点である。従って上の様な美学的研究と同時に、今持っている摂動論的理論によって、現象をどこまで細かく記述出来るかを追求する事もまた重要である。

CORRELATION AND SCREENING IN FINITE TEMPERATURE SU(2) GAUGE THEORY

K. Kanaya

Institut für Theoretische Physik E
RWTH Aachen, D-51 Aachen, F.R. Germany

and

H. Satz

Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany

and

Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

We study the temperature dependence of the correlation length in SU(2) gauge theory around the deconfinement point, using high statistics Monte Carlo simulation on large lattices.

$$\Gamma(r, T) = N(T) \left\{ \frac{e^{-r/\xi(T)}}{r} + \frac{e^{-(N_{\sigma}a-r)/\xi(T)}}{(N_{\sigma}a-r)} \right\};$$

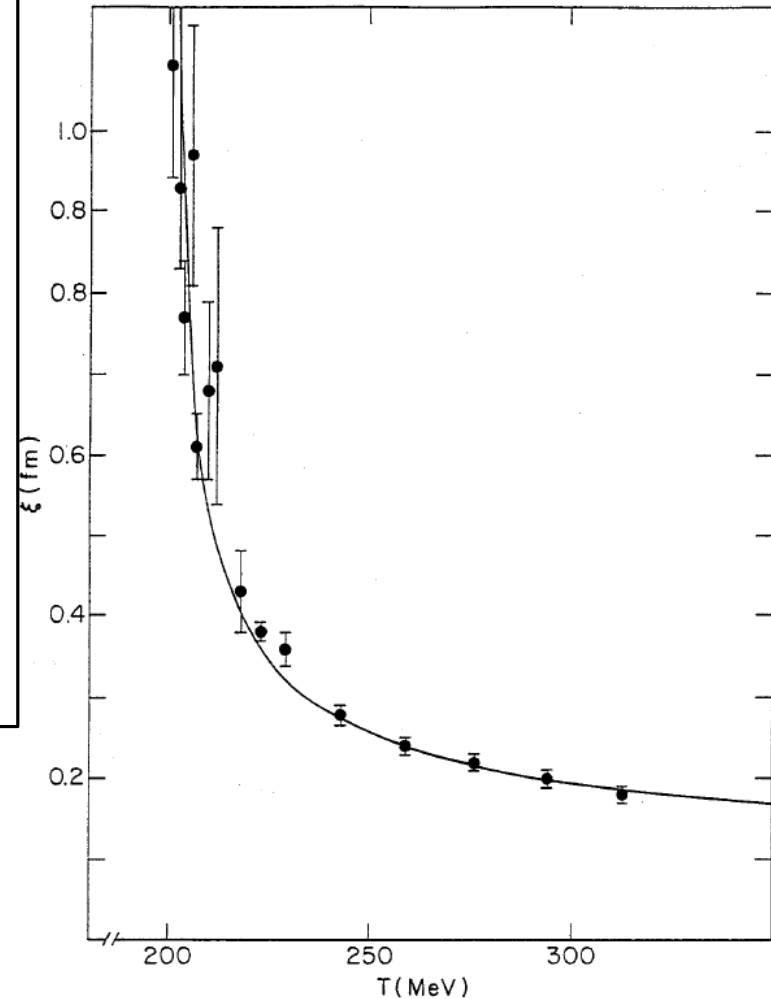


Figure 7

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

T. Matsui

Center for Theoretical Physics
Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

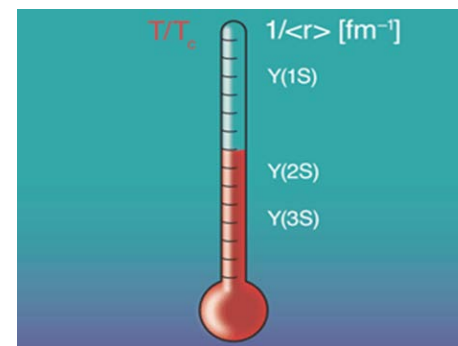
and

H. Satz

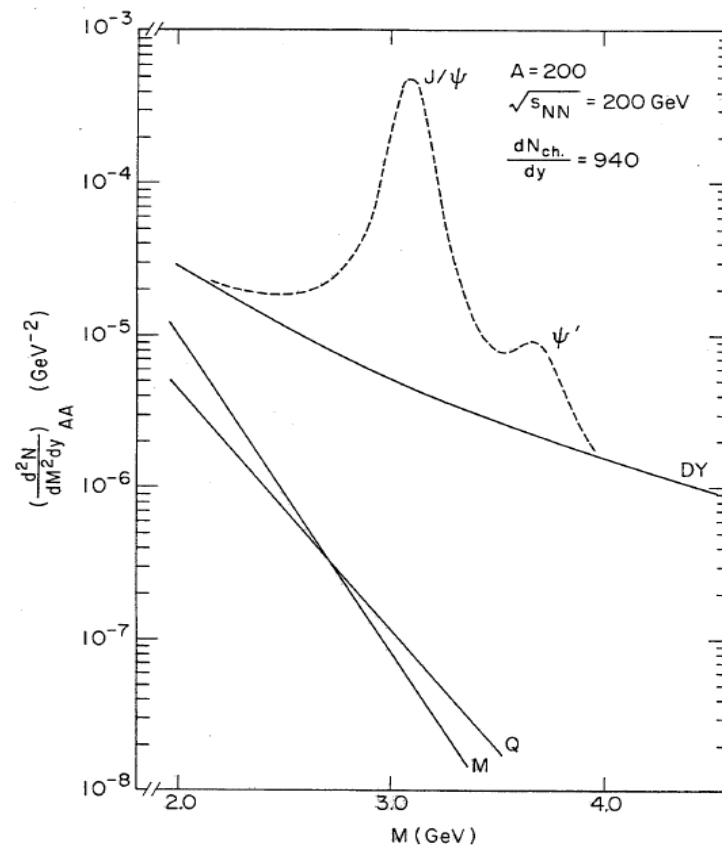
Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany
and
Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.



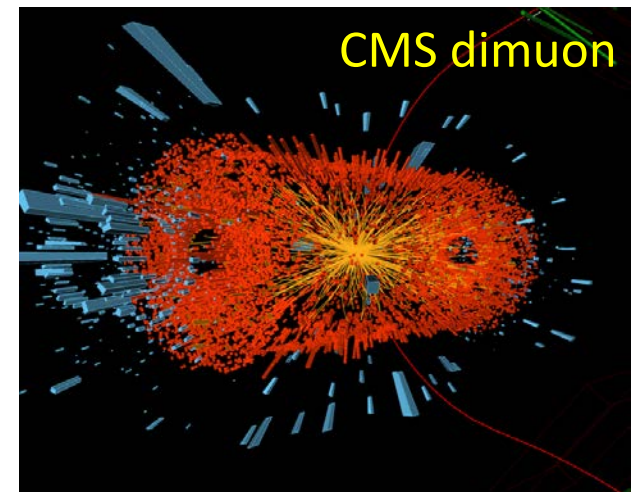
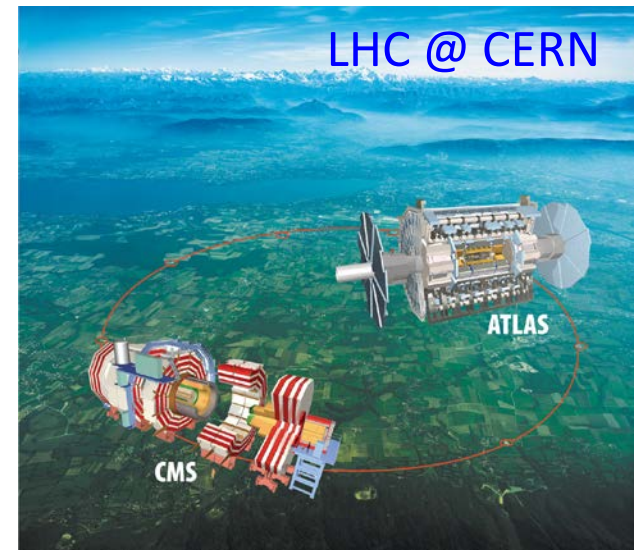
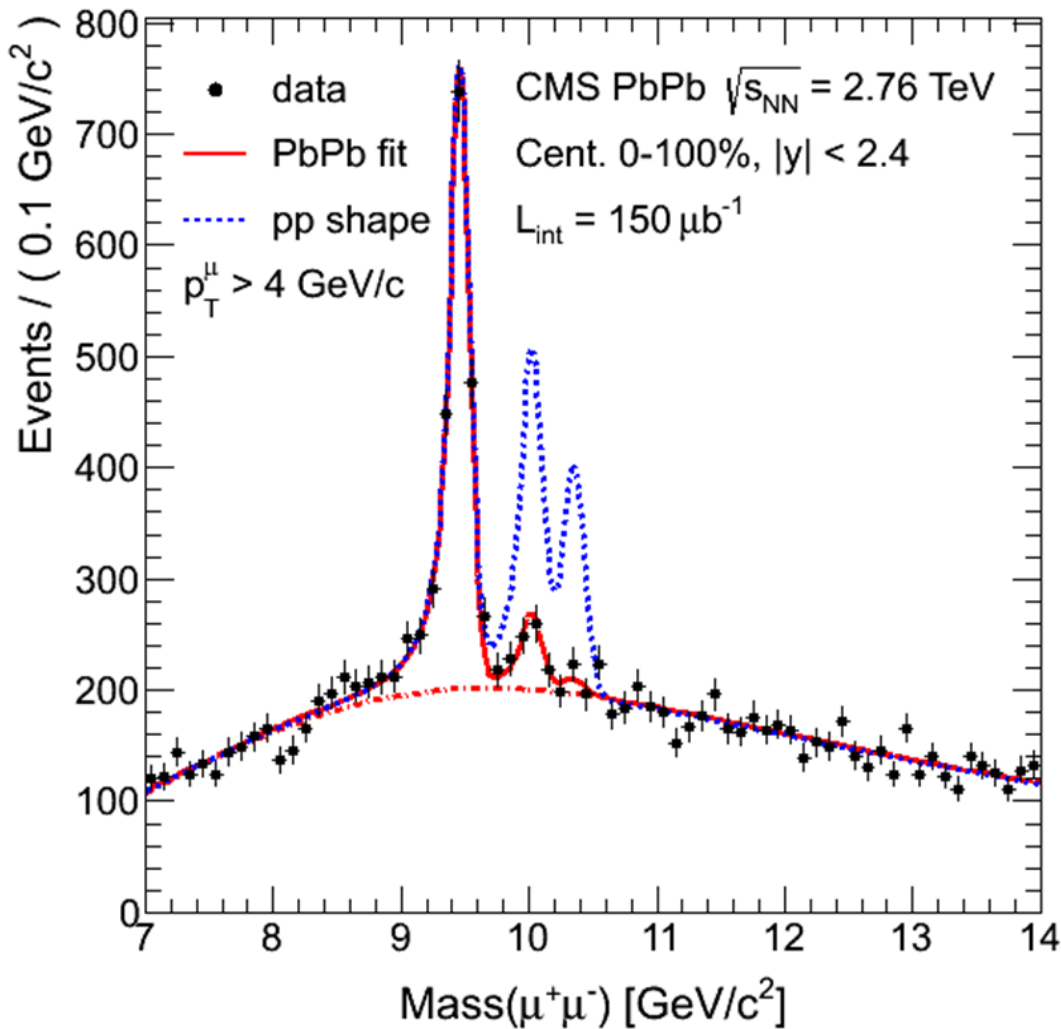
$$T > 0.15 \times m_Q \sqrt{\alpha_s} \sim \begin{cases} 0.16 \text{ GeV} & \text{(charm)} \\ 0.46 \text{ GeV} & \text{(bottom)}, \end{cases}$$



Observation of Sequential Υ Suppression in PbPb Collisions

S. Chatrchyan *et al.* (CMS Collaboration)

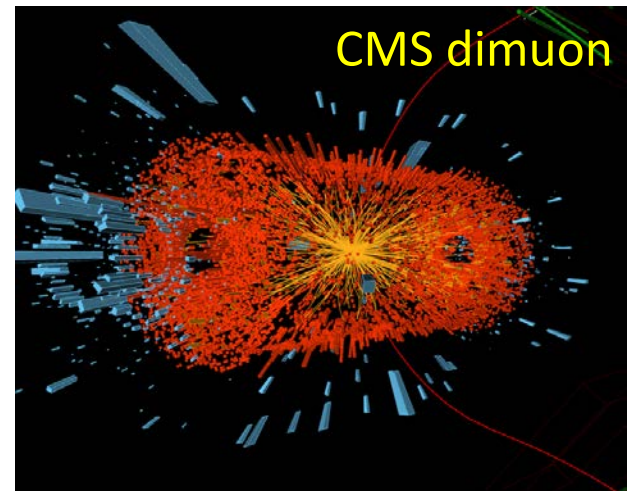
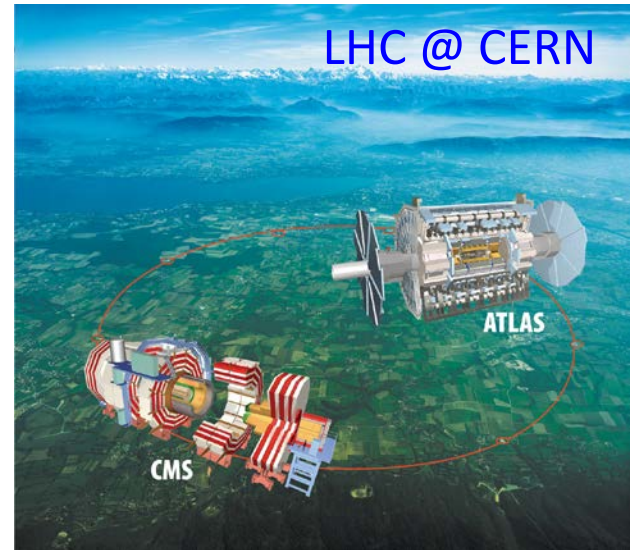
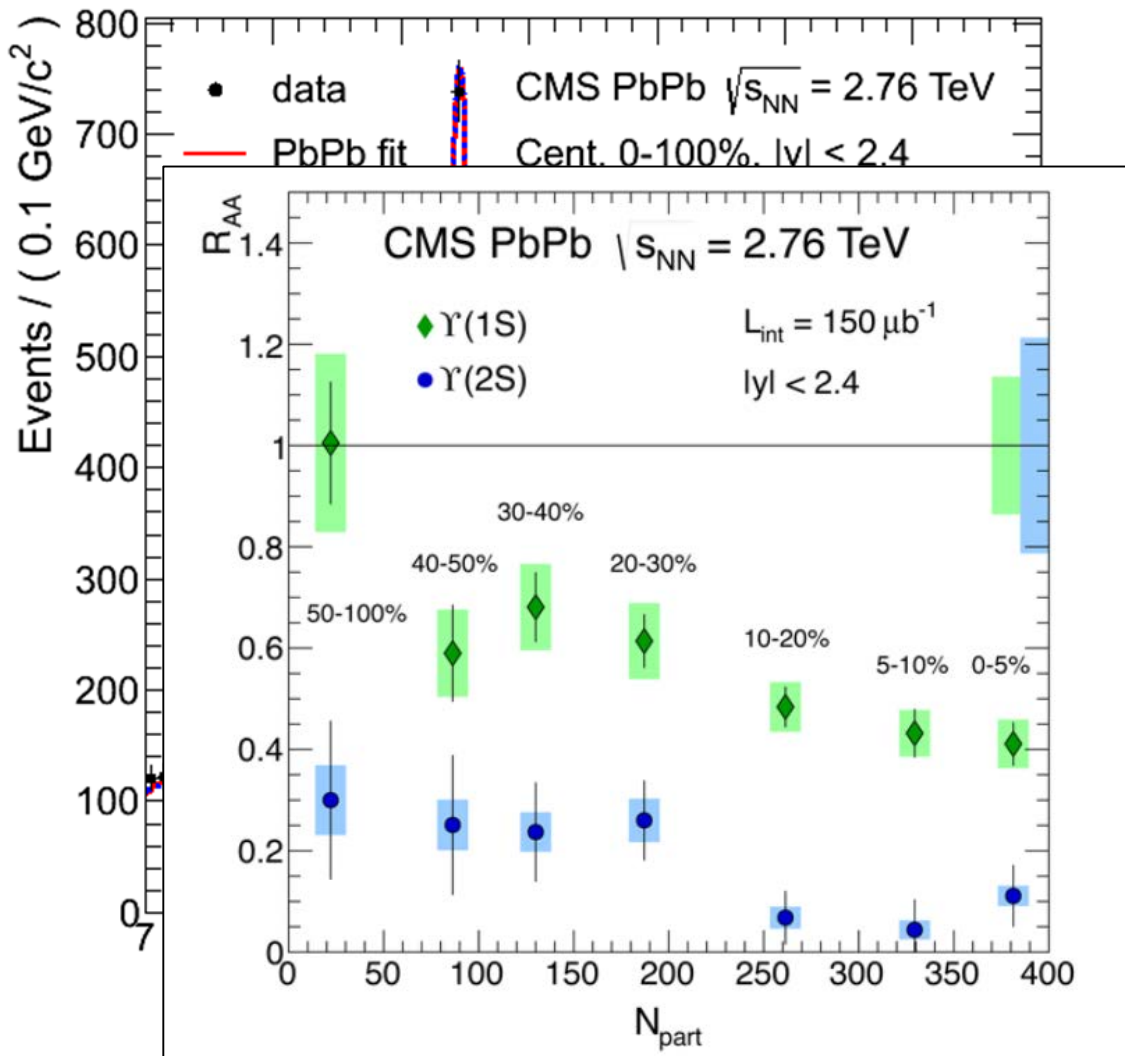
Phys. Rev. Lett. **109**, 222301 – Published 26 November 2012



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7th Quark Matter 1988 @ LENOX

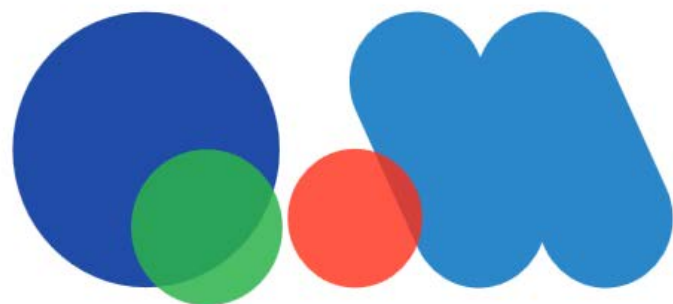


K. Kanaya

T. Matsui

25th Quark Matter 2015 @ Kobe

<http://qm2015.riken.jp/>



The XXVth International
Conference on Ultrarelativistic
Nucleus-Nucleus Collisions

Sep. 27 – Oct. 3, 2015
Kobe, Japan

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- Baryon Rich QCD Matter
- QGP in Small Systems
- Initial State Physics & Approach to Equilibrium
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- Open Heavy Flavors & Strangeness
- Quarkonia
- Electromagnetic Probes
- Collective Dynamics
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- Quark Matter in Astrophysics
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X QM1993	Borlänge, Sweden
IX QM1991	Gatlinburg (TN), USA
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VI QM1987	Nordkirchen, Germany
V QM1986	Pacific Grove (CA), USA
IV QM1984	Helsinki, Finland
III QM1983	Upton (NY), USA
II QM1982	Bielefeld, Germany
I QM1980	Darmstadt, Germany
Pre QM1979	Berkeley (CA), USA

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5. Energy momentum tensor が拓く未来

Energy-Momentum Tensor

-- Doorway to the future of lattice QCD --

$T_{\mu\nu}$ Generator of the Poincare group (Translation + Lorentz)

Conservation law

$$\partial^\mu T_{\mu\nu} = 0$$

YM Trace anomaly

$$T_\mu{}^\mu = \frac{\beta}{2g} G_{\mu\nu} G^{\mu\nu}$$

Yang-Mills theory at finite T

$$\langle T_{\mu\nu} \rangle \iff \varepsilon(T), P(T), s(T)$$

Bulk thermodynamics

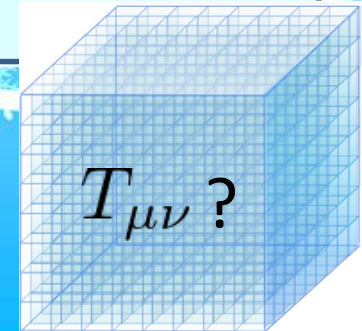
$$\langle (T_{\mu\nu})^n \rangle \iff C_V(T) \text{ etc}$$

Fluctuations

$$\langle T_{\mu\nu}(x) T_{\lambda\rho}(0) \rangle \iff \eta(T), \zeta(T)$$

Transports

However,
apparent conflict with Lattice discretization



Energy-Momentum Tensor on the Lattice and Gradient Flow

FlowQCD Collaboration

M. Asakawa (Osaka)
T. Hatsuda (RIKEN)
T. Iritani (Stony Brook)
E. Itou (KEK)
M. Kitazawa (Osaka)
H. Suzuki (Kyushu)

Phys. Rev. D90 (2014) 011501 & Erratum
+ some preliminary results

(ロゴも決定)



EM TENSOR

©M.Kitazawa

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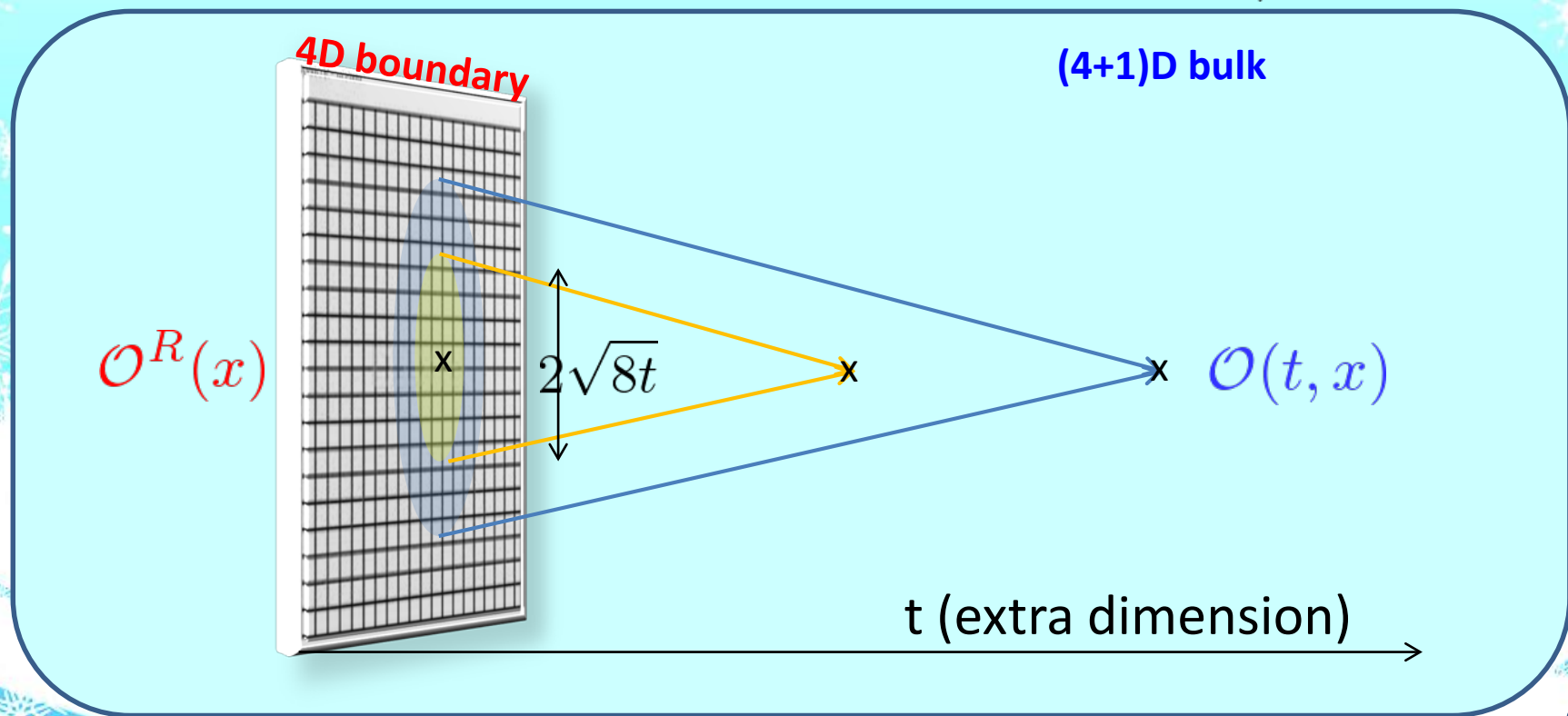


Yang-Mills Gradient Flow (1): 4D world from (4+1)D bulk

a=0

Diffusion equation towards extra dimension

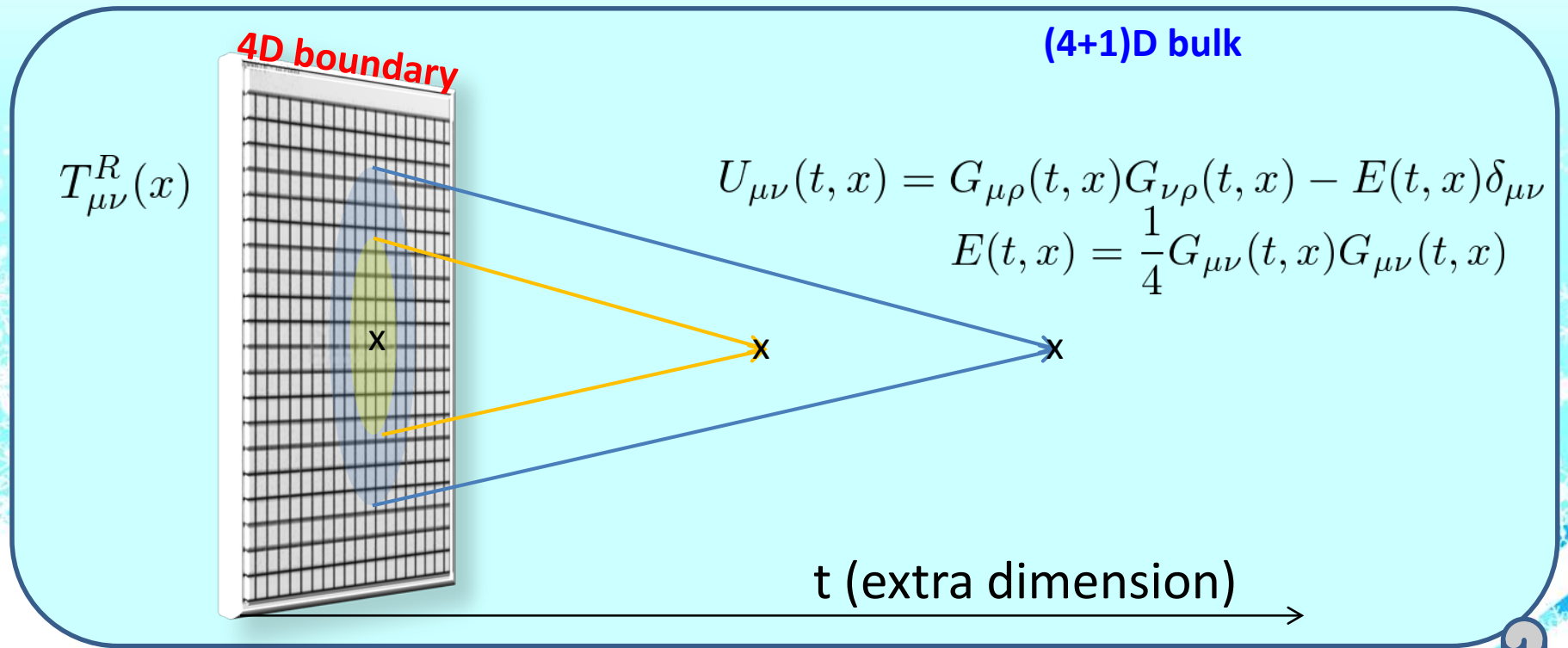
$$\partial_t B_\mu(t, x) = D_\nu G_{\nu\mu}(t, x), \quad B_\mu(0, x) = A_\mu^{\text{bare}}(x)$$



$$O(t, x) \xrightarrow{t \rightarrow 0} \sum_k c_k(t) O_k^R(x) + (\text{powers in } t)$$

Yang-Mills Gradient Flow (2): 4D world from (4+1)D bulk

a=0



$$U_{\mu\nu}(t, x) \Big|_{\bar{1}} = \alpha_U(t) \left[\{T_{\mu\nu}\}_R(x) - \frac{1}{4}\delta_{\mu\nu} \{T_{\rho\rho}\}_R(x) \right] + O(t),$$

$$E(t, x) = \langle E(t, x) \rangle + \alpha_E(t) \{T_{\rho\rho}\}_R(x) + O(t),$$

$$\alpha_U(t) = \bar{g}(1/\sqrt{8t})^2 \left[1 + 2b_0\bar{s}_1\bar{g}(1/\sqrt{8t})^2 + O(\bar{g}^4) \right],$$

$$\alpha_E(t) = \frac{1}{2b_0} \left[1 + 2b_0\bar{s}_2\bar{g}(1/\sqrt{8t})^2 + O(\bar{g}^4) \right]$$

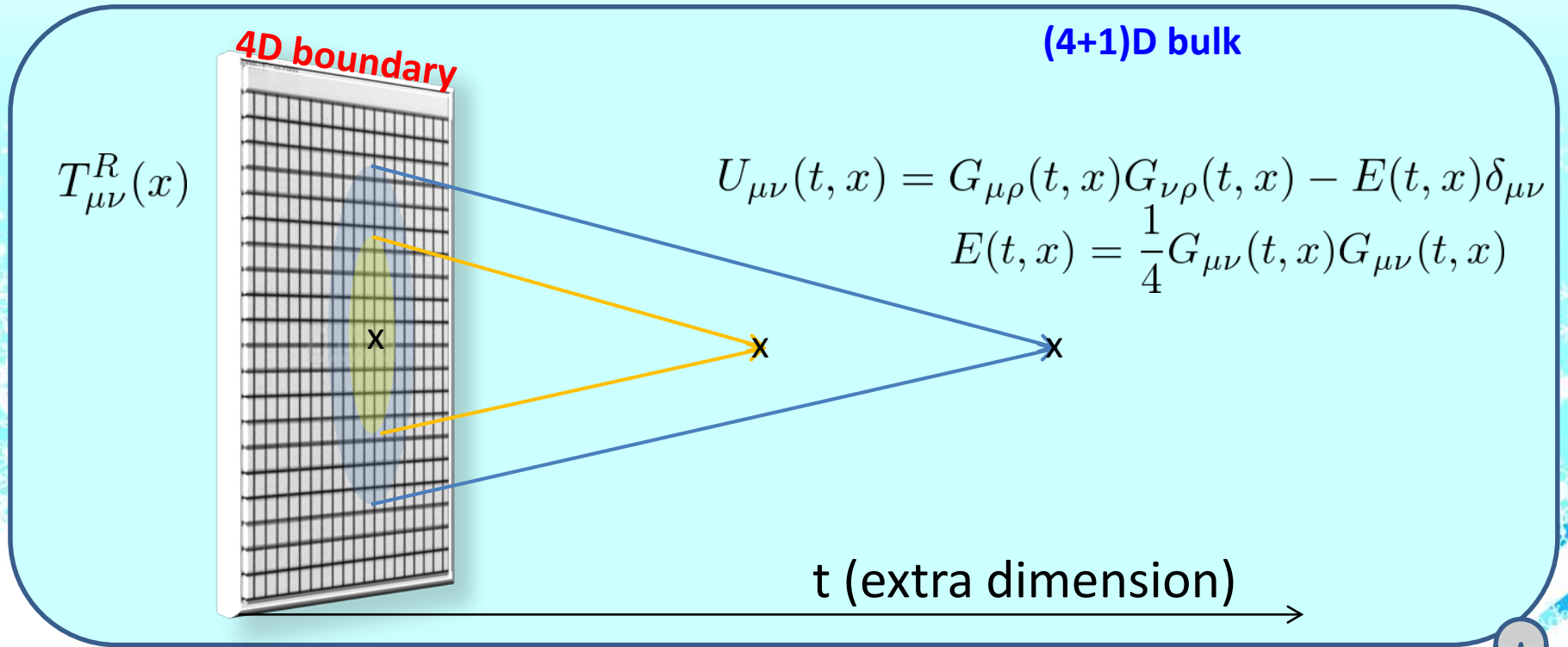
H. Suzuki,

PTEP 2013 (2013) 083B03+erratum

ArXiv: 1507.02360

Yang-Mills Gradient Flow (2): 4D world from (4+1)D bulk

a=0



$$\{T_{\mu\nu}\}_R(x) = \frac{1}{\alpha_U(t)} U_{\mu\nu}(t, x) + \frac{1}{4\alpha_E(t)} \delta_{\mu\nu} [E(t, x) - \langle E(t, x) \rangle] + O(t)$$

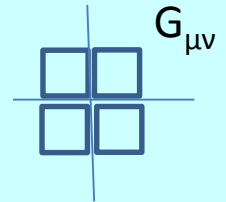
Yang-Mills thermodynamics (1): Four steps to go

$a \neq 0$

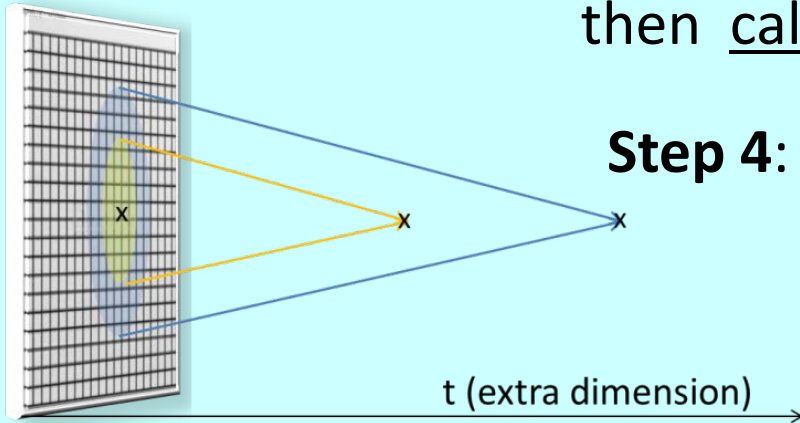
Step 1: Generate gauge configuration at $t=0$ as usual

Step 2: Solve the gradient flow for each configuration

Step 3: Construct $U_{\mu\nu}(t,x)$ & $E(t,x)$,
then calculate $\langle U_{\mu\nu}(t,x) \rangle$ & $\langle E(t,x) \rangle$



Step 4: Take the limit ($t \rightarrow 0$ after $a \rightarrow 0$)
to obtain $\langle T_{\mu\nu}(x) \rangle$

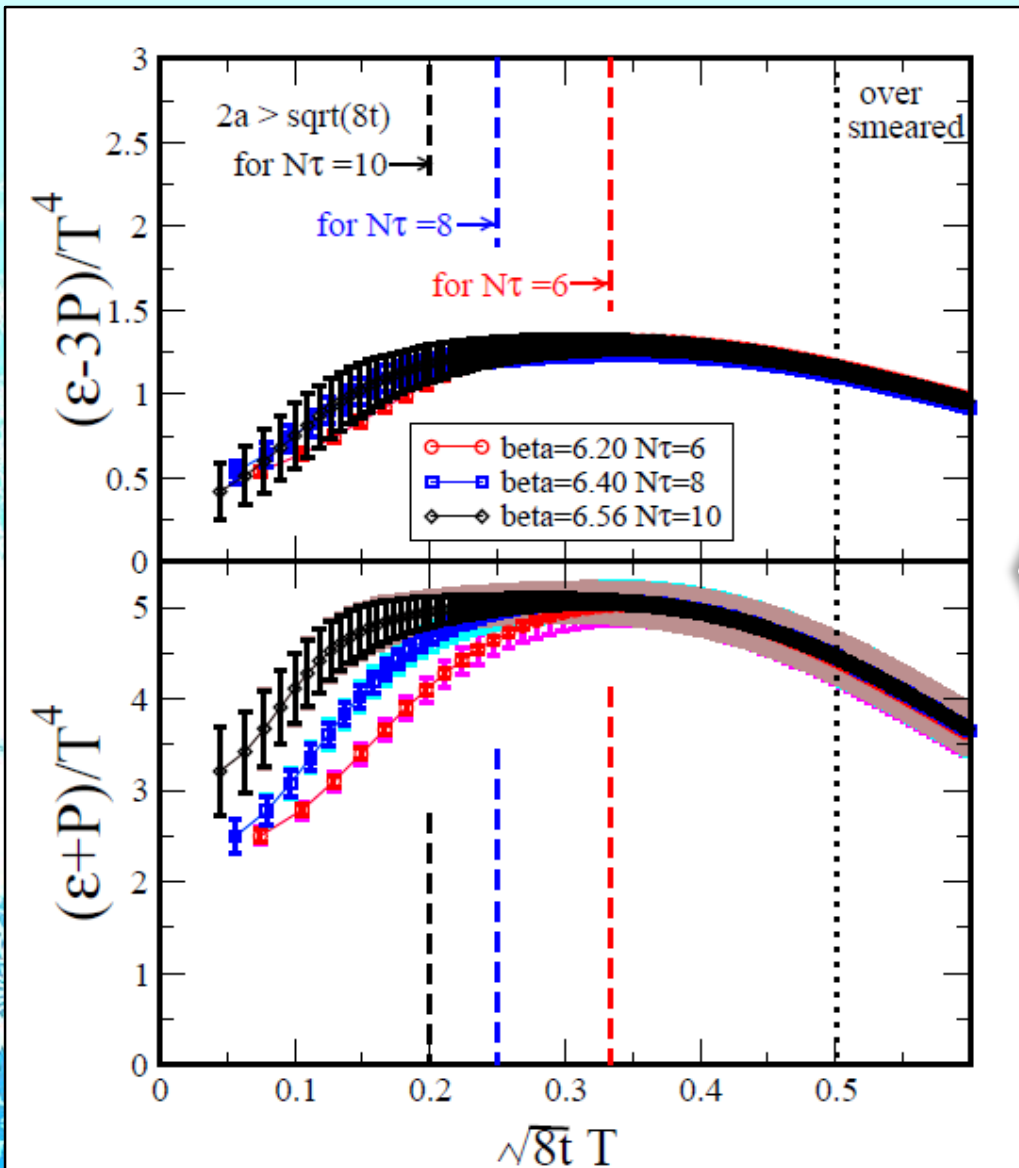


$$2a \ll \sqrt{8t} \ll R$$

$$\Delta = \varepsilon - 3P = -\langle T_{\mu\mu}^R(x) \rangle$$

$$sT = \varepsilon + P = -\langle T_{00}^R(x) \rangle + \frac{1}{3} \sum_{i=1,2,3} \langle T_{ii}^R(x) \rangle$$

Yang-Mills thermodynamics (2) : extrapolation back to $t=0$

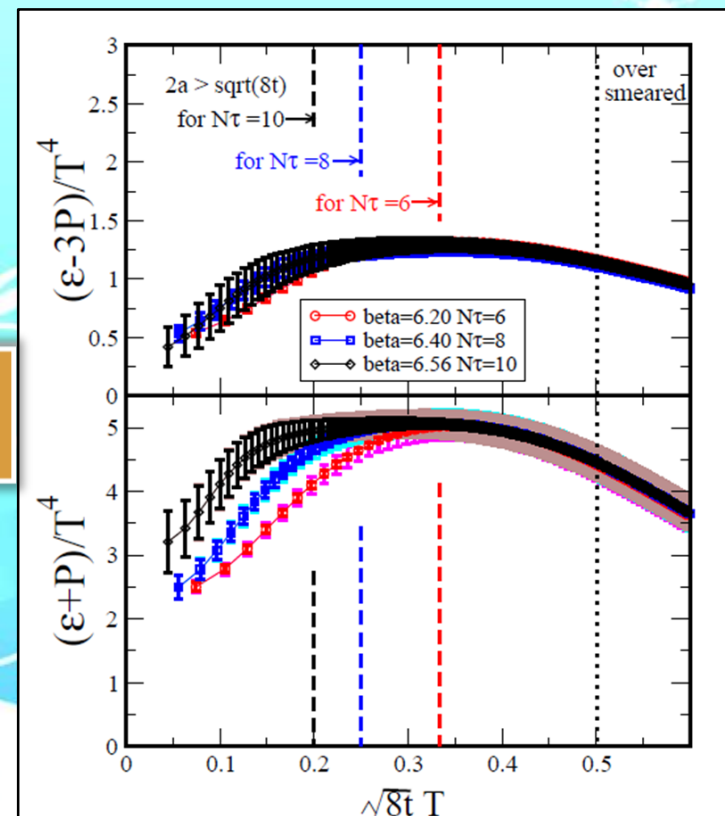
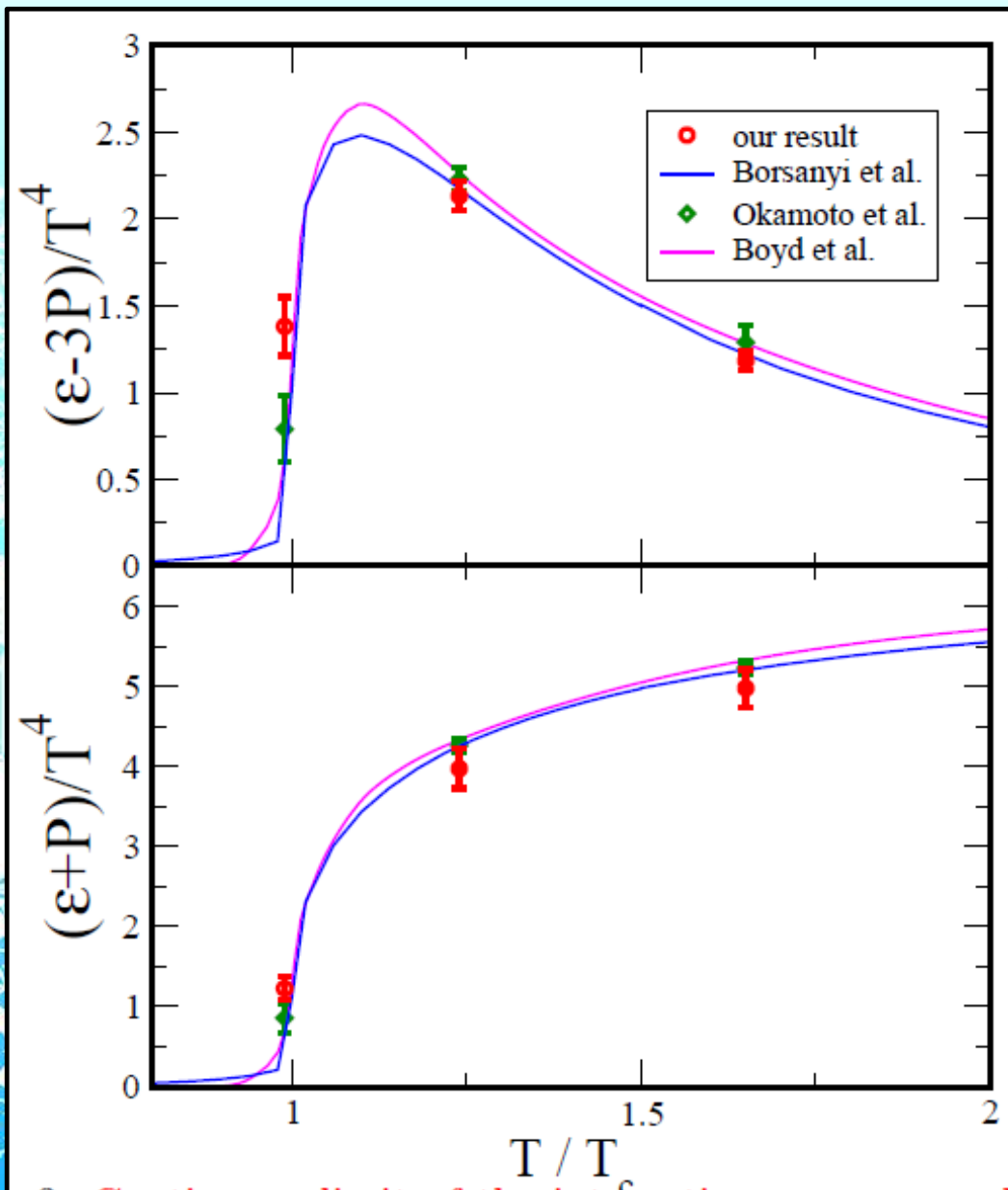


- SU(3) YM theory
- Wilson action
- $32^3 \times (6,8,10)$
- $\beta=5.89-6.56$
- 100-300 config.

$$2a \ll \sqrt{8t} \ll R$$

$T/T_c = 1.65$
 $a = 0.074$ fm
 0.055 fm
 0.043 fm

Yang-Mills thermodynamics (3) : continuum extrapolation



Yang-Mills thermodynamics (4) : larger & finer lattices

過去

- SU(3) YM theory
- Wilson action
- $32^3 \times (6,8,10)$
- $\beta=5.89-6.56$
- 100-300 config.

$T/T_c=1.65$
 $a = 0.074$ fm
 0.055 fm
 0.043 fm



現在

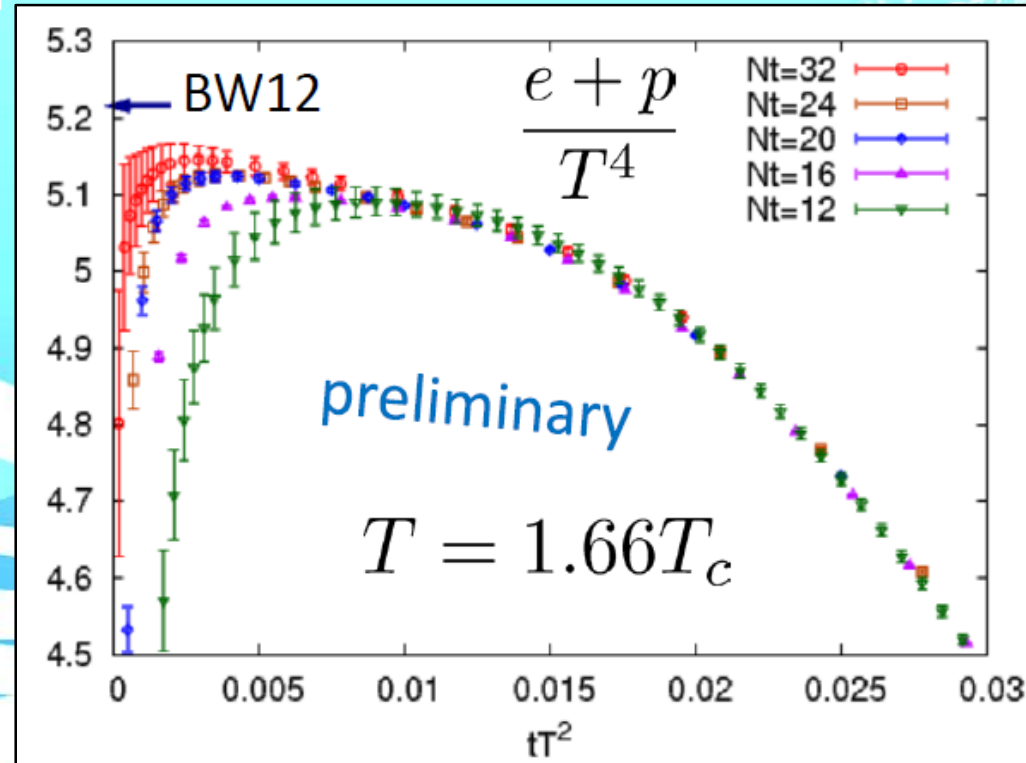
- SU(3) YM theory
- Wilson action
- $(64-256)^3 \times (12--32)$
- $\beta=6.72-7.50$
- ~ 2000 config.

$T/T_c=1.66$
 $a = 0.037$ fm
 0.027 fm
 0.021 fm
 0.018 fm
 0.014 fm



未来

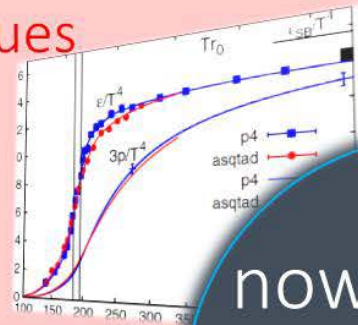
Full QCD (FlowQCD + WHOT QCD)



Thermodynamics

direct measurement of expectation values

$$\langle T_{00} \rangle, \langle T_{ii} \rangle$$



now we have

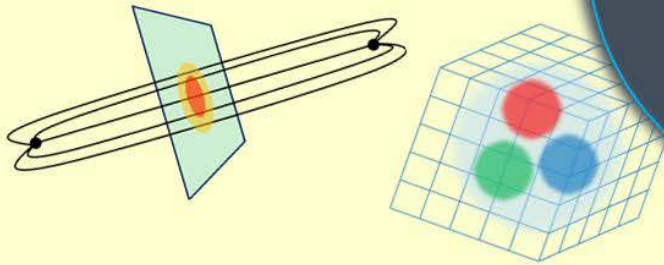
$$T_{\mu\nu}$$

Fluctuations and Correlations

viscosity, specific heat, ...

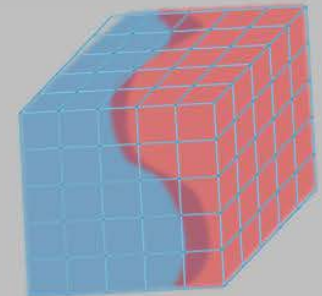
$$c_V \sim \langle \delta T_{00}^2 \rangle$$

$$\eta = \langle T_{12}; T_{12} \rangle$$



- confinement string
- EM distribution in hadrons

Hadron Structure



- vacuum configuration
- mixed state on 1st transition

Vacuum Structure

金谷さん

還暦おめでとうございます！

これからも、ますます**ホット**によろしくお願いします！

