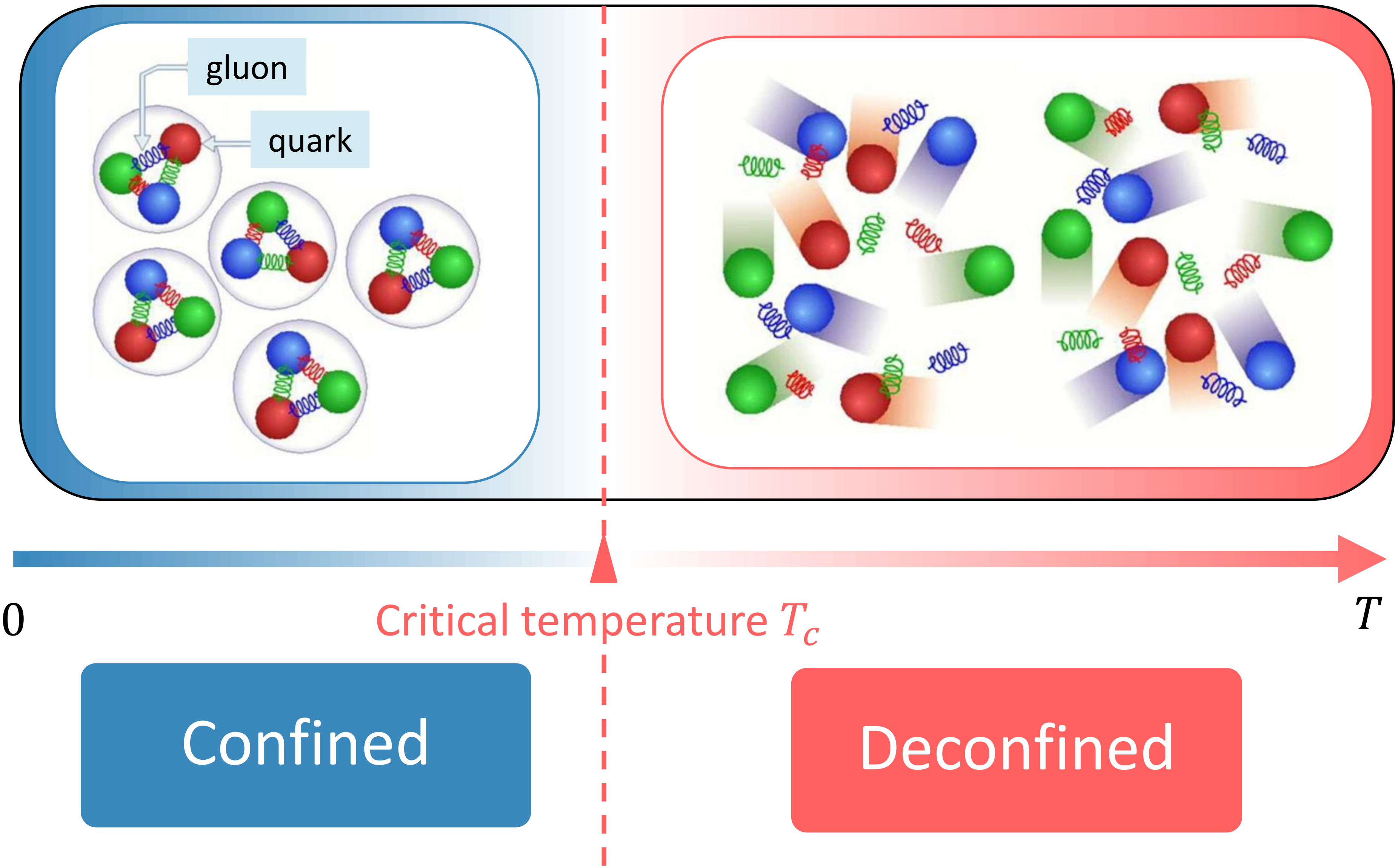
Stress distribution in quark—anti-quark and single quark systems at nonzero temperature

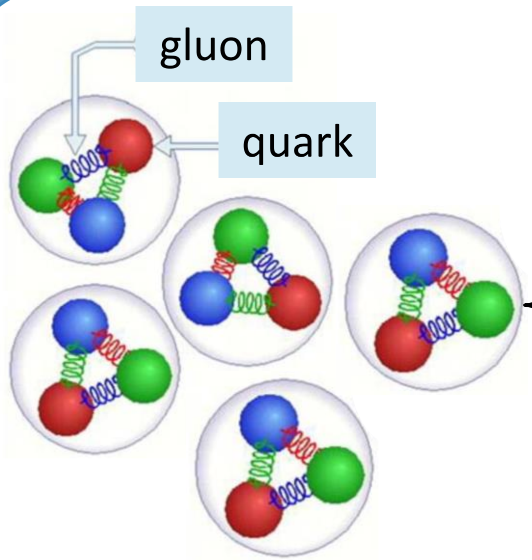
Ryosuke Yanagihara (Osaka University)

For FlowQCD collaboration :
Takumi Iritani, Masakiyo Kitazawa, Masayuki Asakawa, Tetsuo Hatsuda

Confined vs. Deconfined



Confined vs. Deconfined



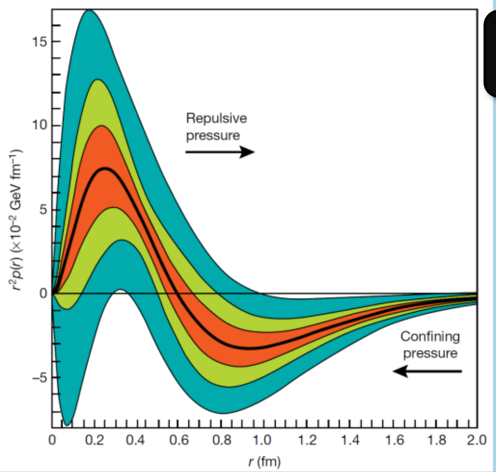
0

T_c

Confined

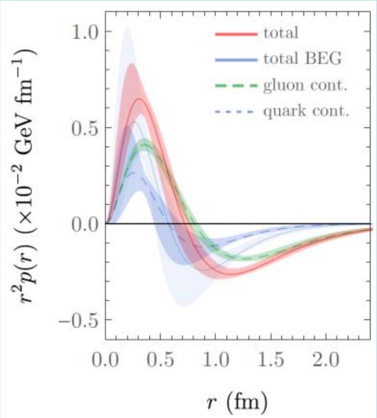
Pressure distribution inside Hadrons

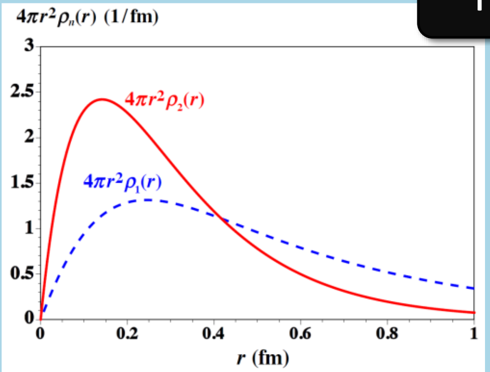
Exp.



Burkert *et al.*, Nature **557** (2018) 396.

Th.

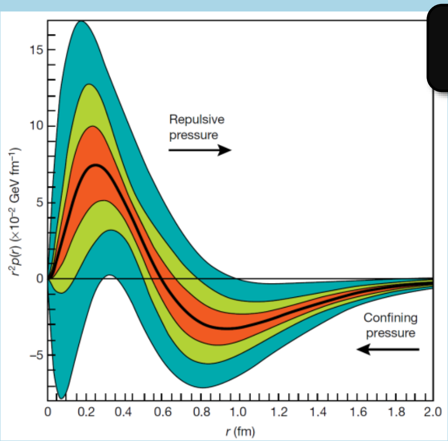




Shanahan *et al.*, PRL **122** (2019) no7, 072003.
Kumano *et al.*, PRD **97** (2018) 014020.

Pressure distribution inside hadrons vs. Our study

Pressure distribution inside Hadrons



Exp.

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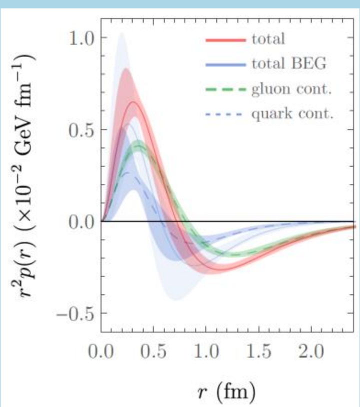

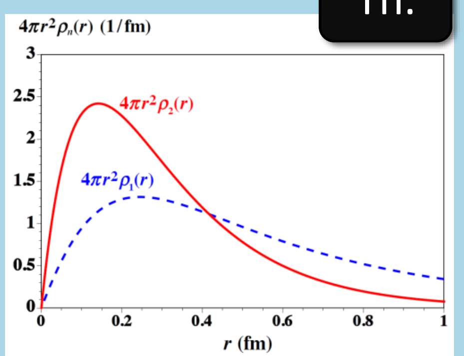

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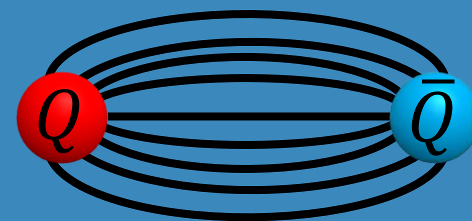
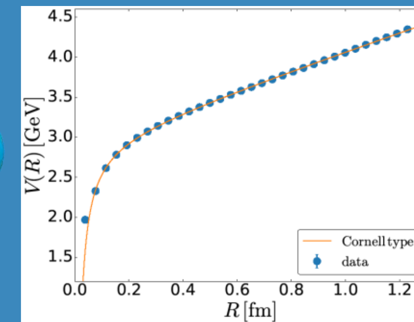
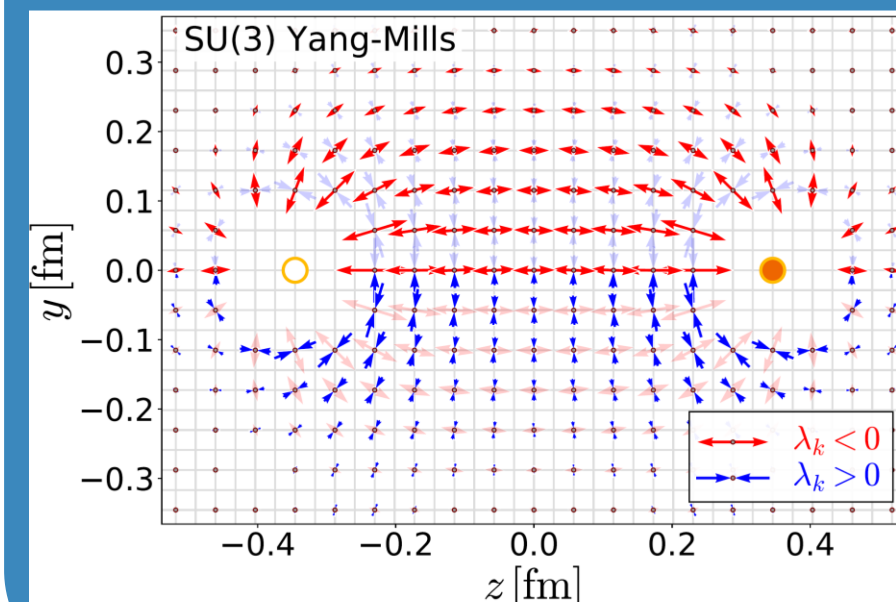
Our study

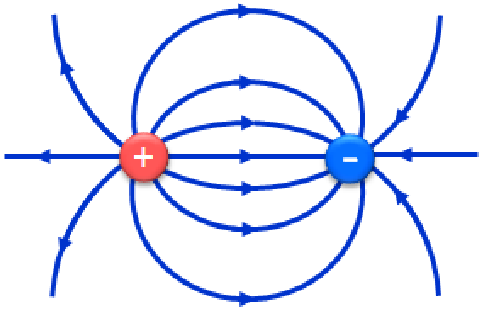


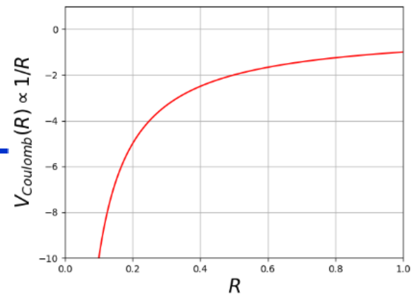




Flux tube

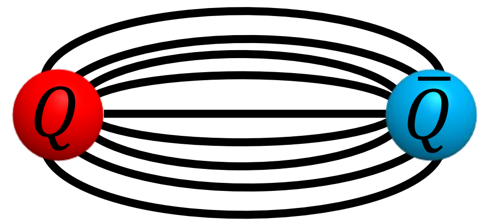
QED

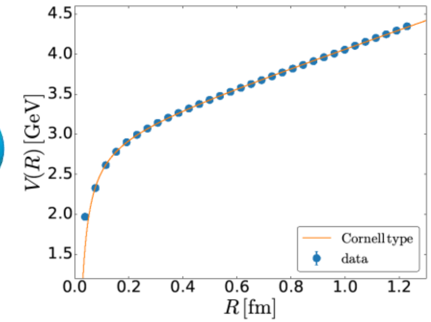




- ✓ Electric field spreads all over the space
- ✓ Coulomb potential

QCD

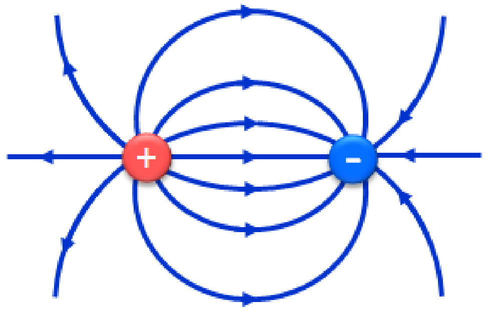


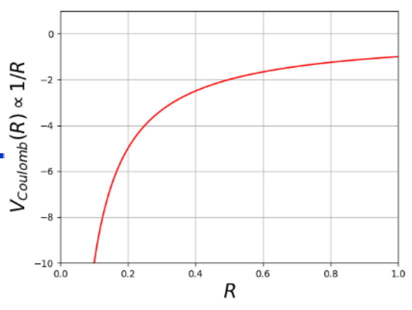


- ✓ Flux tube, squeezed one-dimensionally
- ✓ Confinement potential

Flux tube

QED





- ✓ Electric field spreads all over the space
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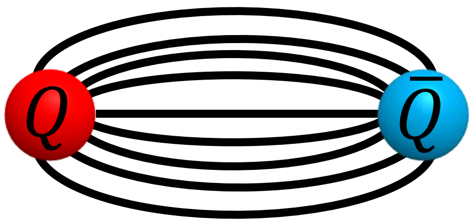
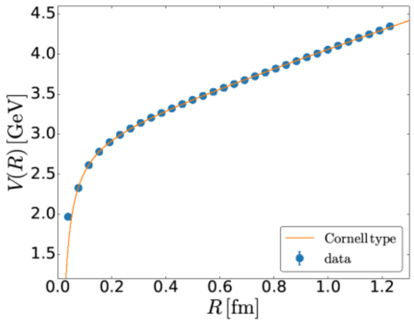
QCD





- ✓ Flux tube, squeezed one-dimensionally
- ✓ Confinement potential

Local interaction

Maxwell stress

Energy momentum tensor (EMT)

Energy density

Momentum density

$$T_{\mu\nu} = \begin{pmatrix} \boxed{T_{00}} & T_{01} & T_{02} & T_{03} \\ T_{10} & T_{11} & T_{12} & T_{13} \\ T_{20} & T_{21} & T_{22} & T_{23} \\ T_{30} & T_{31} & T_{32} & T_{33} \end{pmatrix}$$

Pressure

Stress tensor

✓ **Stress is force per unit area**

$f_i = \sigma_{ij} n_j \;\; ; \;\; \sigma_{ij} = -T_{ij}$

Landau and Lifshitz

Energy momentum tensor (EMT)

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Momentum density

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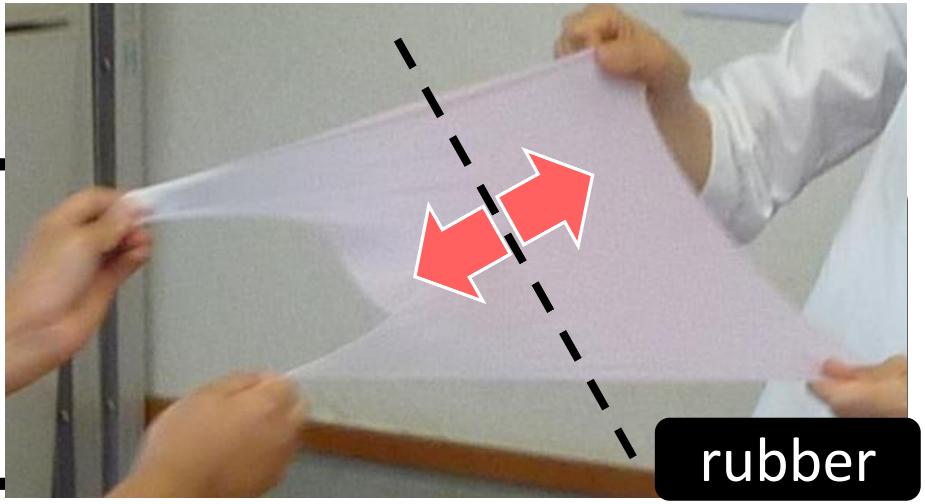
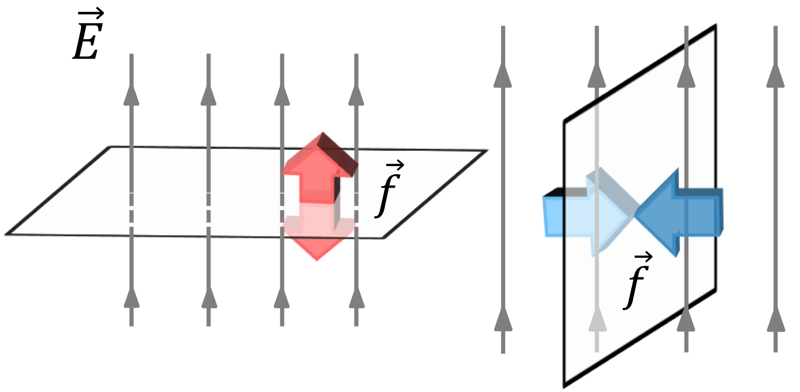
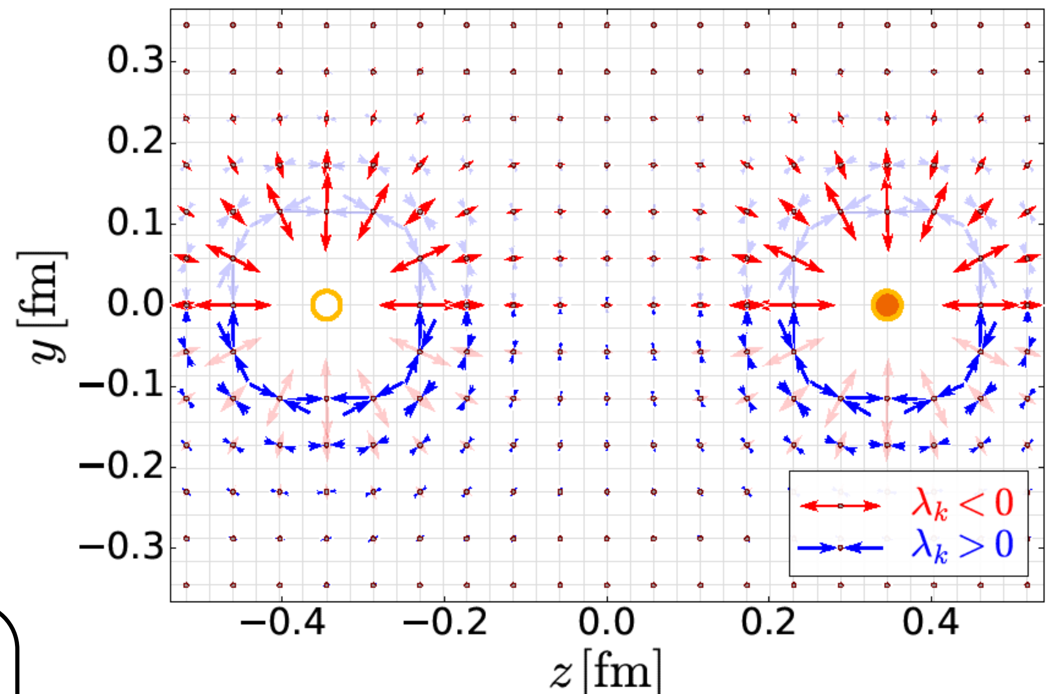


Maxwell stress

$$T_{ij} = \epsilon_0\left(E_iE_j - \frac{\delta_{ij}}{2}E^2\right) + \frac{1}{\mu_0}\left(B_iB_j - \frac{\delta_{ij}}{2}B^2\right)$$





- ✓ Perpendicular plane: $\lambda_k < 0$
- ✓ Parallel plane: $\lambda_k > 0$

✓ Stress tensor

$$T_{ij}n_j^{(k)} = \lambda_k n_i^{(k)}$$

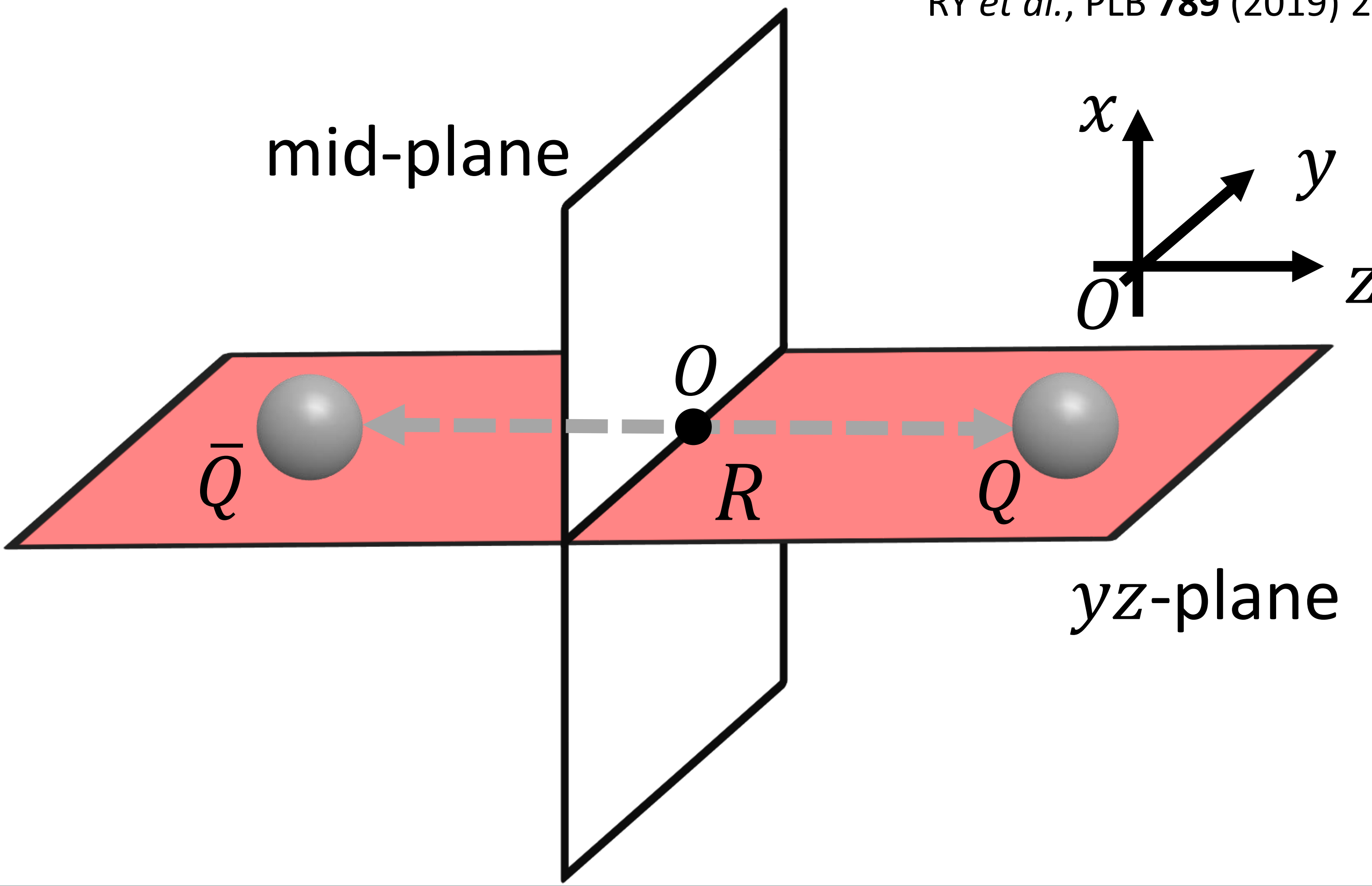
$$(i,j = 1,2,3\,;\ k = 1,2,3)$$

(Length of arrows= $\sqrt{|\lambda_k|}$)

A lattice study of stress distribution around $Q\bar{Q}$ in vacuum

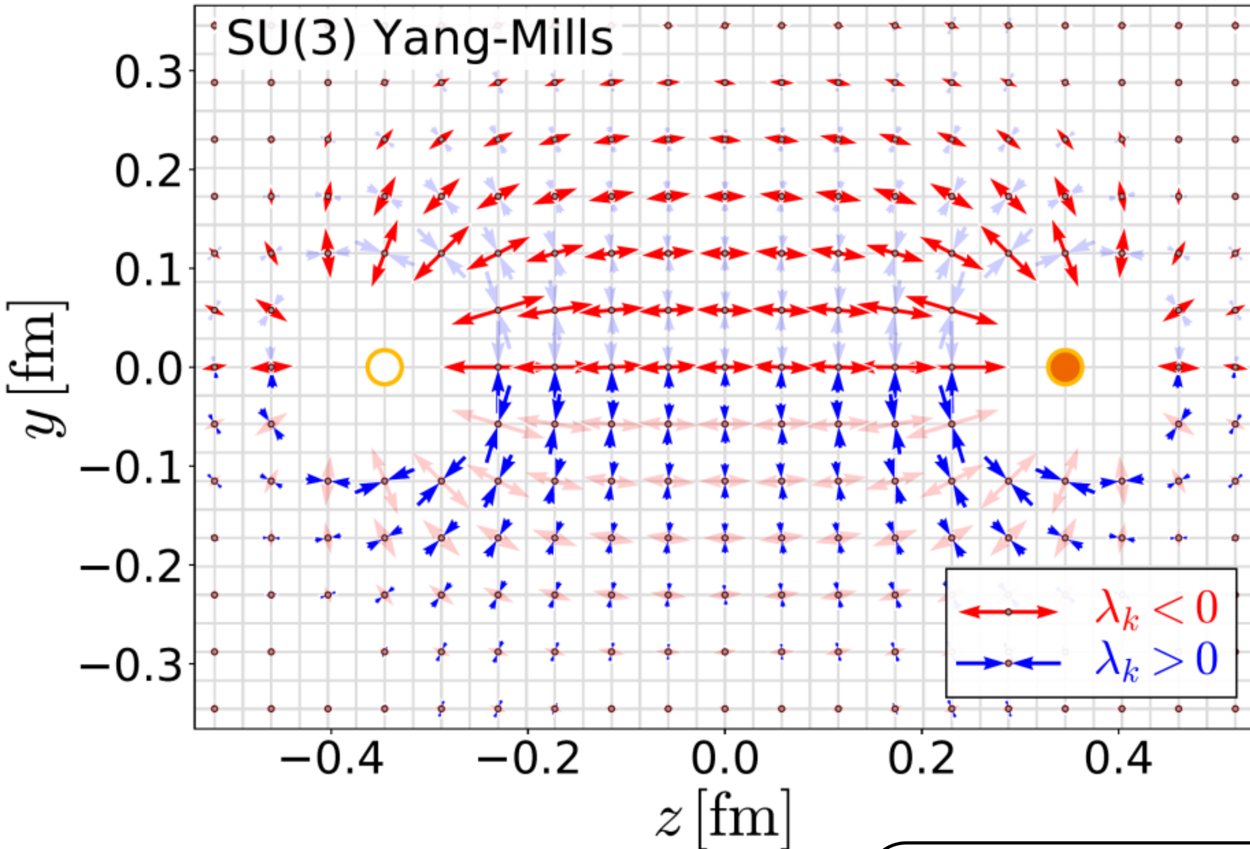
Stress distribution in terms of local interaction

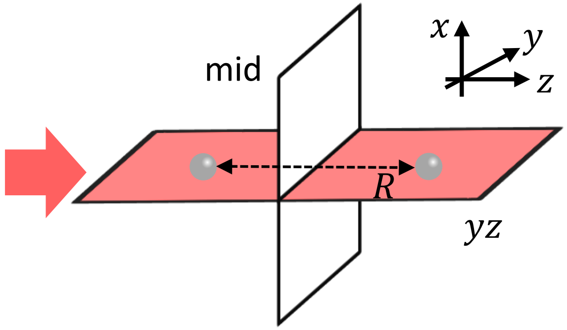
RY *et al.*, PLB **789** (2019) 210.



Stress distribution around $Q\bar{Q}$

RY *et al.*, PLB **789** (2019) 210.





- ✓ $a = 0.029$ fm
- ✓ $t/a^2 = 2.0$
- ✓ $R = 0.69$ fm
- ✓ Length of arrows = $\sqrt{|\lambda_k|}$

- ✓ Gauge invariant
- ✓ Local interaction
- ✓ squeezed

Stress distribution around $Q\bar{Q}$: Cylindrical coordinates

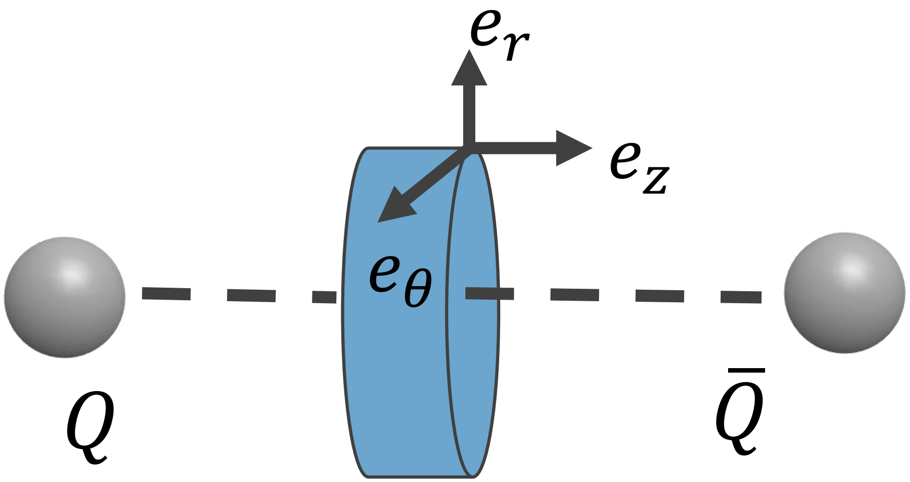
$$T_{\mu\nu} = \begin{pmatrix} T_{44} & & & O \\ & T_{zz} & & \\ & & T_{rr} & \\ O & & & T_{\theta\theta} \end{pmatrix}$$

Diagonalized EMT

(Cylindrical / Parity symmetry)

Degeneracy (Maxwell Theory)

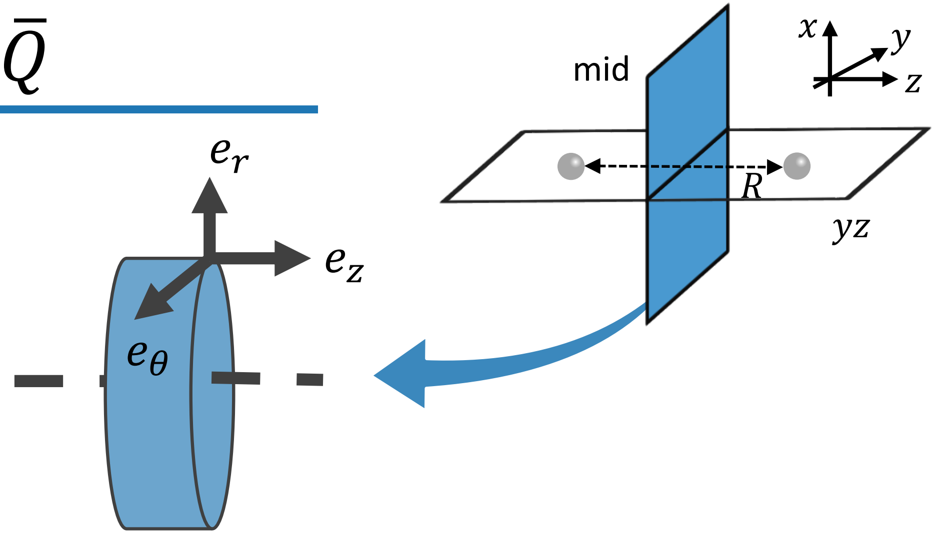
$$|T_{44}| = |T_{zz}| = |T_{rr}| = |T_{\theta\theta}|$$



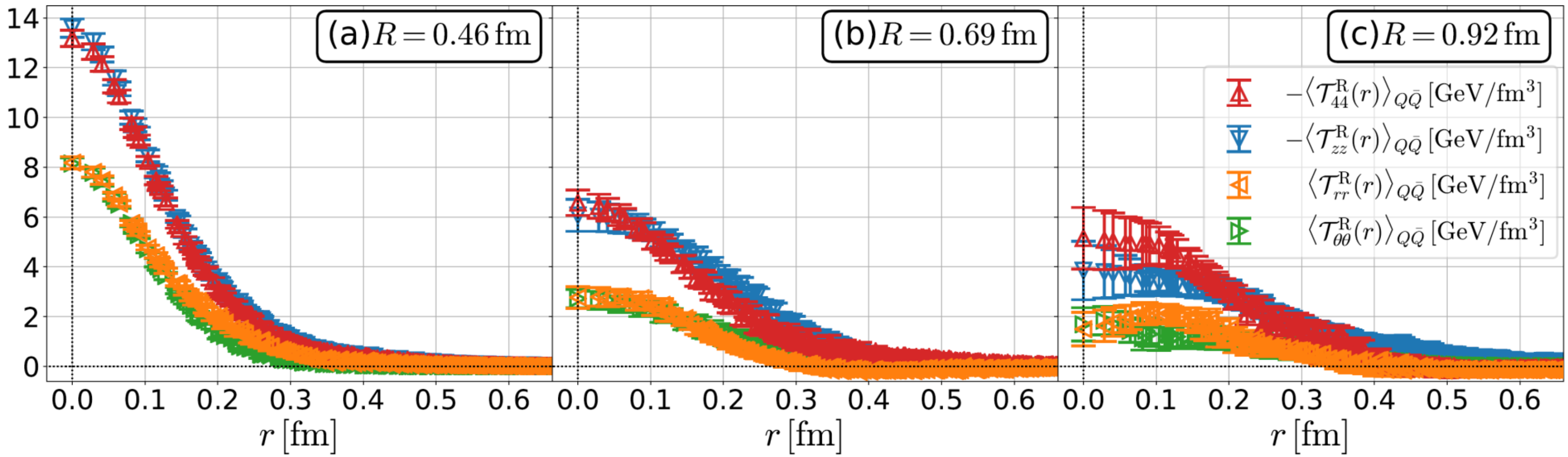
Stress distribution around $Q\bar{Q}$

Properties in non-Abelian theory

- ✓ $T_{44} \approx T_{zz}, T_{rr} \approx T_{\theta\theta}$ (Degeneracy)
- ✓ $T_{44} \neq T_{rr}$ (Separation)
- ✓ $\sum_\mu T_{\mu\mu} \neq 0$ (Trace anomaly$\neq$ 0)



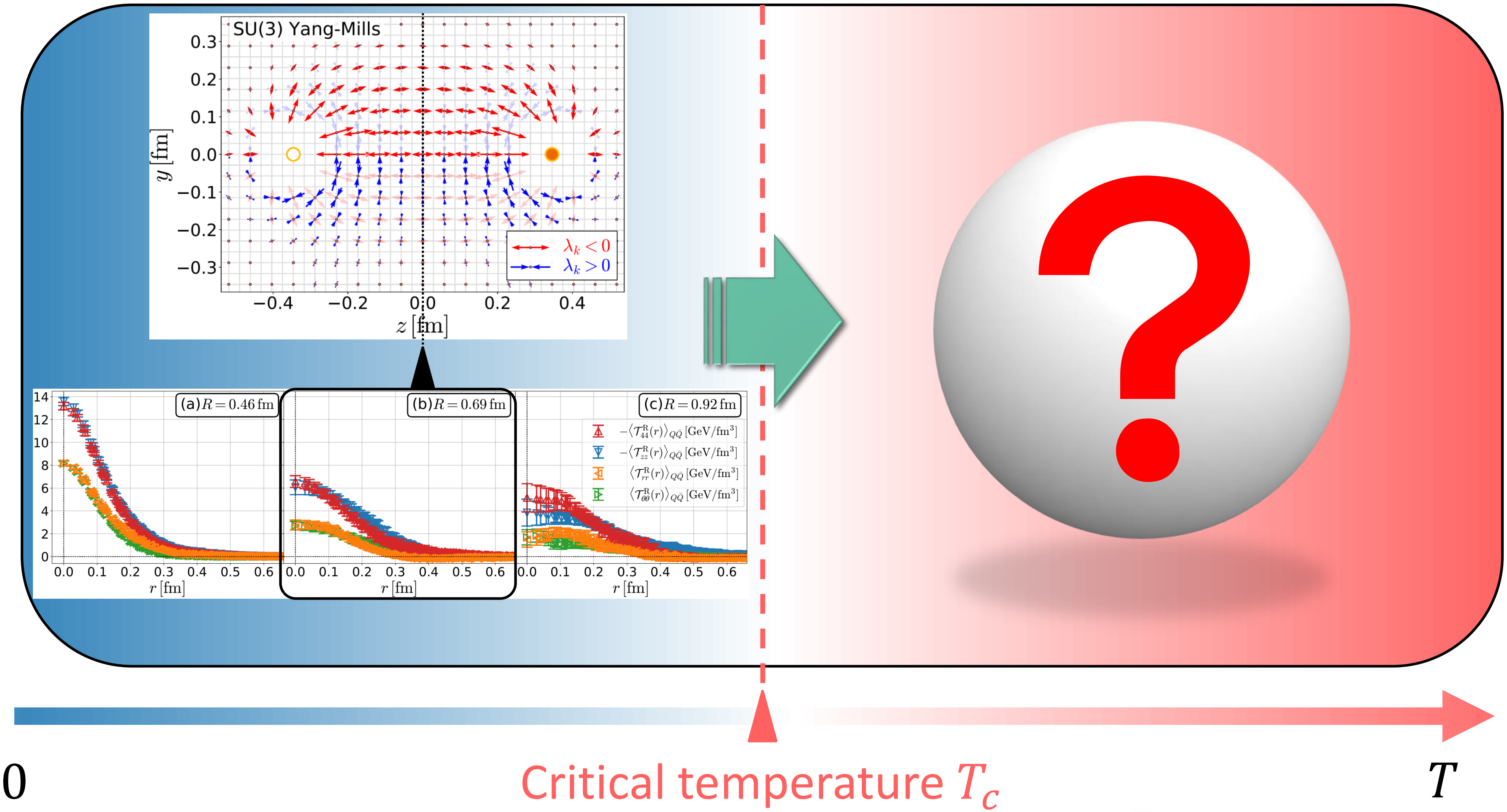
RY *et al.*, PLB **789** (2019) 210.



(Note : after double limit)

Toward analysis at nonzero temperature

Stress distribution around $Q\bar{Q}/Q$ at nonzero temperature



Measurement on the lattice

To do

①Prepare $Q(\bar{Q})$ on the lattice ②Measure EMT around $Q/\bar{Q}$

Measurement on the lattice

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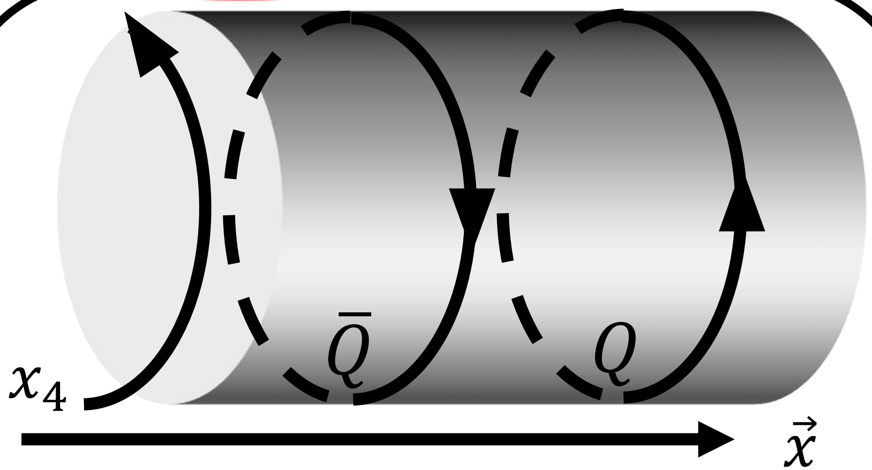
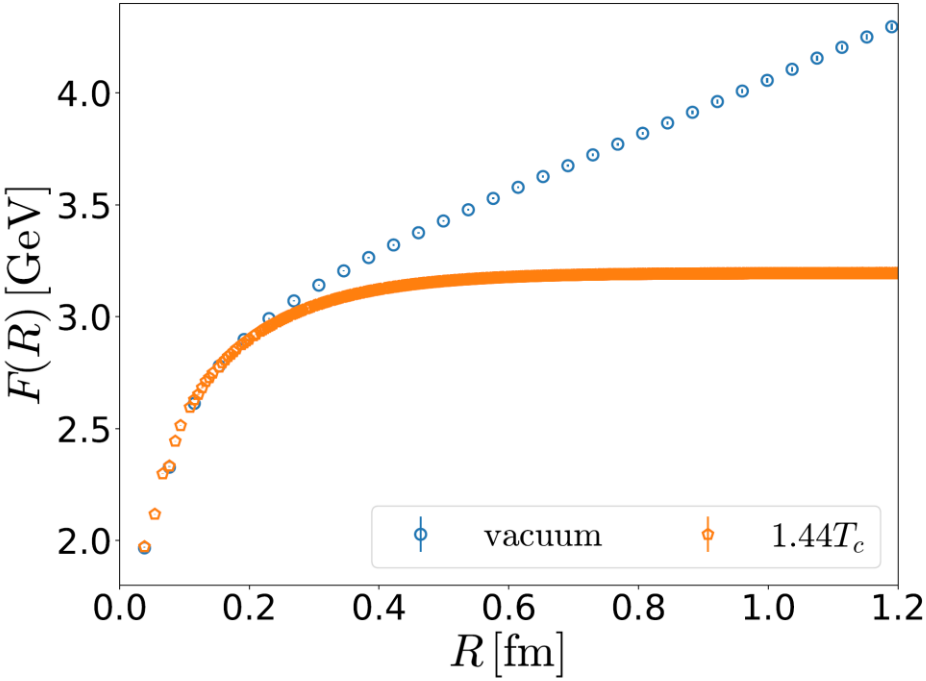
Polyakov Loop



$$e^{-F(R)/T} = \frac{1}{3}\langle \mathrm{Tr}\,\Omega^\dagger(\vec{x})\Omega\,(\vec{y})\rangle$$

Color singlet free energy
(We use Coulomb gauge fixing)

Free energy



- ✓ quenched SU(3) Yang-Mills
- ✓ $\beta = 6.600$ ($a = 0.038$ fm)

Measurement on the lattice

To do

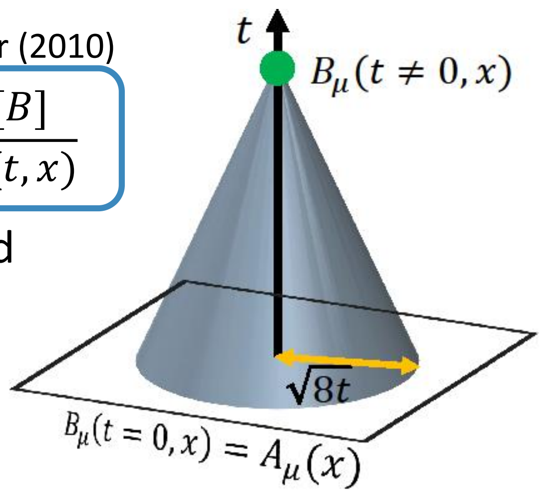
①Prepare $Q(\bar{Q})$ on the lattice ②Measure EMT around $Q/\bar{Q}$

Gradient flow

Flow eq. Lüscher (2010)

$$\frac{\partial B_\mu(t,x)}{\partial t} = -g_0^2 \frac{\delta S[B]}{\delta B_\mu(t,x)}$$

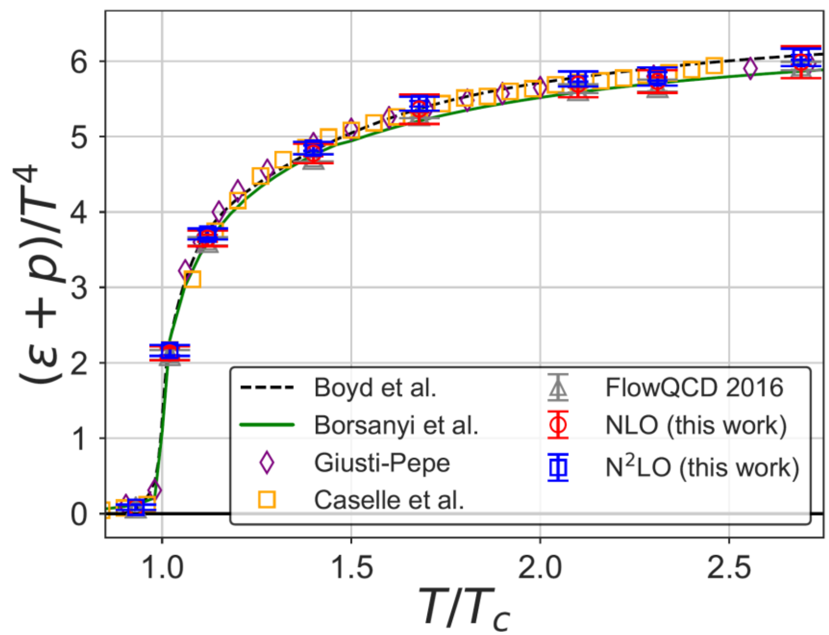
B_μ : smeared field



EMT defined via gradient flow Suzuki (2013)

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

Iritani *et al*. (2018)



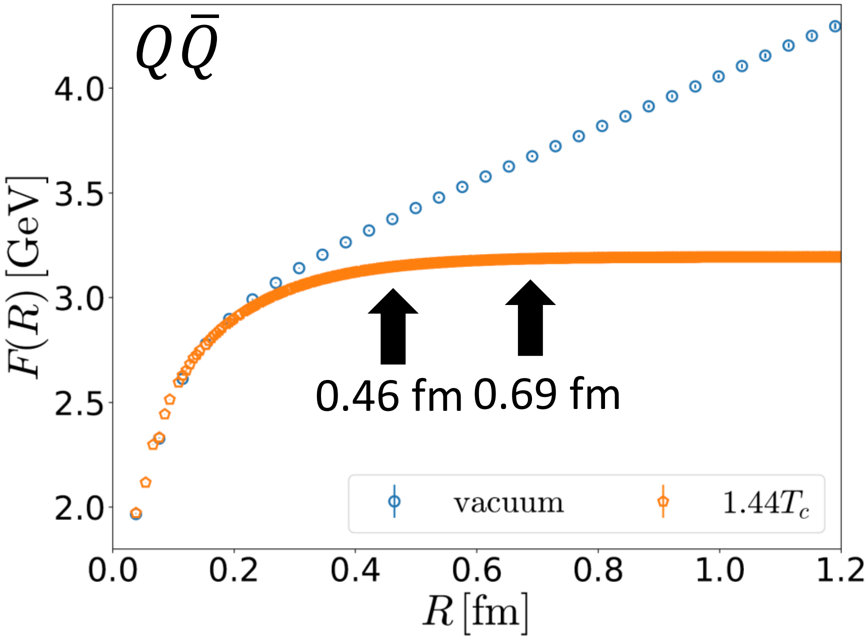
Entropy density vs. temperature

✓ 2-loop coefficient is now available !

Harlander *et al*. (2018)

Set up (quark—anti-quark, single quark)

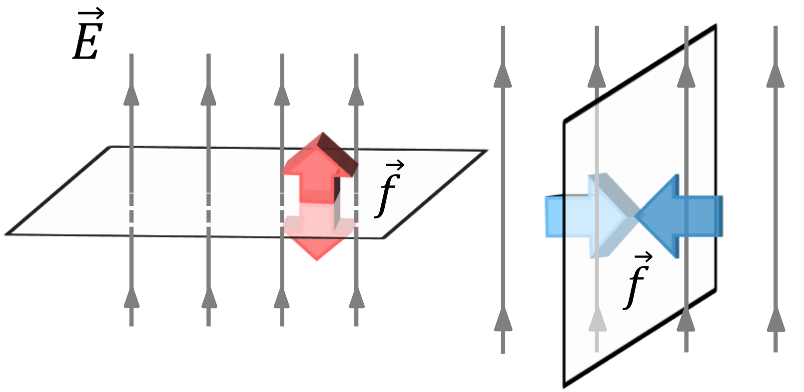
- ✓ Quenched SU(3) Yang-Mills gauge theory
- ✓ Wilson gauge action
- ✓ Clover operator
- ✓ Fixed a, t
- ✓ Multihit improvement in temporal links
- ✓ Coulomb gauge fixing
- ✓ Simulation using OCTOPUS, Reedbush



β	Lattice spacing	Spatial size	Temporal size	T/T_c	# of statistics
6.600	0.038 fm	48^3	12	1.44	640
7.166	0.019 fm	48^3	12	2.97	300

Maxwell stress (revisit)

$$T_{ij} = \epsilon_0 \left(E_i E_j - \frac{\delta_{ij}}{2} E^2 \right) + \frac{1}{\mu_0} \left(B_i B_j - \frac{\delta_{ij}}{2} B^2 \right)$$



- ✓ Perpendicular plane: $\lambda_k < 0$
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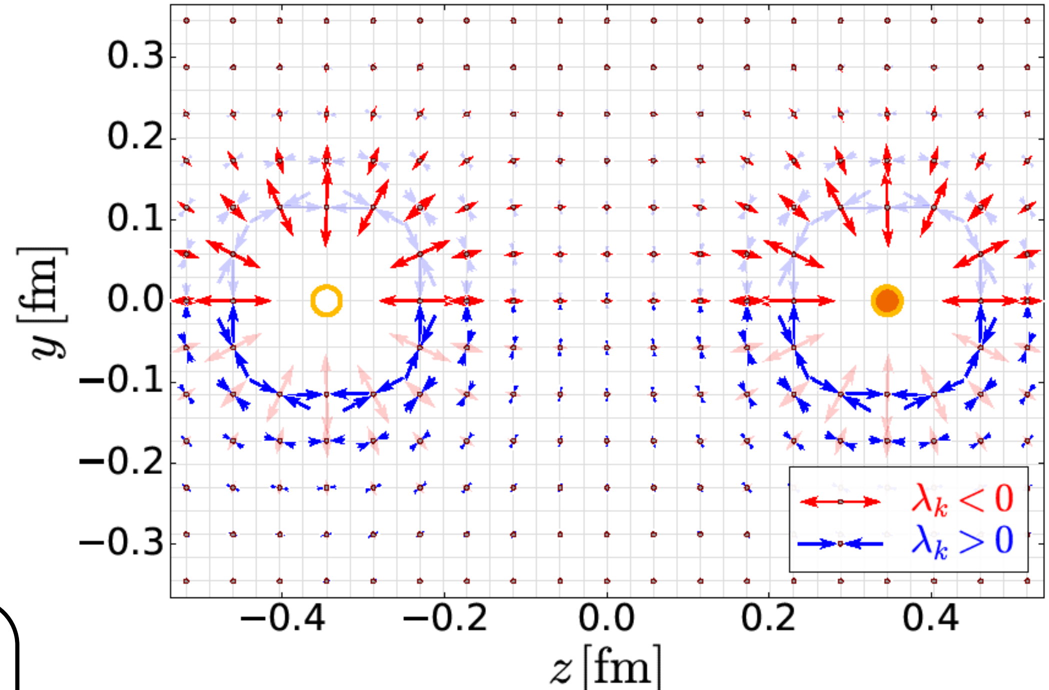


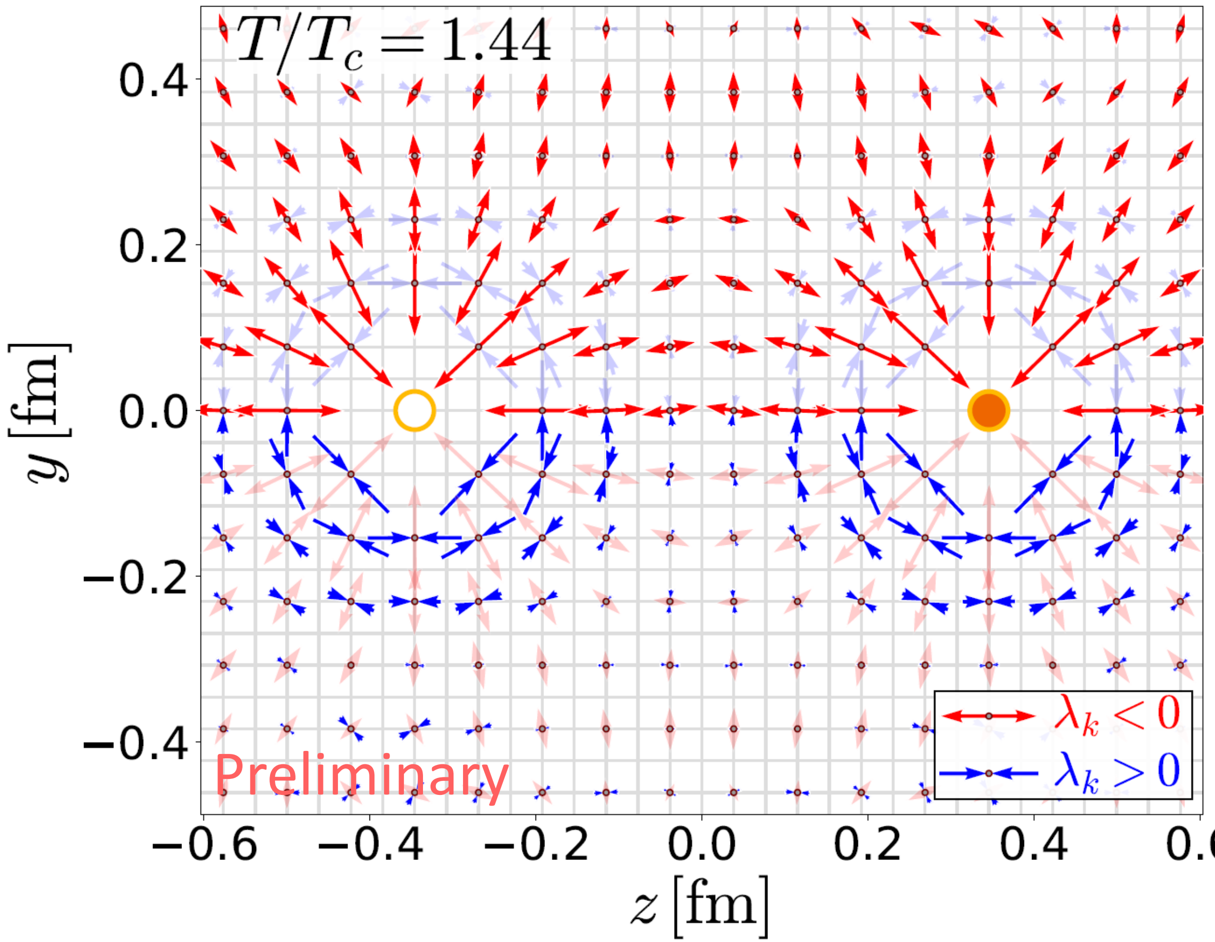
✓ Stress tensor

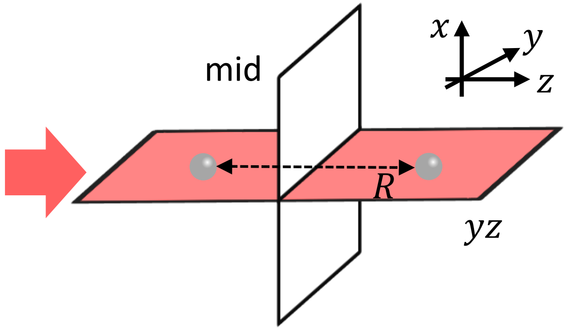
$$T_{ij} n_j^{(k)} = \lambda_k n_i^{(k)}$$

$$(i, j = 1,2,3\ ;\ k = 1,2,3)$$

(Length of arrows= $\sqrt{|\lambda_k|}$)

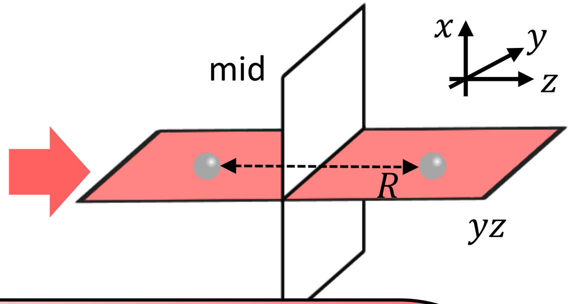
Stress distribution around $Q\bar{Q}$

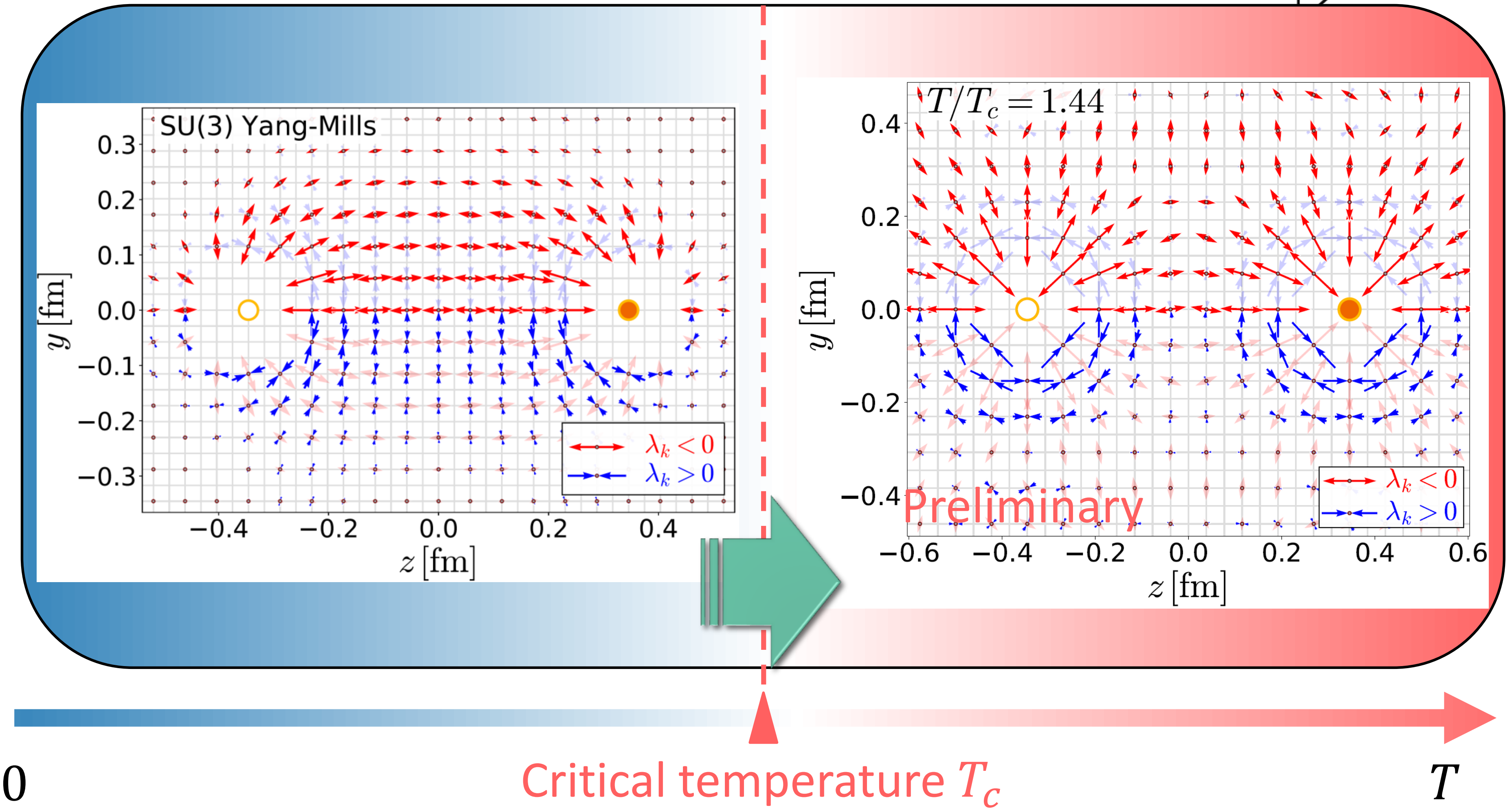




- ✓ singlet
- ✓ $a = 0.038$ fm (fixed)
- ✓ $t/a^2 = 2.0$ (fixed)
- ✓ $R = 0.69$ fm
- ✓ Length of arrows $= \sqrt{|\lambda_k|}$

Stress distribution around $Q\bar{Q}$



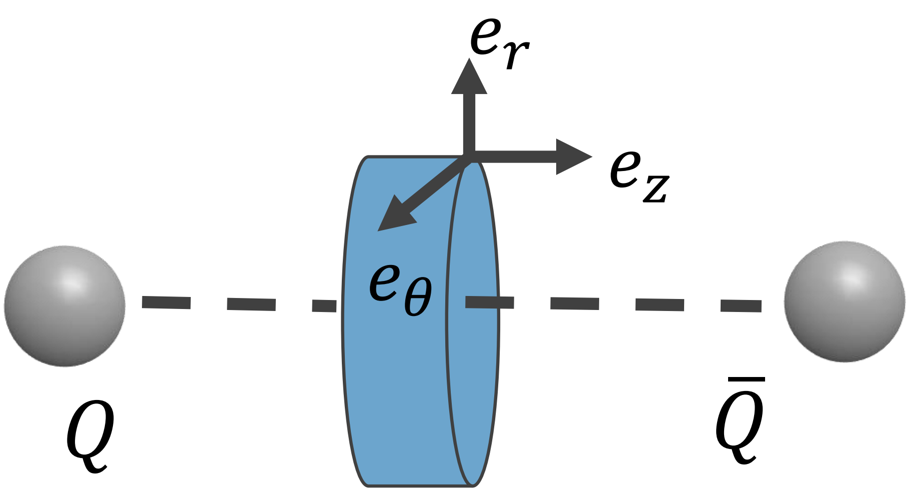


Stress distribution around $Q\bar{Q}$: Cylindrical coordinates

$$T_{\mu\nu} = \begin{pmatrix} T_{44} & & & O \\ & T_{zz} & & \\ & & T_{rr} & \\ O & & & T_{\theta\theta} \end{pmatrix}$$

Diagonalized EMT

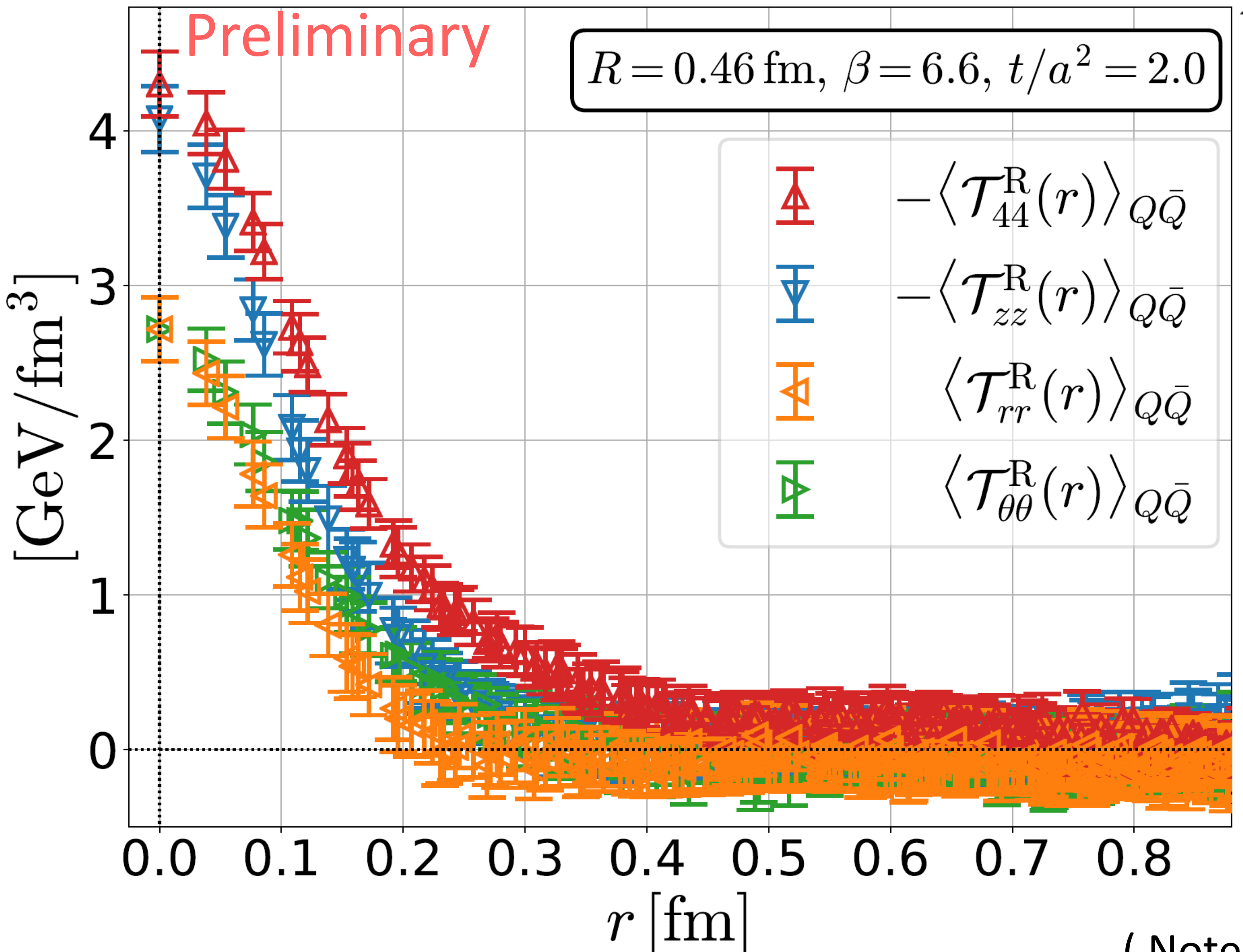
(Cylindrical / Parity symmetry)

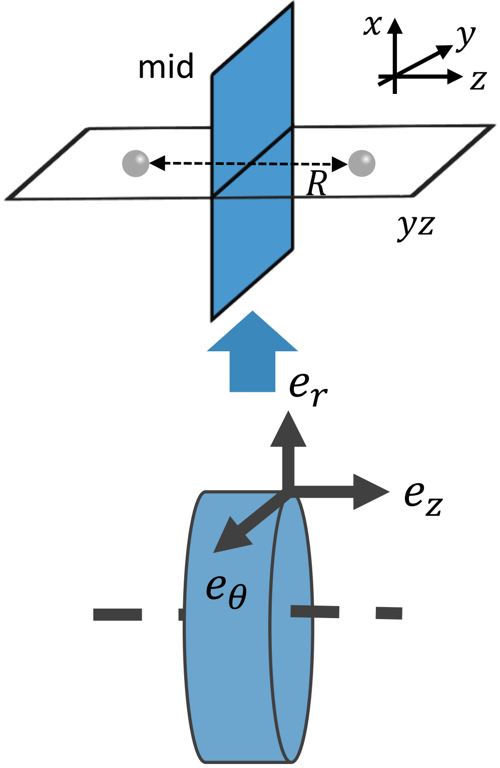


Degeneracy (Maxwell Theory)

$$|T_{44}| = |T_{zz}| = |T_{rr}| = |T_{\theta\theta}|$$

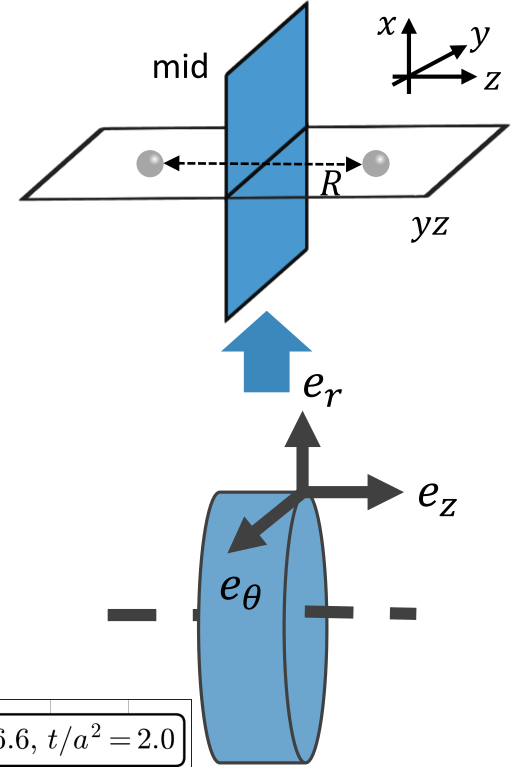
Stress distribution around $Q\bar{Q}$



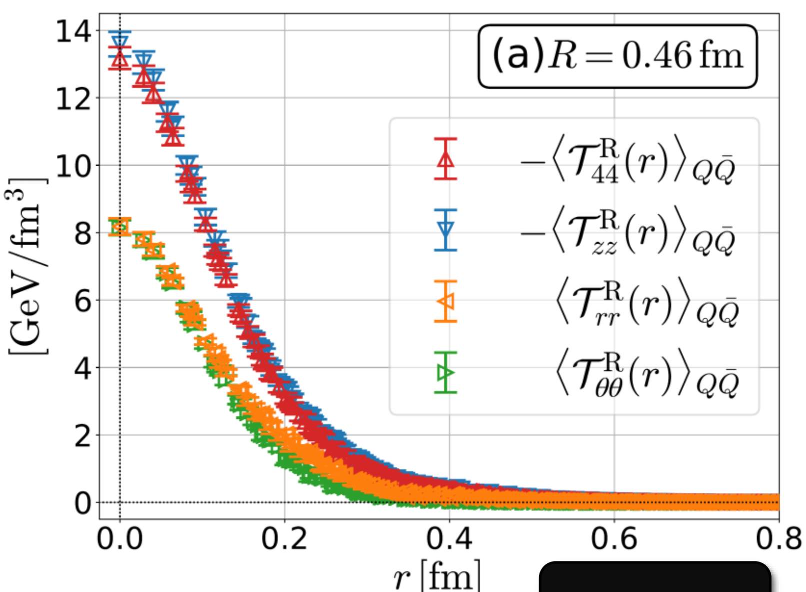


(Note : singlet)

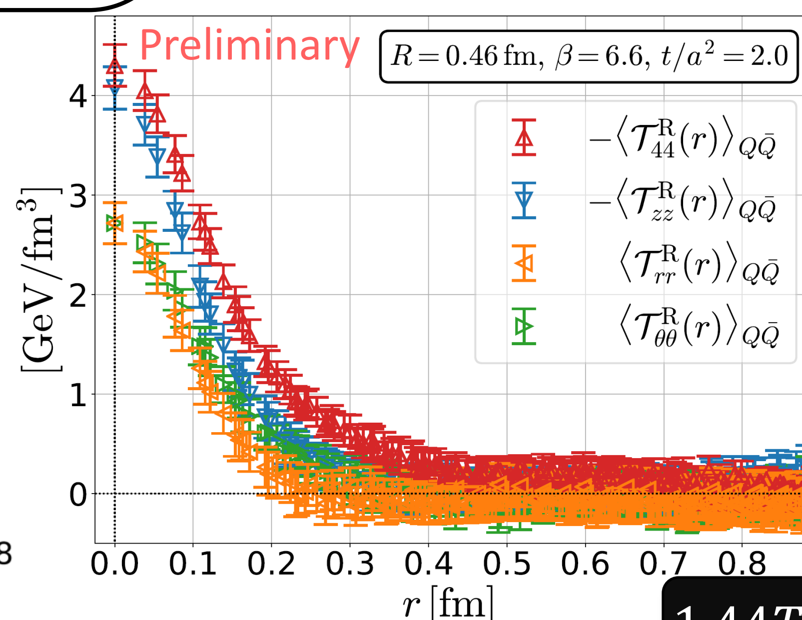
Stress distribution around $Q\bar{Q}$



- ✓ $T_{rr} \approx T_{\theta\theta}$ (Degeneracy)
- ✓ $T_{44} \neq T_{rr}$ (Separation)
- ✓ $\sum_\mu T_{\mu\mu} \neq 0$ (Trace anomaly$\neq 0$)
- ✓ Damping $\leftrightarrow$ Debye mass
- ✓ $dF/dR \leftrightarrow \int T_{zz}\, d^2x$

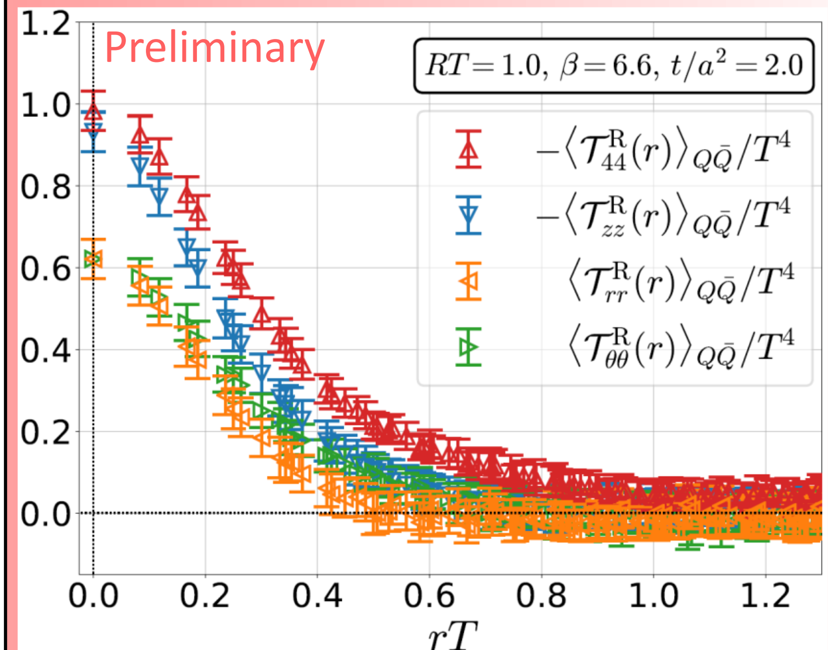


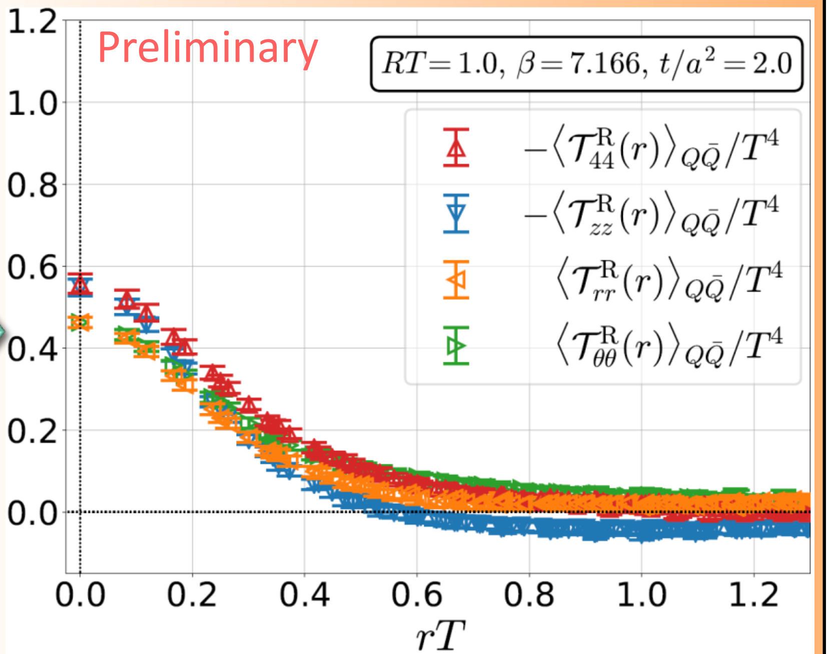
Vacuum



$1.44T_c$

Stress distribution around $Q\bar{Q}$: Temperature-dependence





- ✓ Scaled by T
- ✓ Degeneracy (≈ Maxwell)

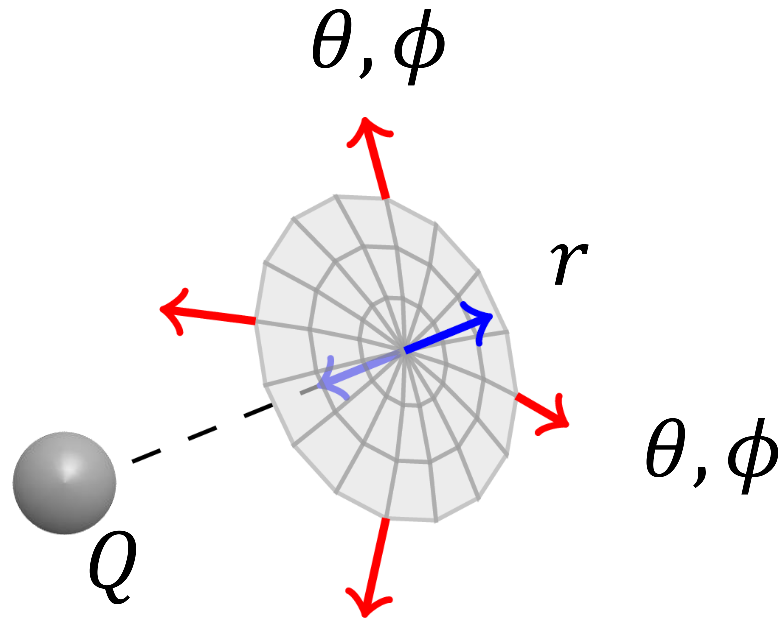
$1.44T_c$ $2.97T_c$

Stress distribution around Q : Spherical coordinates

$$T_{\mu\nu} = \begin{pmatrix} T_{44} & & & O \\ & T_{rr} & & \\ & & T_{tt} & \\ O & & & T_{tt} \end{pmatrix}$$

Diagonalized EMT

(Spherical symmetry)

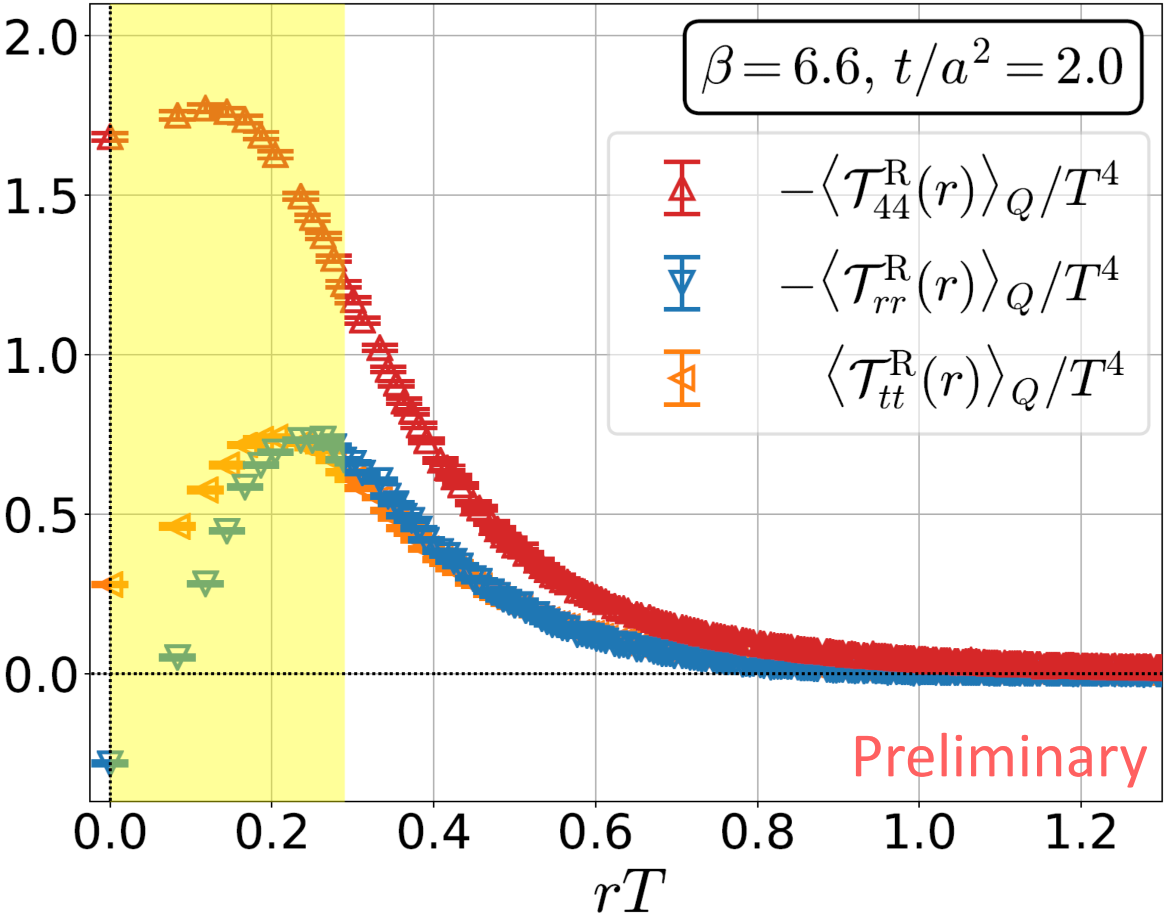


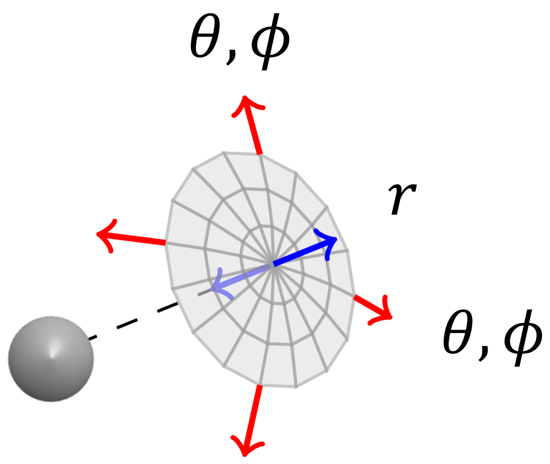
Degeneracy (Maxwell Theory)

$$|T_{44}| = |T_{rr}| = |T_{tt}|$$

$(t\colon \theta, \phi)$

Stress distribution around Q

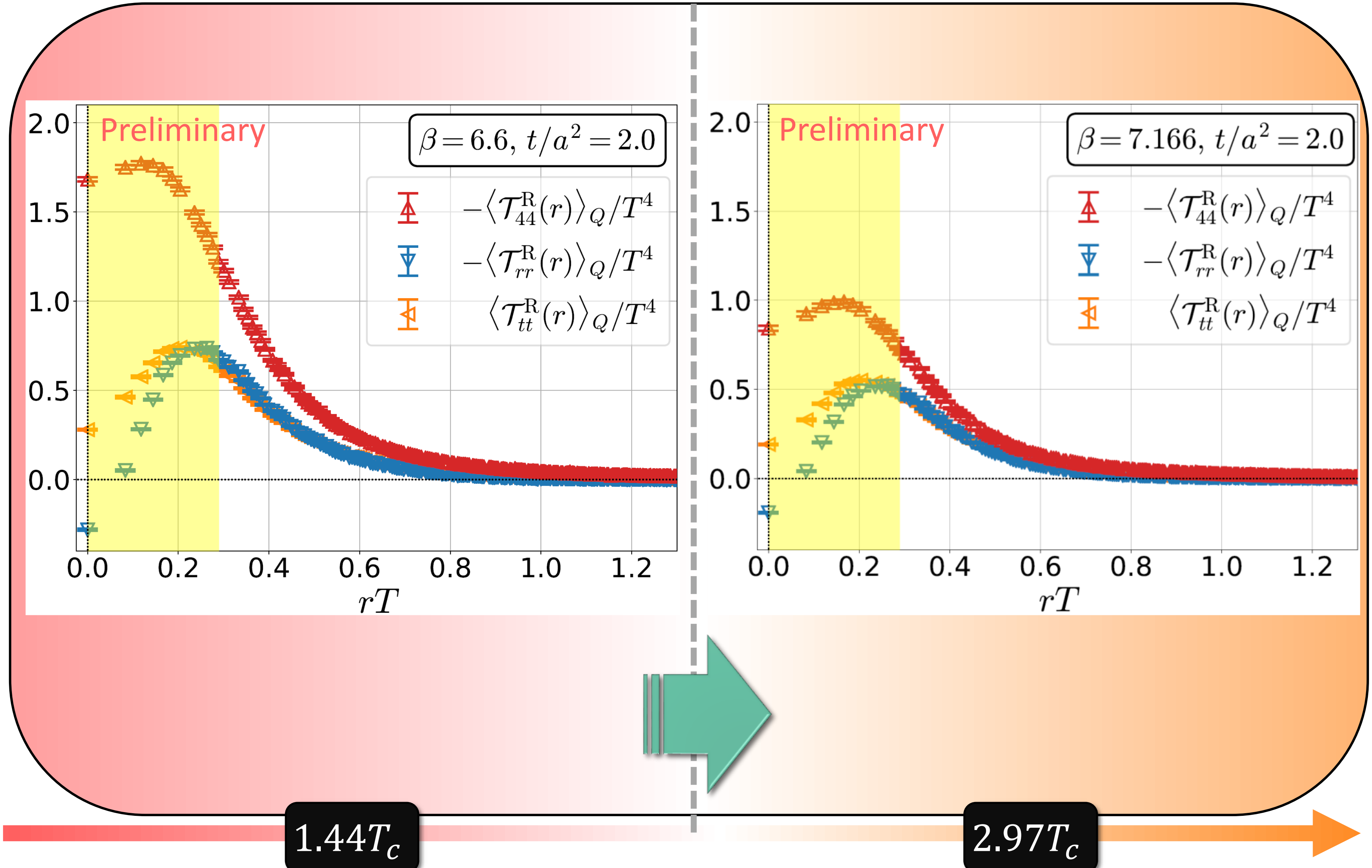




- ✓ Overlap : $r \lesssim \sqrt{2t}$
- ✓ Separation
- ✓ Around origin $\sim \alpha_s^2(r)/r^4$
- ✓ Damping $\sim e^{-m_D r}$
- ✓ Conservation law :

$$\partial_r(r^2 T_{rr}) = rT_{tt}$$

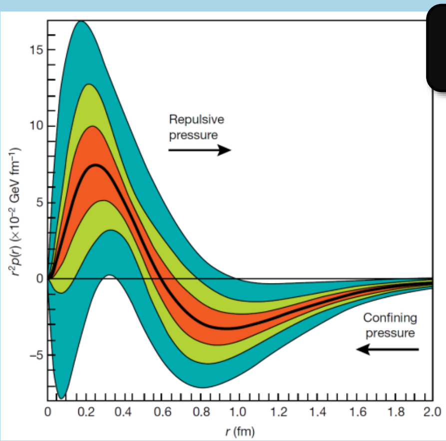
Stress distribution around Q : Temperature-dependence



Pressure distribution inside hadrons vs. Our study

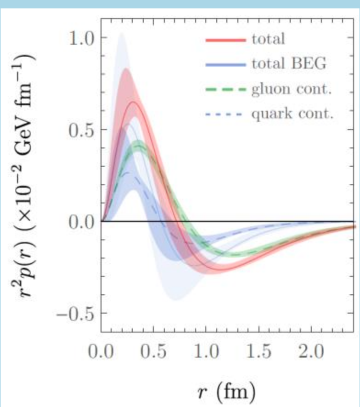
Pressure distribution inside Hadrons

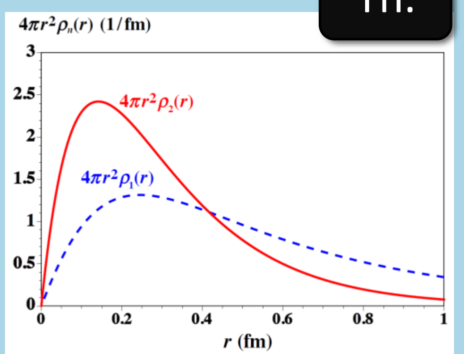
Exp.



Burkert *et al.*, Nature **557** (2018) 396.

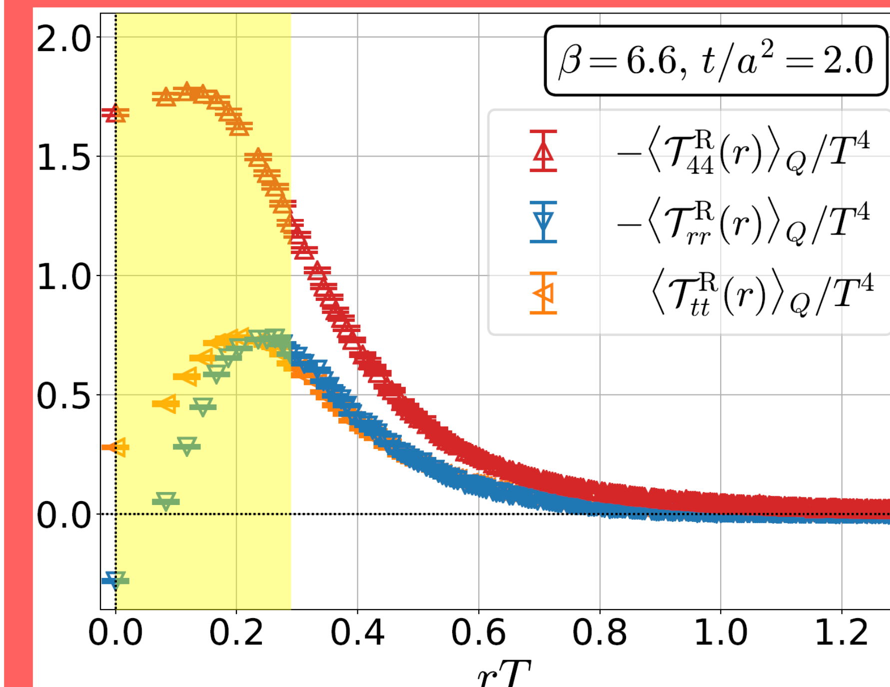
Th.





Shanahan *et al.*, PRL **122** (2019) no7, 072003.
Kumano *et al.*, PRD **97** (2018) 014020.

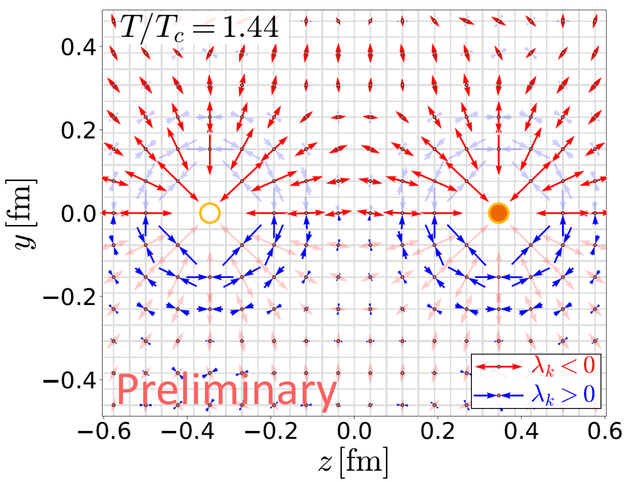
Our study

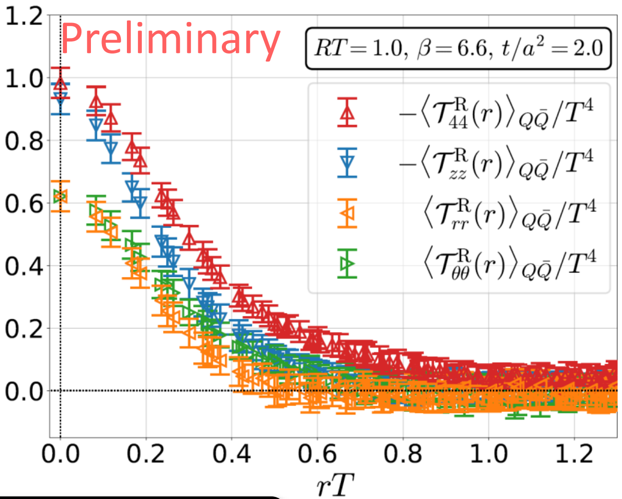


Summary and Outlook

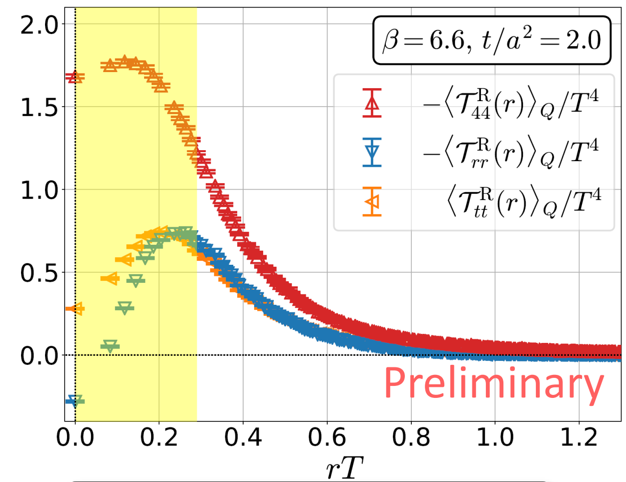
Summary

✓ We measure stress distribution around $Q\bar{Q}/Q$ at zero/nonzero temperature on the lattice





Quark—Anti-Quark



Single Quark

Outlook

✓ $a, t \to 0$ (double limit)

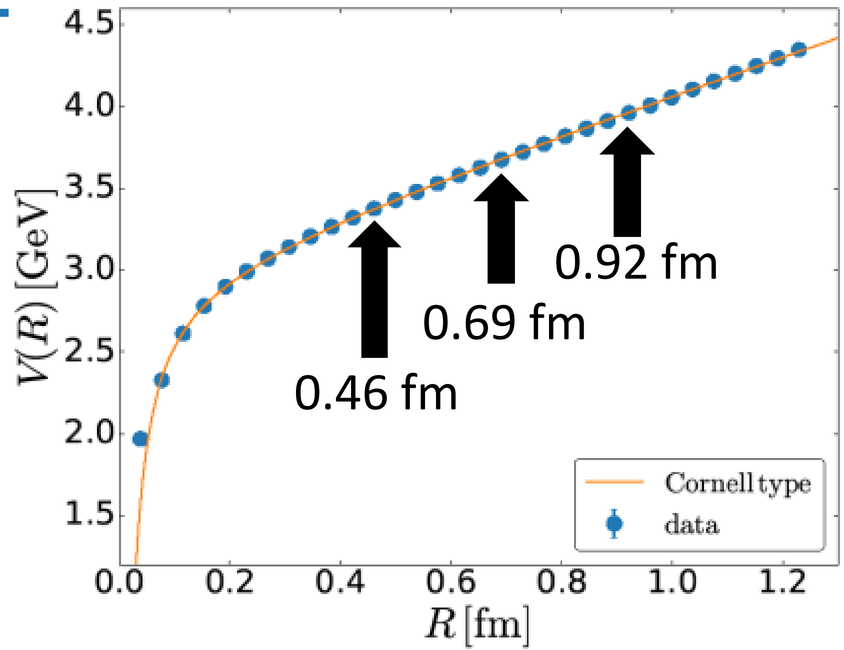
✓ Temperature dependence

✓ Application : QQ, QQQ, excited state, hadron (full QCD)…

Back up

Set up (vacuum analysis)

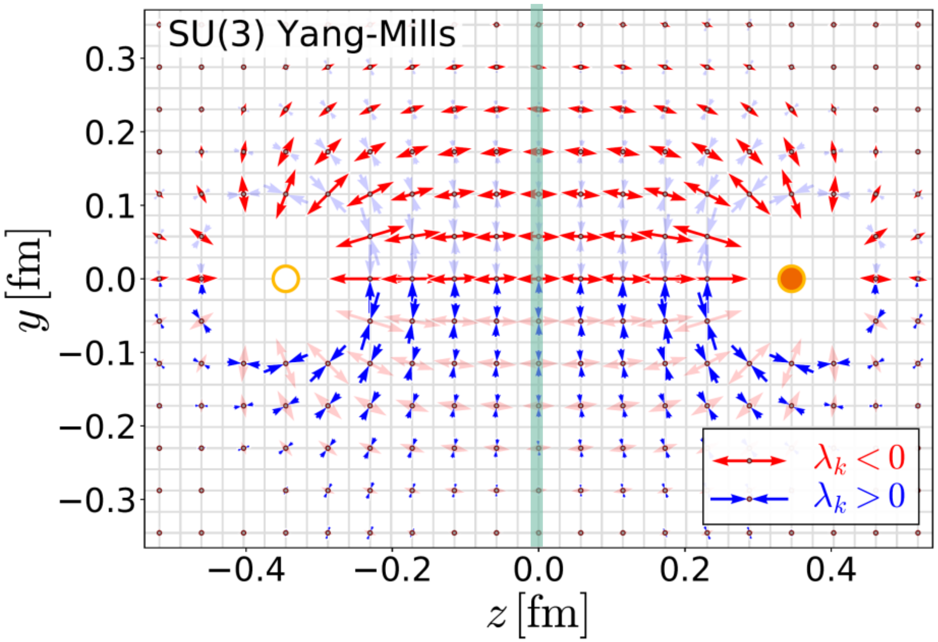
- ✓ Quenched SU(3) Yang-Mills gauge theory
- ✓ Wilson gauge action
- ✓ Clover operator
- ✓ Continuum limit
- ✓ APE smearing for spatial links
- ✓ Multihit improvement in temporal links
- ✓ Simulation using BlueGene/Q @ KEK



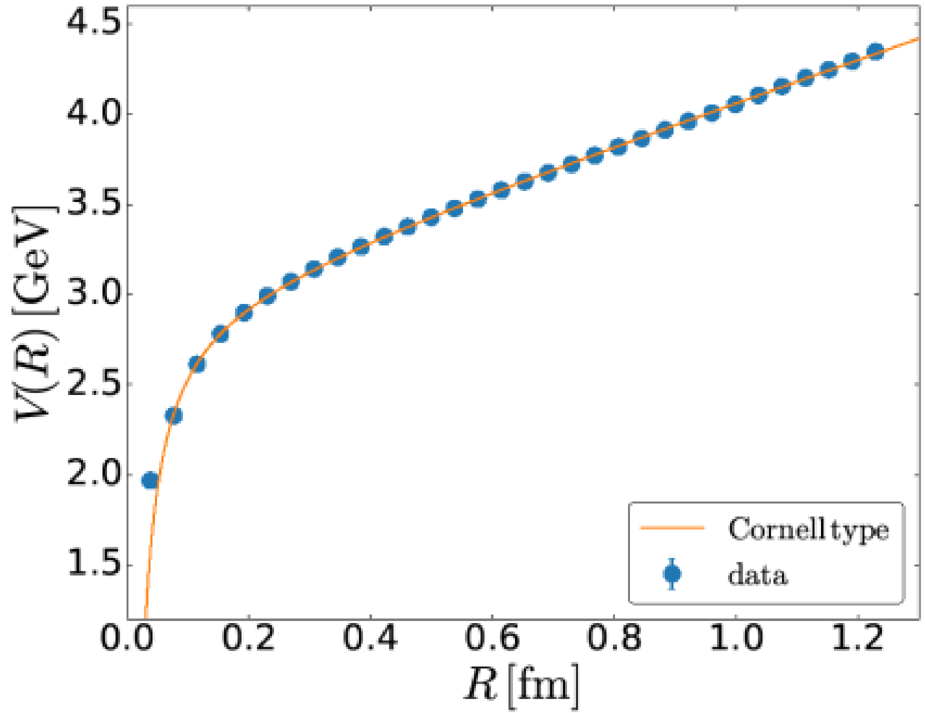
β	Lattice spacing	Lattice size	# of statistics
6.304	0.057 fm	48^4	140
6.465	0.046 fm	48^4	440
6.513	0.043 fm	48^4	600
6.600	0.038 fm	48^4	1500
6.819	0.029 fm	64^4	1000

EMT and confinement potential

From EMT



confinement potential



$$F_{\text{stress}} \coloneqq \int_{\text{mid}} \langle T_{zz} \rangle_{Q\bar{Q}}\, d^2x$$

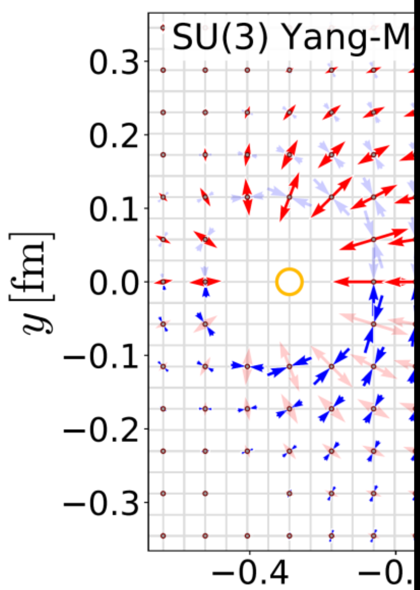
$$V(R) = a + bR + c/R$$

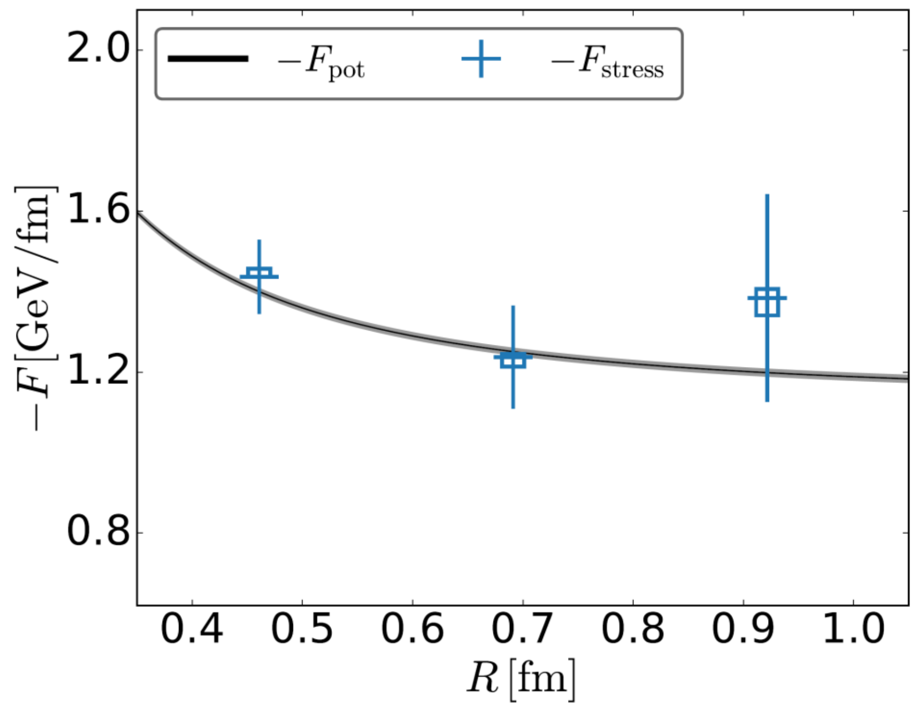
$$F_{\text{pot}} \coloneqq -\frac{dV(R)}{dR}$$

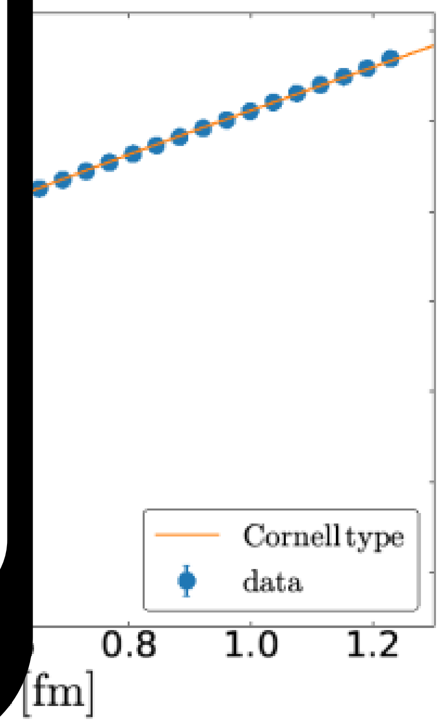
EMT and confinement potential

From EMT

ntial







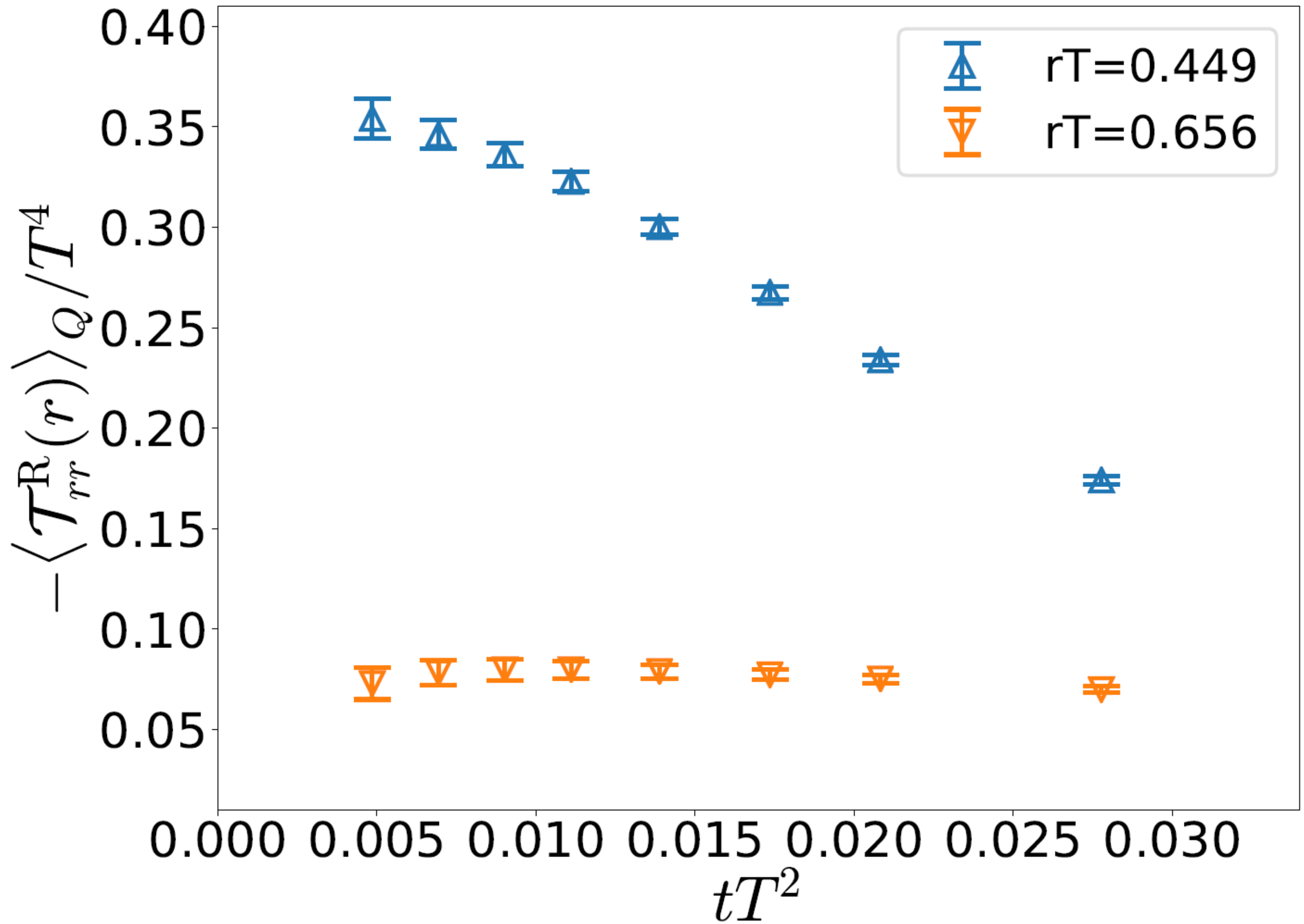
Good agreement !!

$$V(R) = a + bR + c/R$$

$$F_{\rm stress} \coloneqq \int_{\rm mid} \langle T_{zz} \rangle_{Q\bar{Q}}\, d^2x$$

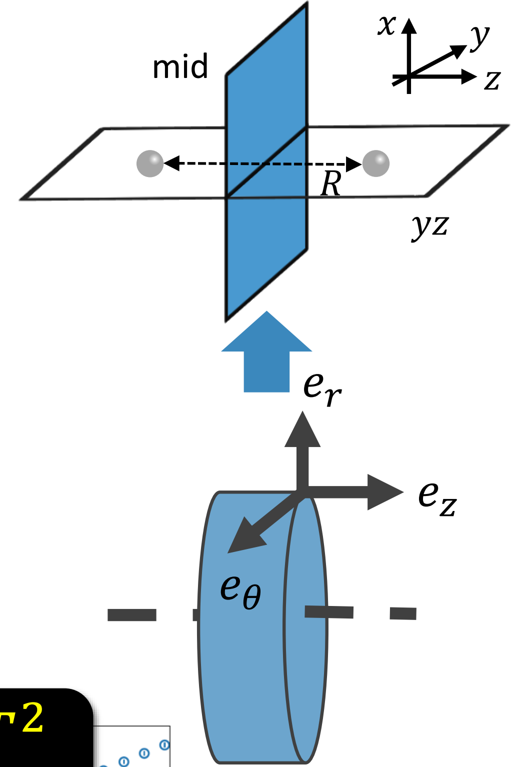
$$F_{\rm pot} \coloneqq -\frac{dV(R)}{dR}$$

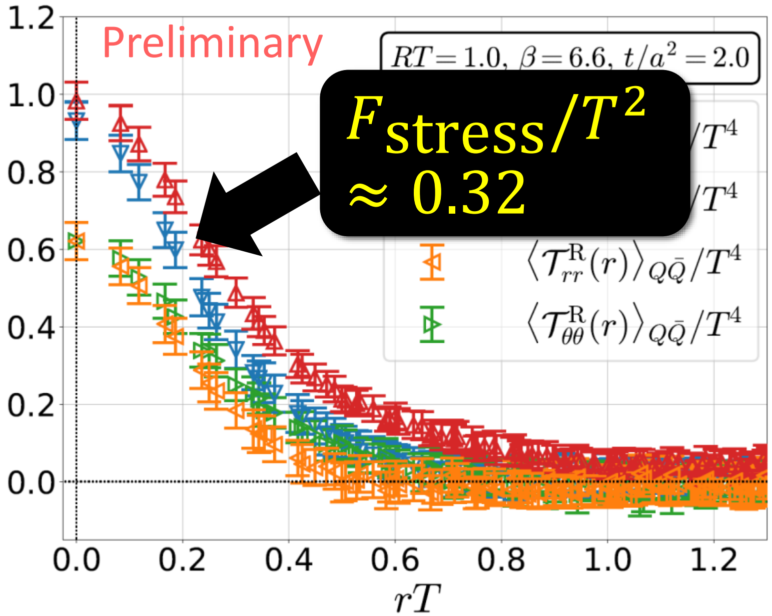
Flow time dependence (single quark system)

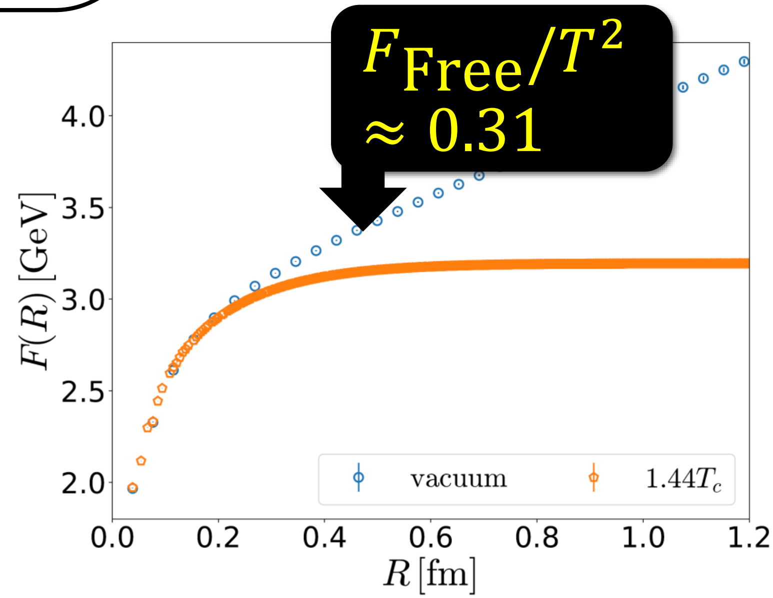


Stress distribution around $Q\bar{Q}$

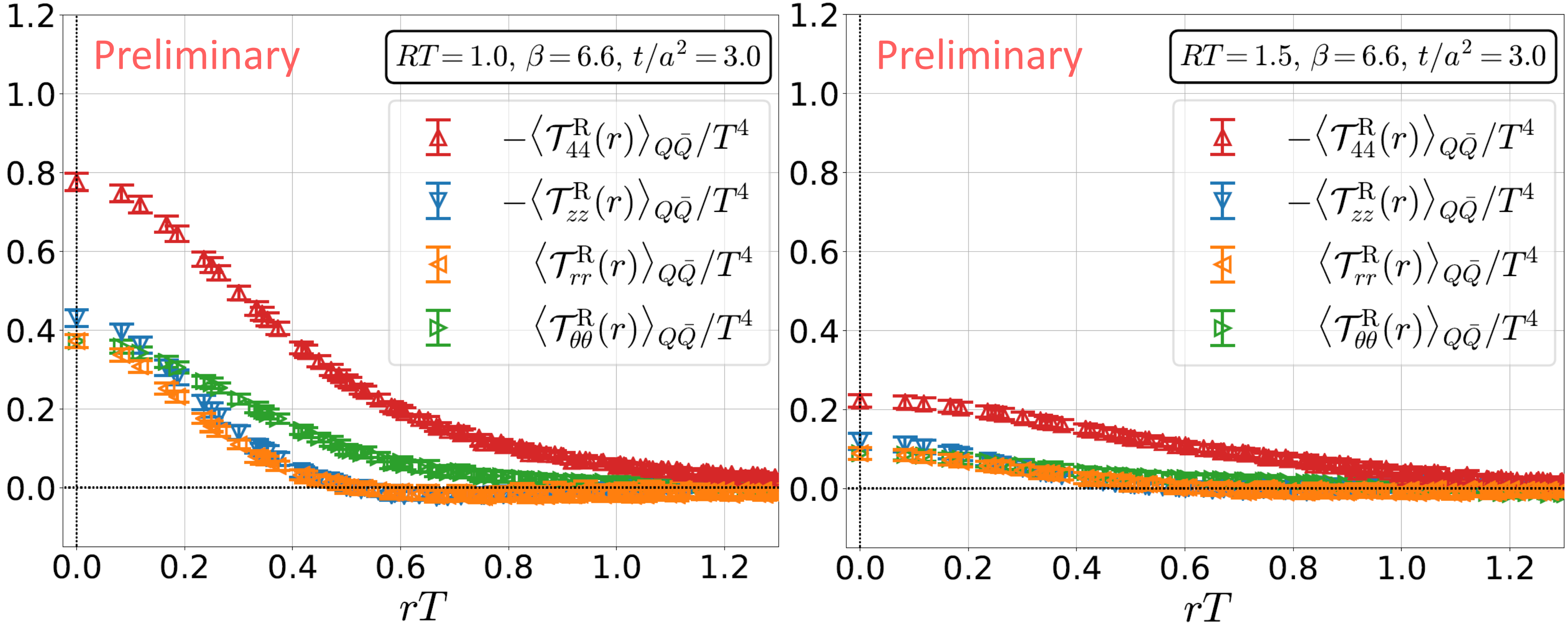
- ✓ $T_{rr} \approx T_{\theta\theta}$ (Degeneracy)
- ✓ $T_{44} \neq T_{rr}$ (Separation)
- ✓ $\sum_\mu T_{\mu\mu} \neq 0$ (Trace anomaly$\neq 0$)
- ✓ Damping $\leftrightarrow$ Debye mass
- ✓ $dF/dR \leftrightarrow \int T_{zz}\, d^2x$



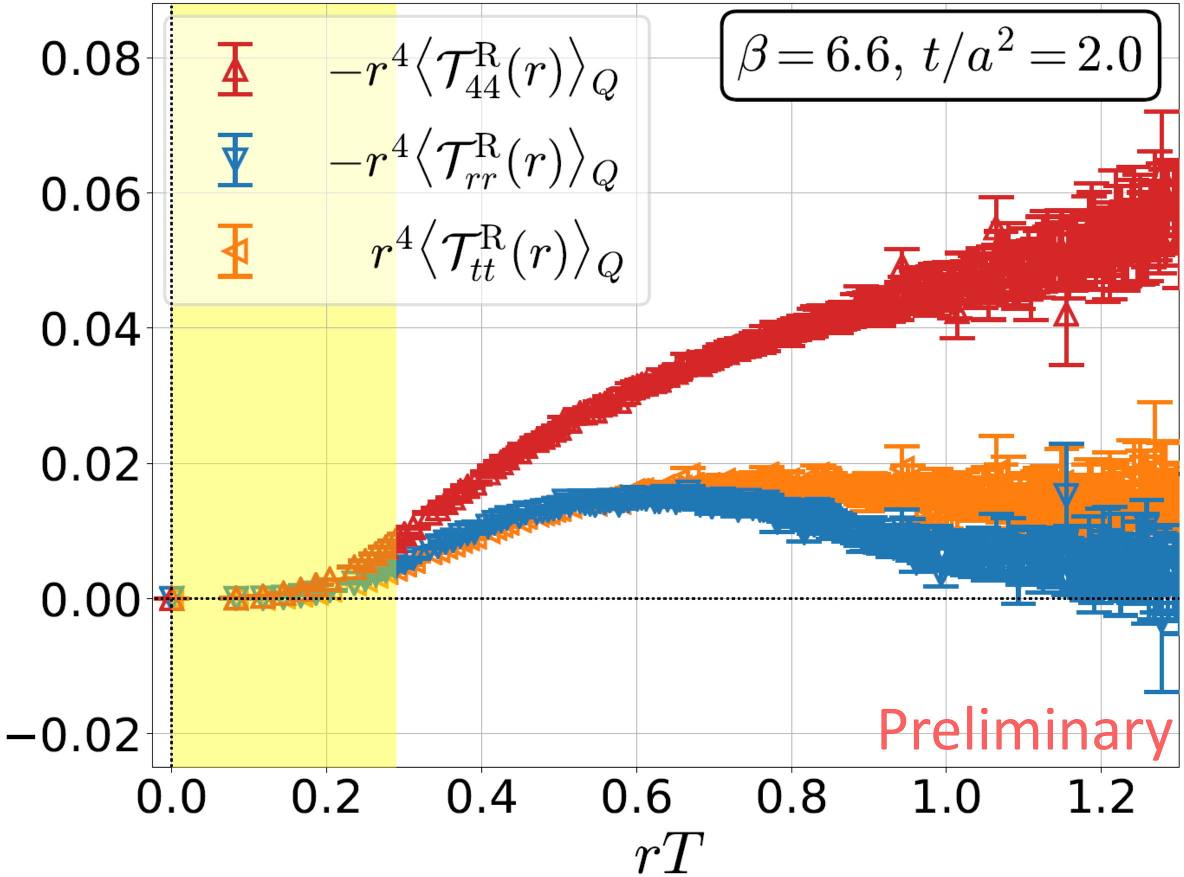


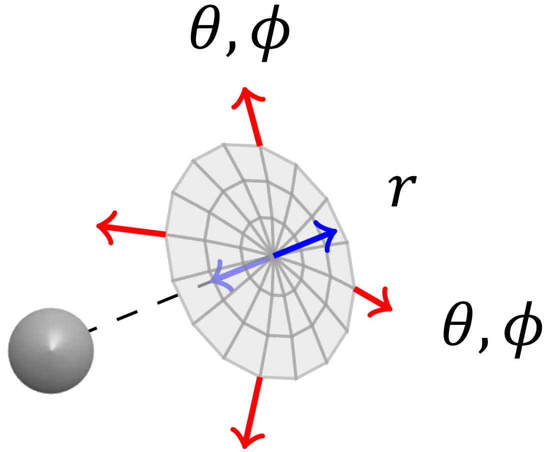


Interference b/w singlet and octet state



Stress distribution around Q





- ✓ Overlap : $r \lesssim \sqrt{2t}$
- ✓ Separation
- ✓ Around origin $\sim \alpha_s^2(r)/r^4$
- ✓ Damping $\sim e^{-m_D r}$
- ✓ Conservation law :

$$\partial_r(r^2 T_{rr}) = rT_{tt}$$