K_1/K^* Enhancement as a Signature of Chiral Symmetry Restoration in Heavy Ion Collisions

QCHSC2024

***Haesom Sung*, Che Ming Ko, Su Houng Lee**

H. Sung et al, Phys. Rev. C 109, 044911
arXiv:2310.11434 [nucl-th] (2023)

H. Sung et al, Phys. Lett B 819 (2019) 136388
arXiv:2102.11665 [nucl-th] (2021)

Aug 21th 2024

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  - Mass degeneracy of Chiral Partner
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  - K_1/K^* ratio in different centralities

Introduction

Chiral partner particles

	J^P	Γ (Decay width)		J^P	Γ (Decay width)
π	0^-		σ	0^+	(400-700) MeV
a_1	1^+	(250 - 600) MeV	ρ	1^-	149 MeV
K_1	1^+	90 MeV	K^*	1^-	47 MeV

$$\Gamma_{K_1}, \Gamma_{K^*} < 100 \text{ MeV}$$

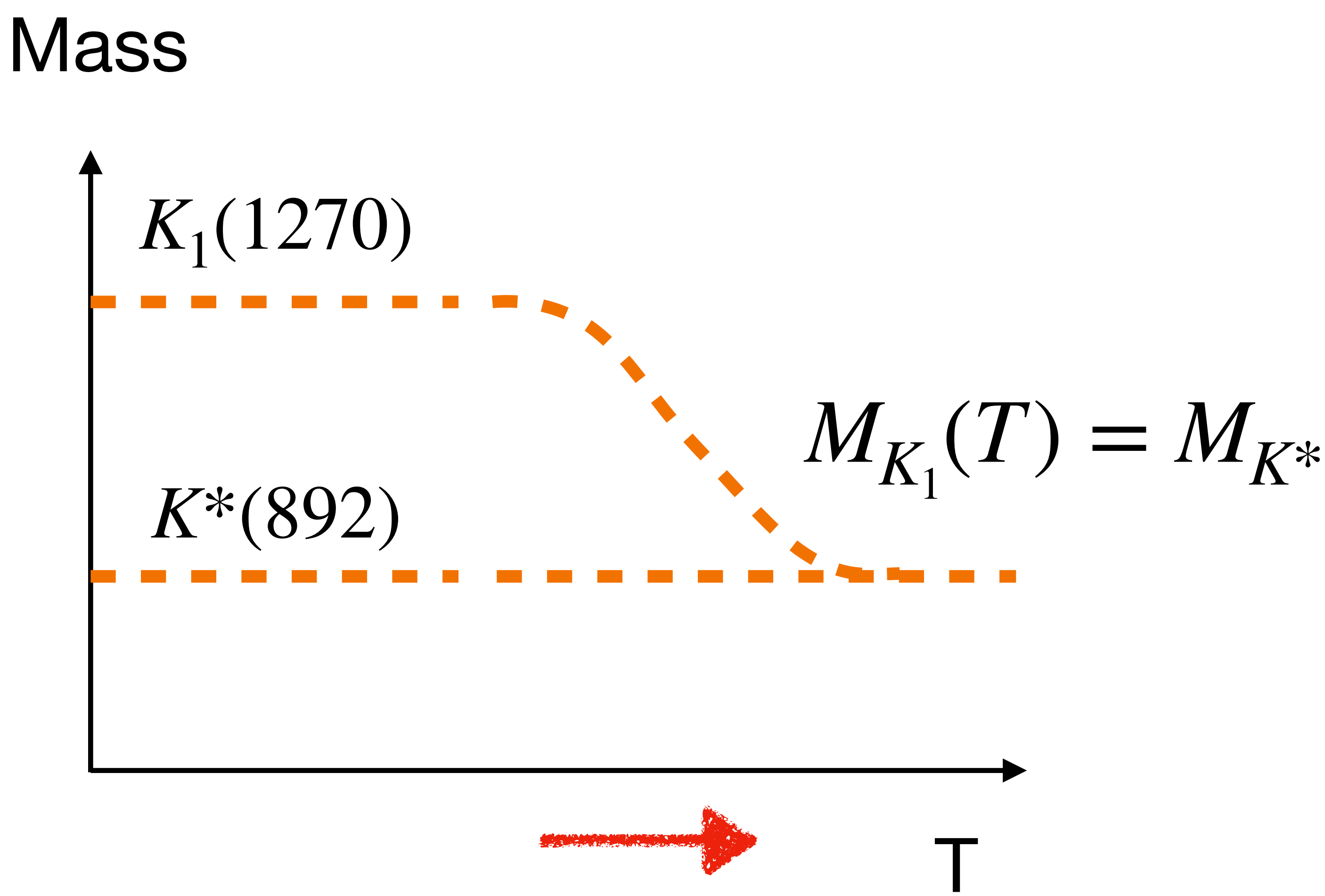
S. Weinberg, Phys. Rev. Lett. 18, 507 (1967)
T. Song, T. Hatsuda and S. H. Lee, Phys. Lett. B 792, 160-169 (2019)
J. Kim and S. H. Lee, Phys. Rev. D 103, no.5, L051501 (2021)

Introduction

Mass of chiral partner

Chiral order parameter

$< \bar{q}q > \neq 0$ → $< \bar{q}q > = 0$



Weinberg Sum Rule:

$$\Pi_A - \Pi_V \propto (m_A^2 - m_V^2)$$
$$\propto < \bar{q}q >$$

—> $M_A = M_V$

when chiral symmetry is restored

QCD Sum rule result:

—> Axial vector meson mass goes down to vector meson vacuum mass.

S. Weinberg, Phys. Rev. Lett. 18, 507 (1967)
T. Song, T. Hatsuda and S. H. Lee, Phys. Lett. B 792, 160-169 (2019)
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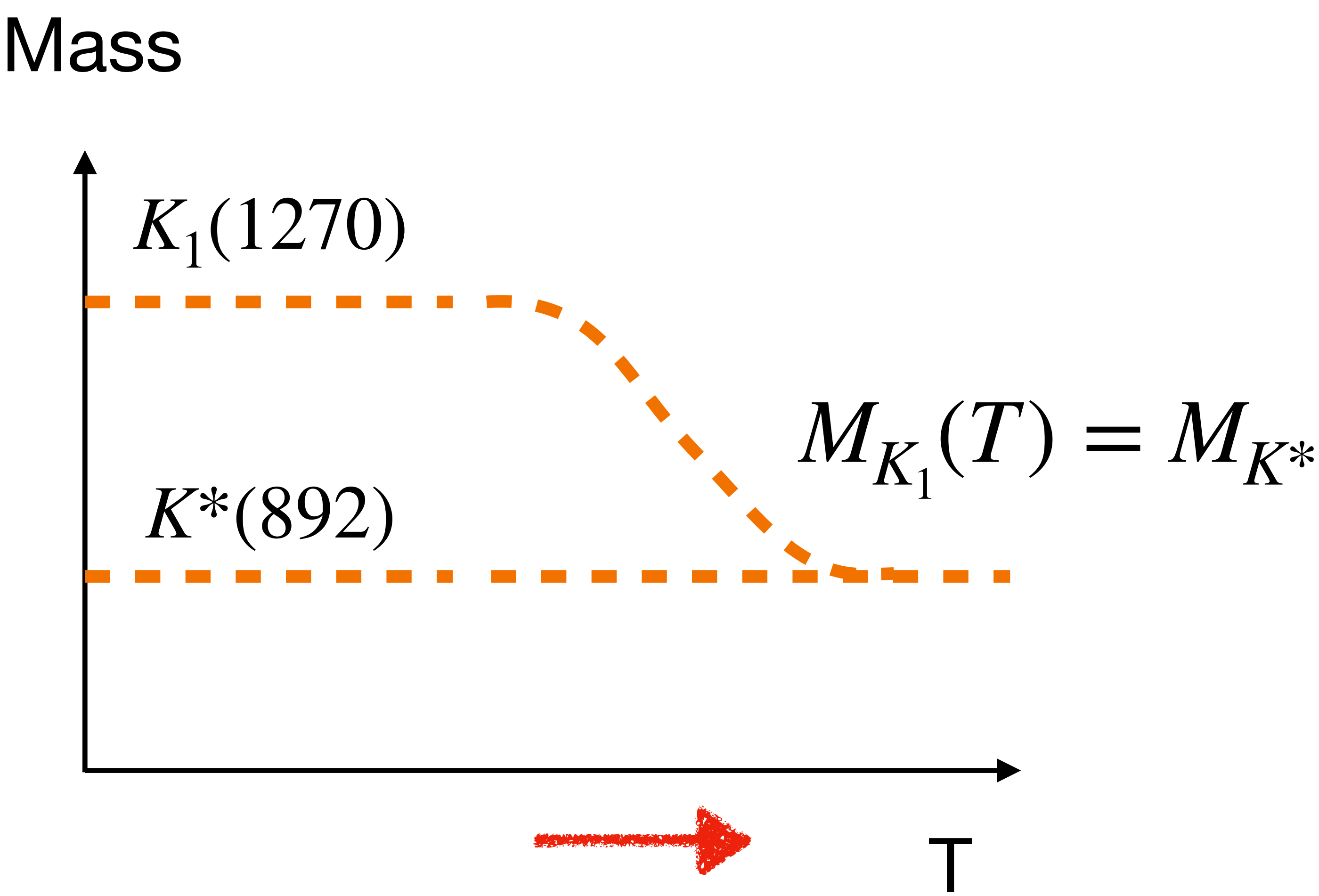
Introduction

Mass of chiral partner

Chiral order parameter

$< \bar{q}q > \neq 0$ → $< \bar{q}q > = 0$



Weinberg Sum Rule:

$$\Pi_A - \Pi_V \propto (m_A^2 - m_V^2)$$
$$\propto < \bar{q}q >$$

$$\text{—>} \; M_A = M_V$$

when chiral symmetry is restored

QCD Sum rule result:

—> Axial vector meson mass goes down to vector meson vacuum mass.

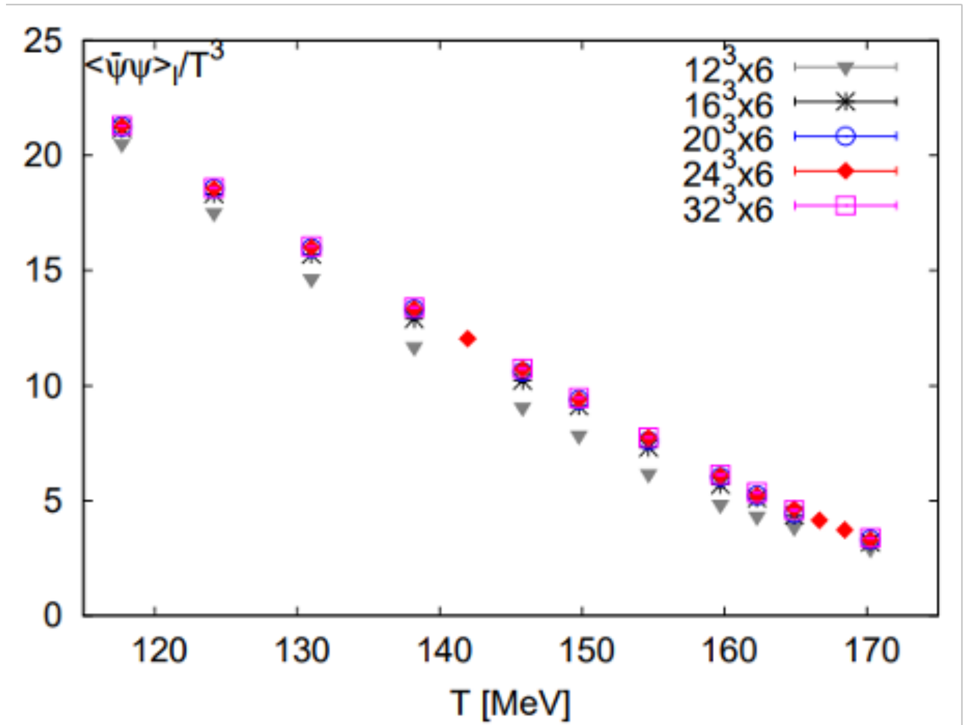
Introduction

Chemical & Critical temperature

$T_{critical} \simeq 156$ MeV $\simeq T_{chemical}$

Bazavov et al. [HotQCD], Phys. Lett. B 795, 15-21 (2019).

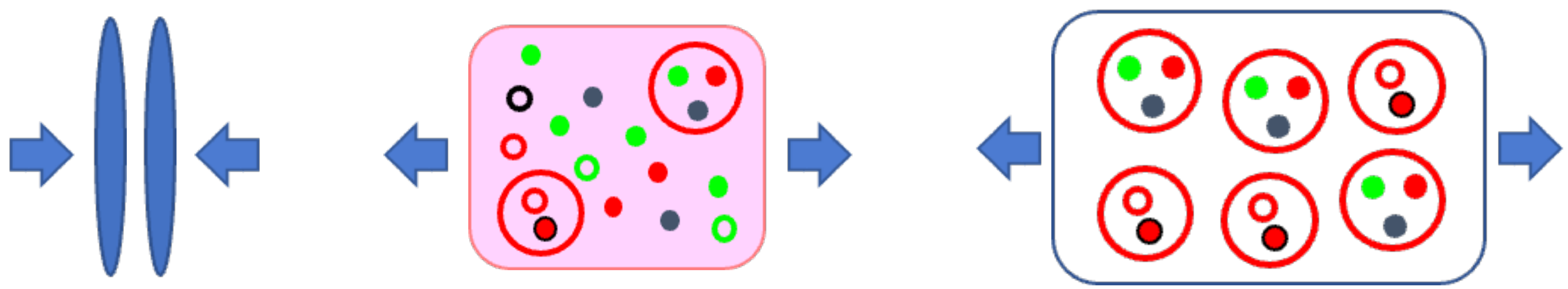
S. Borsanyi et al. [Wuppertal-Budapest], JHEP 09, 073 (2010)

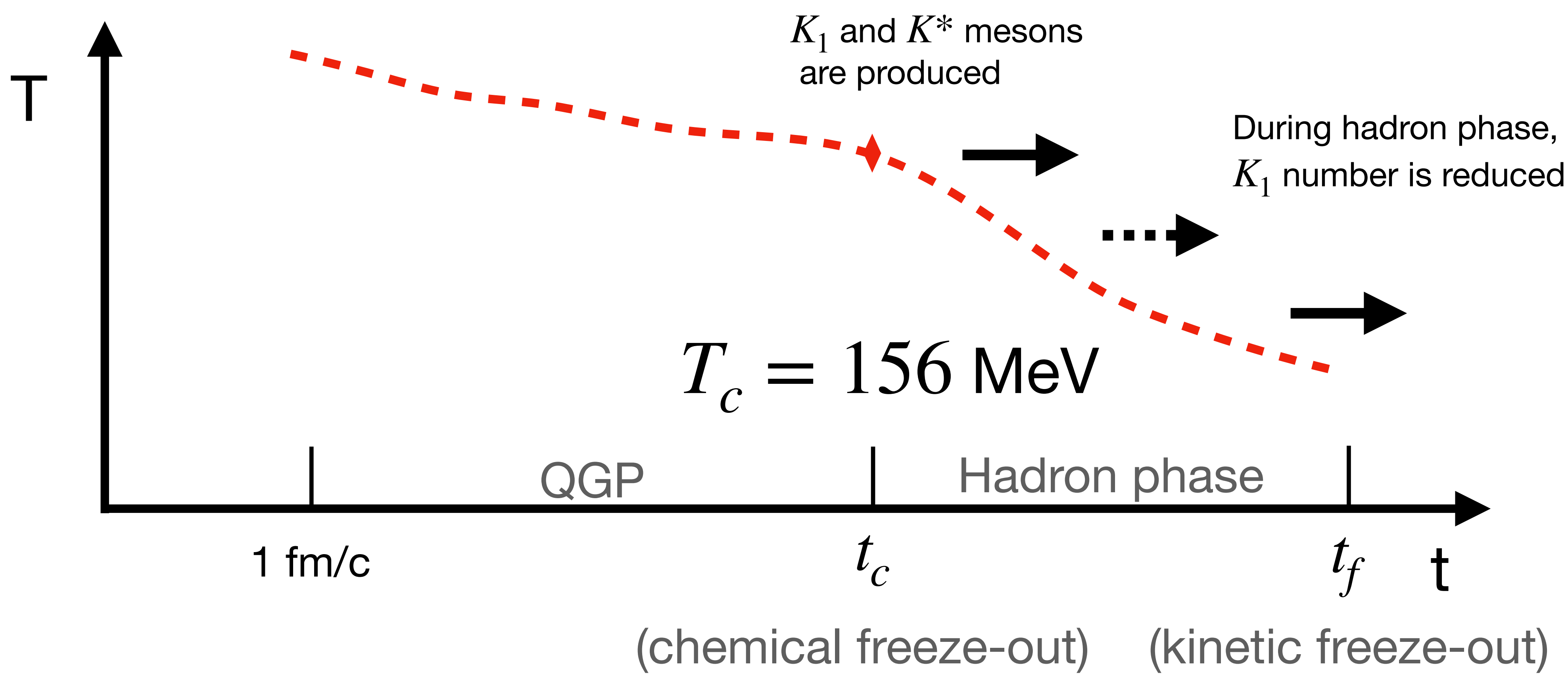


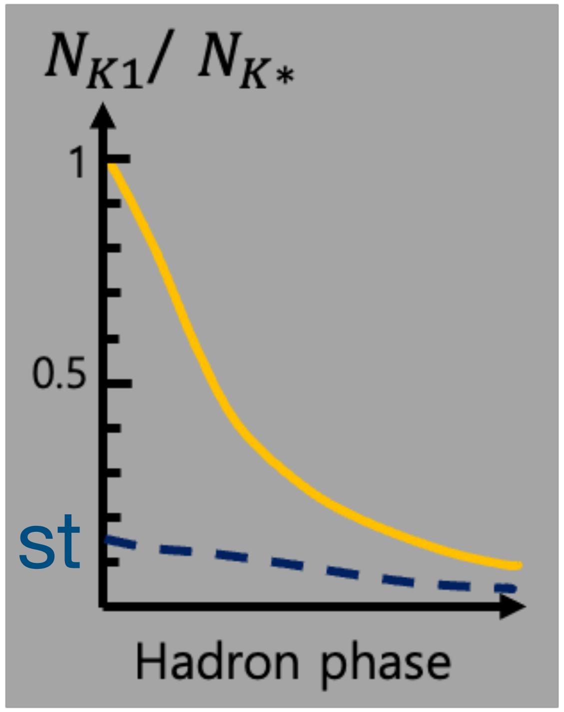
- $<\bar{q}q>$ (chiral order parameter) decreases substantially at $T_{critical}$
- $T_{critical}$ close to chemical freeze out temperature in statistical model
- N_{K_1} and N_{K*} are similar at initial hadronization temperature because their masses are degenerated at T_c

Introduction

In heavy ion collisions

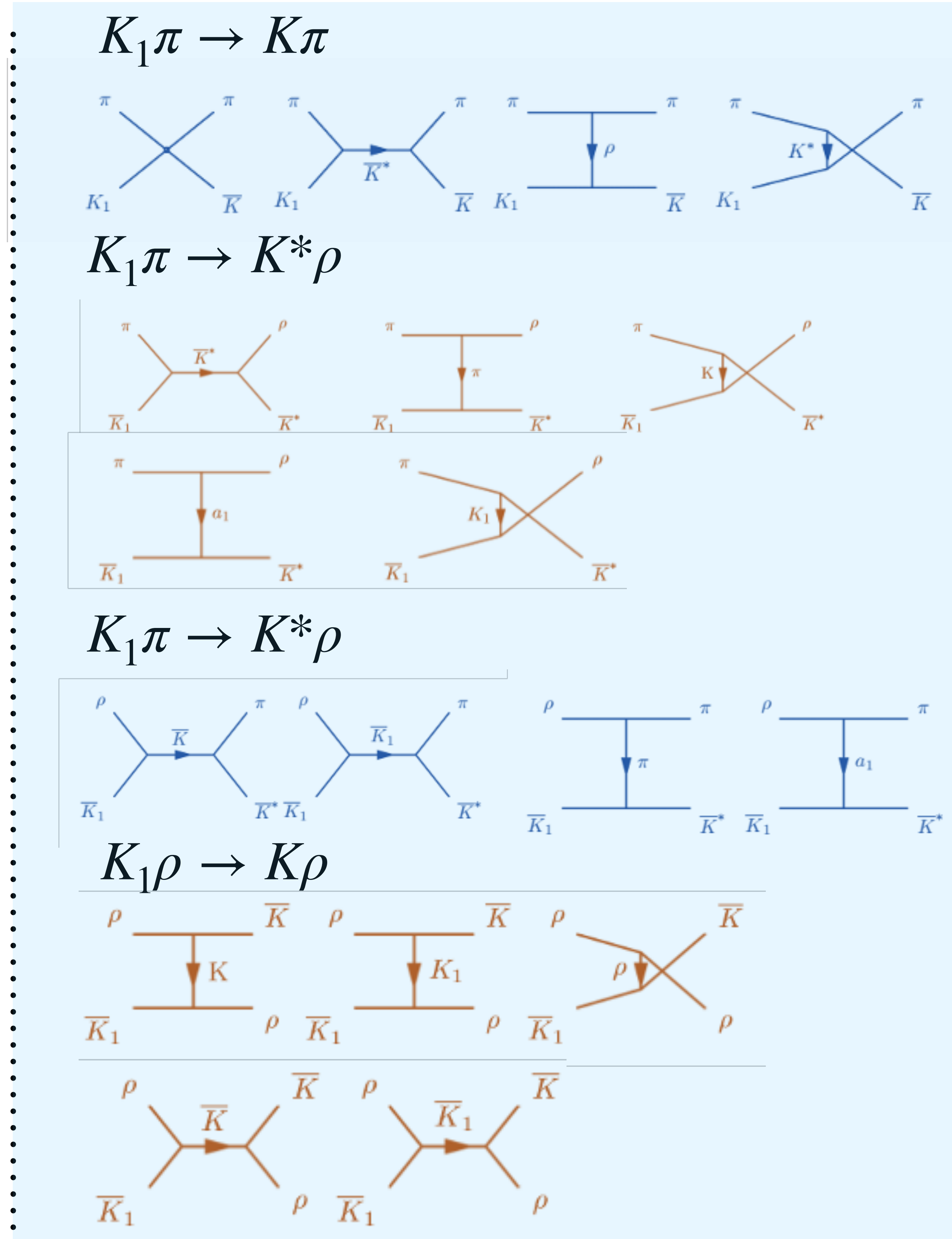






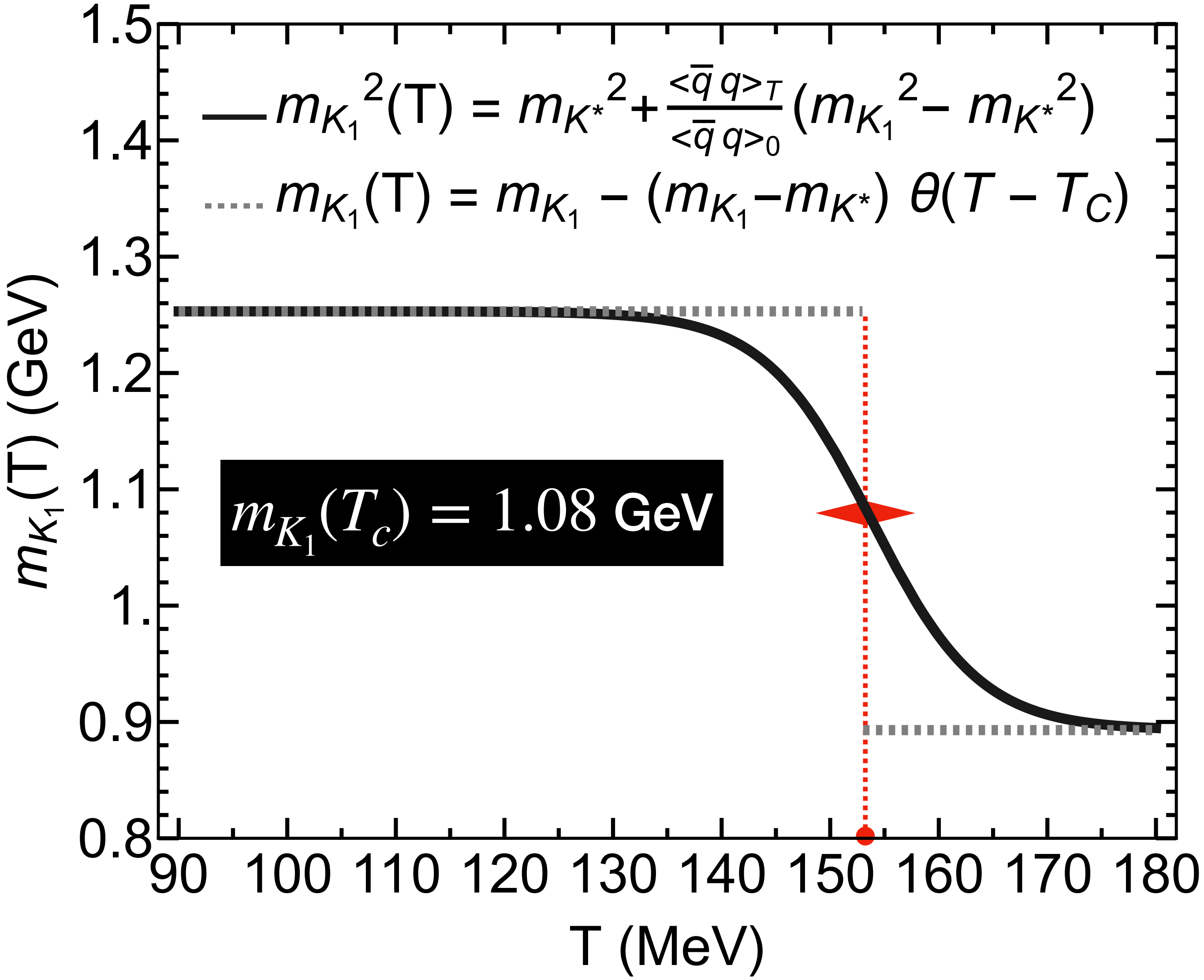
Cross Sections of K_1 scattering with π and ρ mesons

$$
\begin{aligned}
K_1 + \pi &\to K \quad + \pi \\
&\to K^* + \rho \\
K_1 + \rho &\to K^* + \pi \\
&\to K \quad + \rho
\end{aligned}
$$



K_1 Scattering Cross Sections

In-medium K_1 mass



$T_c = 156$ MeV

H. Sung et al, Phys. Lett B 819 (2019) 136388

- Previous work: phase transition immediately

$$m_{K_1}(t_c) = m_{K^*} = 892 \text{ MeV}$$

H. Sung et al, Phys. Rev. C 109 (2024), 044911

- Current work: phase transition smoothly

$$m^2_{K_1}(T) = m^2_{K^*} + \frac{\langle qq\rangle_0}{\langle qq\rangle_T}(m^2_{K_1} - m^2_{K^*})$$

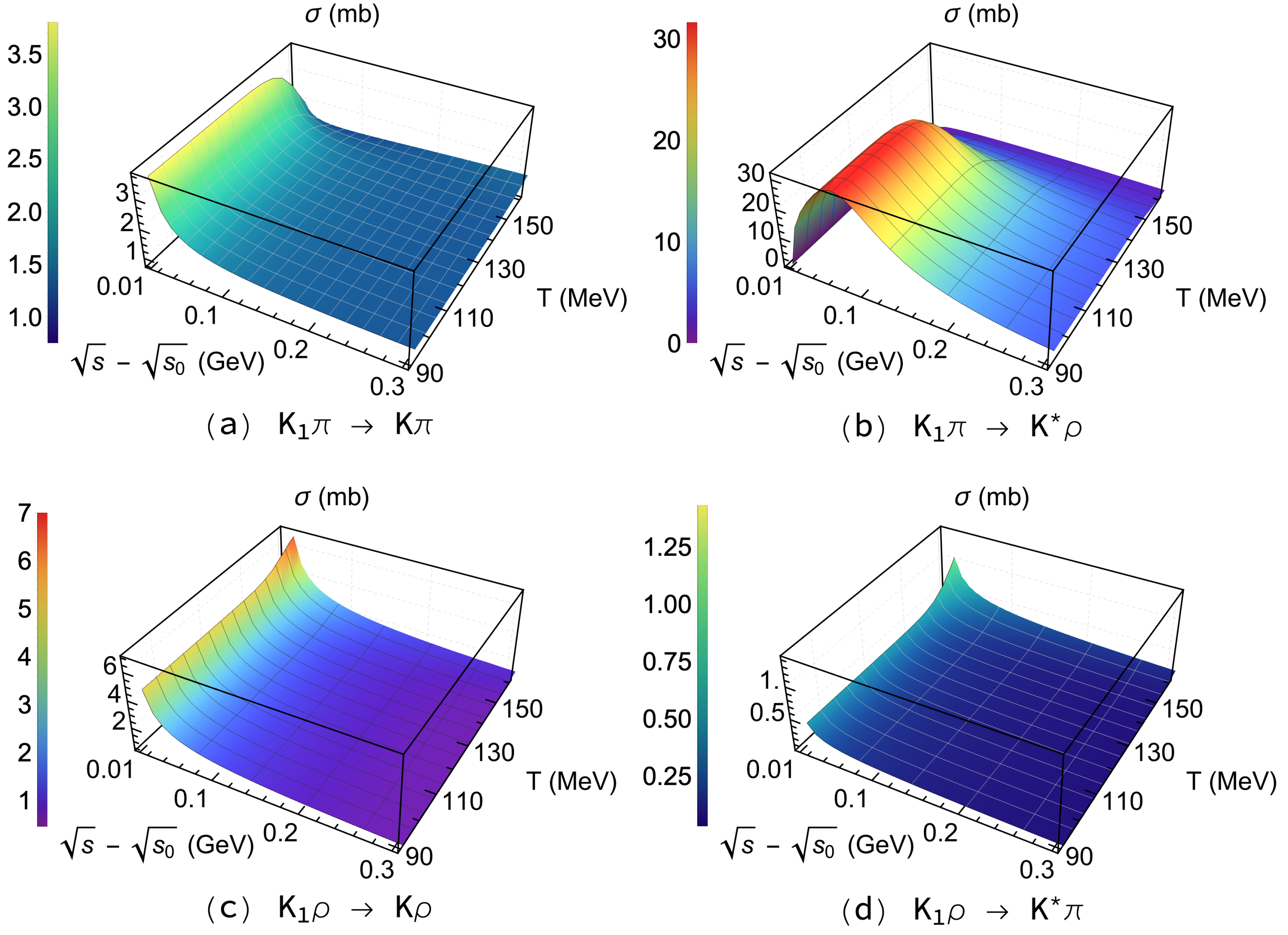
  - Weinberg relation for K_1 and K^* show that K_1 in-medium mass depends on the quark condensate.
    S. H. Lee, Symmetry 15, 799 (2023), arXiv:2303.14415 [hep-ph]

$$m_{K_1}(t_c) = 1.08 \text{ GeV}$$

K_1 Scattering Cross Sections

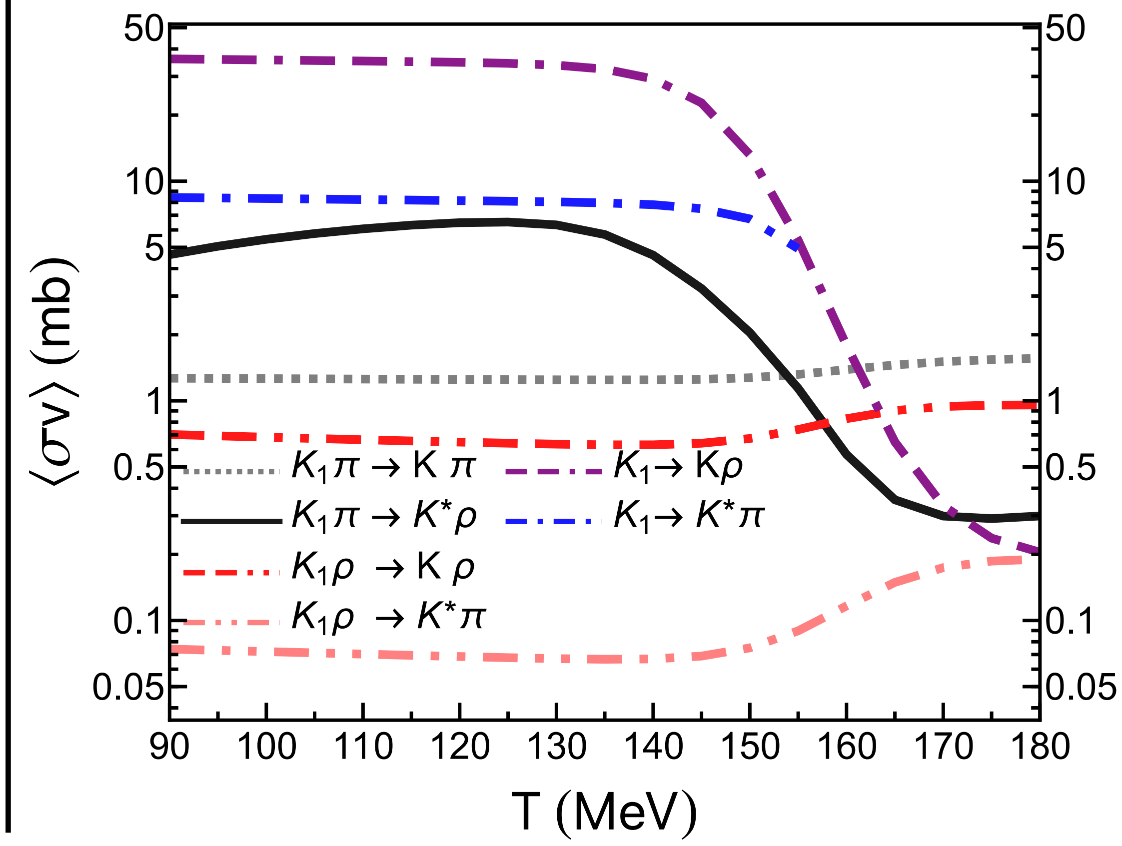
In-medium K_1 mass $$m^2_{K_1}(T) = m^2_{K^*} + \frac{\langle qq\rangle_0}{\langle qq\rangle_T}(m^2_{K_1} - m^2_{K^*})$$

T dependence of K_1 cross sections



Thermal averaged cross sections

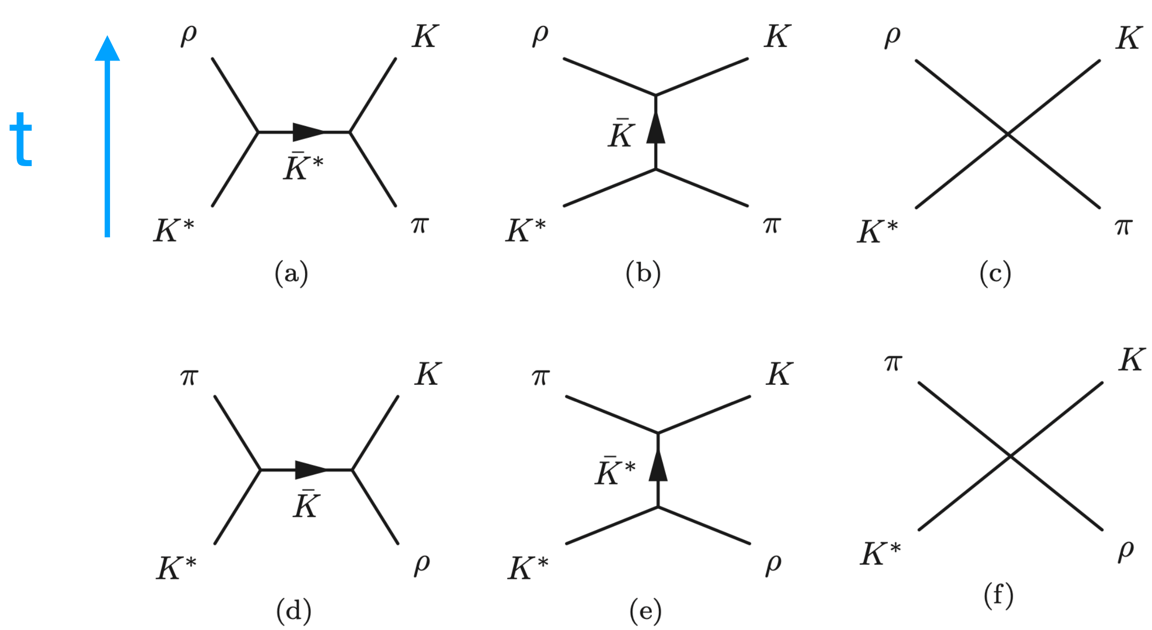
$$\langle \sigma_{ab\to cd} v_{ab}\rangle = \frac{\int d^3\mathbf{p}_a d^3\mathbf{p}_b f_a(\mathbf{p}_a) f_b(\mathbf{p}_b)\sigma_{ab\to cd} v_{ab}}{\int d^3\mathbf{p}_a d^3\mathbf{p}_b f_a(\mathbf{p}_a) f_b(\mathbf{p}_b)}$$

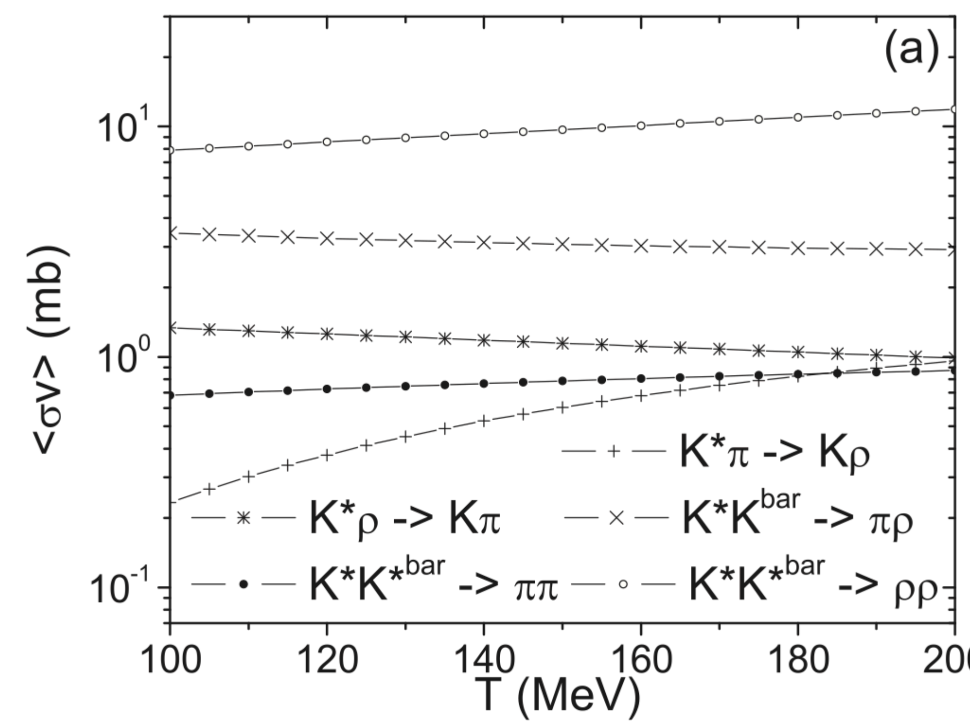


K^* Scattering Cross Sections

S. Cho and S. H. Lee Phys. Rev. C **97**, 034908 (2018)

$$K^* + \pi \rightarrow K + \rho$$
$$K^* + \rho \rightarrow K + \pi$$





Fugacity

Constant S/A and effective particle numbers

Jun Xu, Che Ming Ko, Physics Letters B 772 (2017) 290–293

- $S/A, \pi^{eff}, K^{eff}, N^{eff} \to V, Z_\pi, Z_K, Z_N$

$$S(T)/A(T) = S(T_c)/A(T_c),$$

$$N^{eff}_{\pi,k,n}(T) = N^{eff}_{\pi,k,n}(T_c),$$

where S is total entropy and A is total particle number.

- Effective numbers

$$n_\pi^{\rm eff}(T) = z_\pi n_\pi^T + z_\pi^2 n_\rho^T + z_\pi z_K n_{K*}^T + z_\pi^2 z_K n_{K_1}^T + z_\pi z_N n_\Delta^T + \cdots,$$

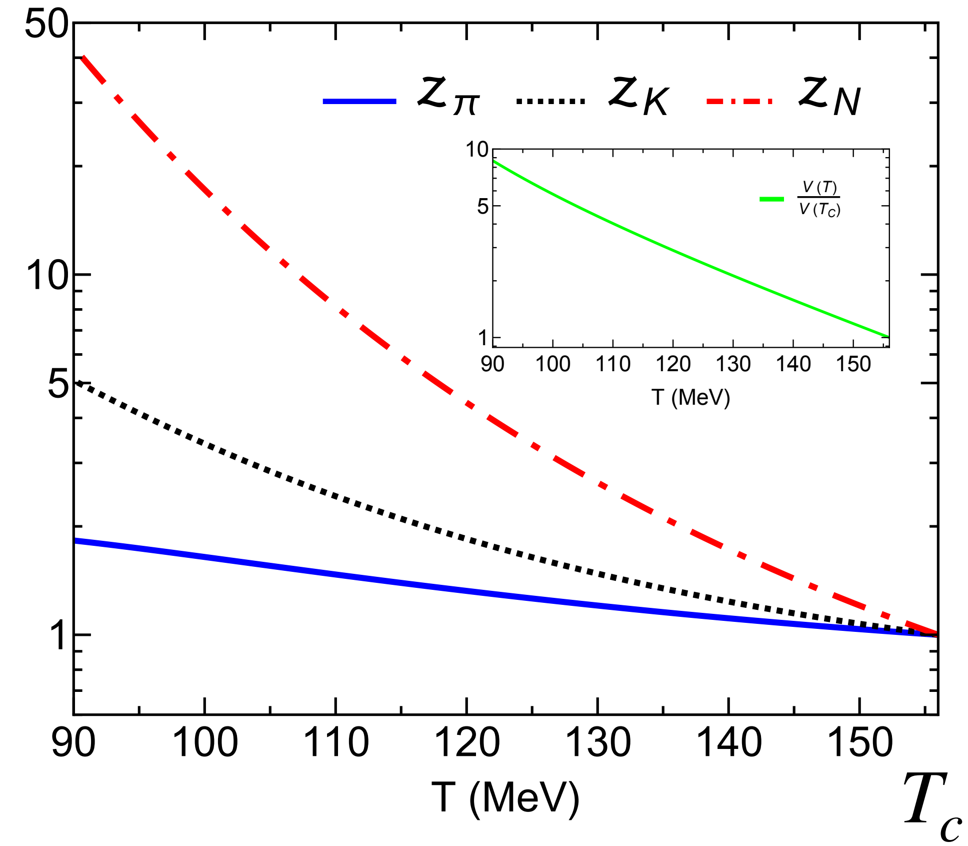
$$n_K^{\rm eff}(T) = z_K n_K^T + z_\pi z_K n_{K*}^T + z_\pi^2 z_K n_{K_1}^T + z_K^2 n_\phi^T + \cdots,$$

$$n_N^{\rm eff}(T) = z_N n_N^T + z_\pi z_N n_\Delta^T + \cdots .$$

- Particle and entropy

$$\rho = \sum_i g_i \int \frac{d^3\mathbf{p}}{(2\pi)^3} z_i f_i(\mathbf{p})$$

$$s = -\sum_i g_i \int \frac{d^3\mathbf{p}}{(2\pi)^3} (z_i f_i)\ln(z_i f_i)$$



Kinetic Equations

K_1 and K^* numbers during hadron evolution

$$\frac{dN_{K_1}}{dt} = \gamma_{K_1,K_1} N_{K_1} + \gamma_{K_1,K^*} N_{K^*} + \gamma_{K_1,K} N_K,$$

where

$$\gamma_{K_1,K_1} = -(\langle \sigma_{K_1\pi\to K\pi}\rangle + \langle \sigma_{K_1\pi\to K^*\rho} v\rangle) z_\pi n_\pi^T - (\langle \sigma_{K_1\rho\to K^*\pi} v\rangle + \langle \sigma_{K_1\rho\to K\rho} v\rangle) z_\pi^2 n_\rho^T - \langle \Gamma_{K_1\to K^*\pi}\rangle - \langle \Gamma_{K_1\to K\rho}\rangle,$$

$$\gamma_{K_1,K^*} = (\langle \sigma_{K_1\pi\to K^*\rho} v\rangle n_\pi^T + \langle \sigma_{K_1\rho\to K^*\pi} v\rangle z_\pi n_\rho^T) \frac{z_\pi^2 n_{K_1}^T}{n_{K^*}^T} + \langle \Gamma_{K_1\to K^*\pi}\rangle \frac{z_\pi n_{K_1}^T}{n_{K^*}^T},$$

$$\gamma_{K_1,K} = (\langle \sigma_{K_1\pi\to K\pi} v\rangle n_\pi^T + \langle \sigma_{K_1\rho\to K\rho} v\rangle z_\pi n_\rho^T) \frac{z_\pi^2 n_{K_1}^T}{n_K^T} + \langle \Gamma_{K_1\to K\rho}\rangle \frac{z_\pi n_{K_1}^T}{n_K^T},$$

$$n_i^T = g_i \int \frac{d^3p}{(2\pi)^3} f_i(p)$$

* Light mesons are determined from thermal distribution

* K_1 regeneration processes are determined from the detailed balance relation

$$N_0 = N_{K_1} + N_{K^*} + N_K$$

Kinetic Equations

K_1 and K^* numbers during hadron evolution

$$\frac{dN_{K_1}}{dt} = \gamma_{K_1,K_1} N_{K_1} + \gamma_{K_1,K^*} N_{K^*} + \gamma_{K_1,K} N_K,$$

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Time Dependent Temperature

H.Sung, S. Cho, J. Hong, S. H. Lee, S. Lim and T. Song
arXiv:2102.11665 [nucl-th] (2021)

$$T(\tau) = T_c - (T_c - T_f)\left(\frac{\tau - \tau_c}{\tau_f - \tau_c}\right)^\alpha$$

LHC(Pb-Pb) $\sqrt{s_{NN}} = 5.02$ TeV

Tc = 156MeV	tc (fm/c)	tf (fm/c)	α
0- 5%	8.7	28.1	0.835
40 – 50%	4.9	13	0.9
70 – 80%	2.2	2.9	0.847

$$N_0 = N_{K_1} + N_{K^*} + N_K$$

Kinetic Equations

K* <-> K Cross section

S. Cho and S. H. Lee Phys. Rev. C **97**, 034908 (2018)

K_1 and K^* numbers during hadron evolution

$$\frac{dN_{K_1}}{dt} = \gamma_{K_1,K_1} N_{K_1} + \gamma_{K_1,K^*} N_{K^*} + \gamma_{K_1,K} N_K,$$

where

$$\gamma_{K_1,K_1} = -(\langle\sigma_{K_1\pi\to K\pi}\rangle + \langle\sigma_{K_1\pi\to K^*\rho}v\rangle) z_\pi n_\pi^T - (\langle\sigma_{K_1\rho\to K^*\pi}v\rangle + \langle\sigma_{K_1\rho\to K\rho}v\rangle) z_\pi^2 n_\rho^T - \langle\Gamma_{K_1\to K^*\pi}\rangle - \langle\Gamma_{K_1\to K\rho}\rangle,$$

$$\gamma_{K_1,K^*} = (\langle\sigma_{K_1\pi\to K^*\rho}v\rangle n_\pi^T + \langle\sigma_{K_1\rho\to K^*\pi}v\rangle z_\pi n_\rho^T)\frac{z_\pi^2 n_{K_1}^T}{n_{K^*}^T} + \langle\Gamma_{K_1\to K^*\pi}\rangle \frac{z_\pi n_{K_1}^T}{n_{K^*}^T},$$

$$\gamma_{K_1,K} = (\langle\sigma_{K_1\pi\to K\pi}v\rangle n_\pi^T + \langle\sigma_{K_1\rho\to K\rho}v\rangle z_\pi n_\rho^T)\frac{z_\pi^2 n_{K_1}^T}{n_K^T} + \langle\Gamma_{K_1\to K\rho}\rangle \frac{z_\pi n_{K_1}^T}{n_K^T},$$

$$\frac{dN_{K^*}}{dt} = \gamma_{K^*,K_1} N_{K_1} + \gamma_{K^*,K^*} N_{K^*} + \gamma_{K^*,K} N_K,$$

where

$$\gamma_{K^*,K_1} = \langle\sigma_{K_1\pi\to K^*\rho}v\rangle z_\pi n_\pi^T + \langle\sigma_{K_1\rho\to K^*\pi}v\rangle z_\pi^2 n_\rho^T + \langle\Gamma_{K_1\to K^*\pi}\rangle,$$

$$\gamma_{K^*,K^*} = -\langle\sigma_{K^*\pi\to K\rho}v\rangle z_\pi n_\pi^T - \langle\sigma_{K^*\rho\to K\pi}v\rangle z_\pi^2 n_\rho^T - (\langle\sigma_{K_1\pi\to K^*\rho}v\rangle n_\pi^T + \langle\sigma_{K_1\rho\to K^*\pi}v\rangle z_\pi n_\rho^T)\frac{z_\pi^2 n_{K_1}^T}{n_{K^*}^T} - \langle\Gamma_{K^*\to K\pi}\rangle - \langle\Gamma_{K_1\to K^*\pi}\rangle \frac{z_\pi n_{K_1}^T}{n_{K^*}^T},$$

$$\gamma_{K^*,K} = (\langle\sigma_{K^*\pi\to K\rho}v\rangle n_\pi^T + \langle\sigma_{K^*\rho\to K\pi}v\rangle z_\pi n_\rho^T)\frac{z_\pi^2 n_{K^*}^T}{n_K^T} + \langle\Gamma_{K^*\to K\pi}\rangle \frac{z_\pi n_{K^*}^T}{n_K^T}.$$

$$N_0 = N_{K_1} + N_{K^*} + N_K$$

Kinetic Equation

Kinetic freeze-out temperature

S. Acharya et al. [ALICE], Phys. Rev. C 101, no.4, 044907 (2020).[arXiv:1910.07678v2]

Production of charged pions, kaons and (anti-)protons in Pb − Pb and inelastic pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE Collaboration*

Centrality	$\langle dN_{ch}/d\eta \rangle$	$\langle \beta_T \rangle$	T_{kin} (GeV)	n
0–5%	1943 ± 56	(1.018)0.663 ± 0.003	(0.947)0.090 ± 0.003	(1.032)0.735 ± 0.013
5–10%	1587 ± 47	(1.022)0.660 ± 0.003	(0.938)0.091 ± 0.003	(1.005)0.736 ± 0.013
10–20%	1180 ± 31	(1.025)0.655 ± 0.003	(0.949)0.094 ± 0.003	(1.001)0.739 ±0.013
20–30%	786 ± 20	(1.029)0.643 ± 0.003	(0.960)0.097 ± 0.003	(0.990)0.771 ±0.014
30–40%	512 ± 15	(1.030)0.622 ± 0.003	(0.953)0.101 ± 0.003	(0.985)0.828 ±0.015
40–50%	318 ± 12	(1.037)0.595 ± 0.004	(0.964)0.108 ± 0.003	(0.962)0.908 ±0.019
50–60%	183 ± 8	(1.041)0.557 ± 0.005	(0.975)0.115 ± 0.003	(0.957)1.052 ± 0.024
60–70%	96.3 ± 5.8	(1.035)0.506 ± 0.008	(1.000)0.129 ± 0.005	(0.977)1.262 ± 0.043
70–80%	44.9 ± 3.4	(0.993)0.435 ± 0.011	(1.058)0.147 ± 0.006	(1.063)1.678 ± 0.088
80–90%	17.5 ± 1.8	(0.994)0.355 ± 0.016	(1.066)0.161 ± 0.006	(1.071)2.423 ± 0.208

The system has a shorter hadronic lifetime in more peripheral collisions

S. Cho, et al., Phys. Rev. C 97, no. 2, 024911 (2018). [arXiv:1511.08019]

0-5% : T_{kin} = 90 MeV

40-50% : T_{kin} = 108 MeV

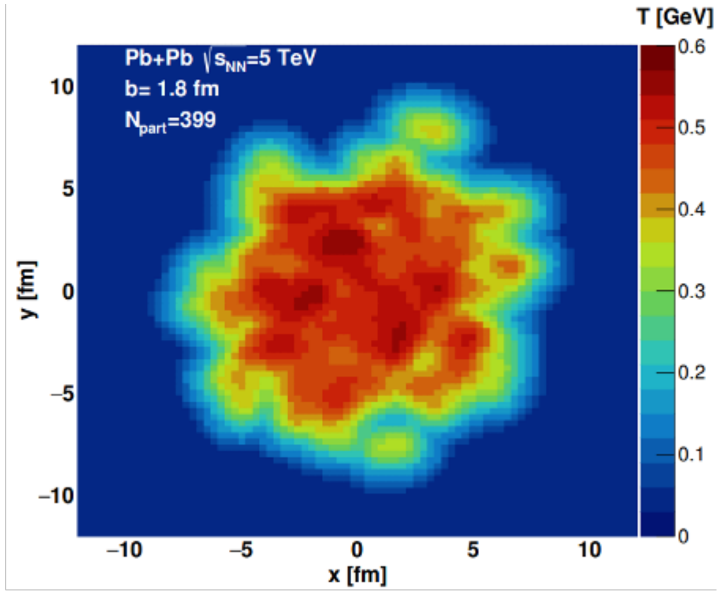
70-80% : T_{kin} = 147 MeV

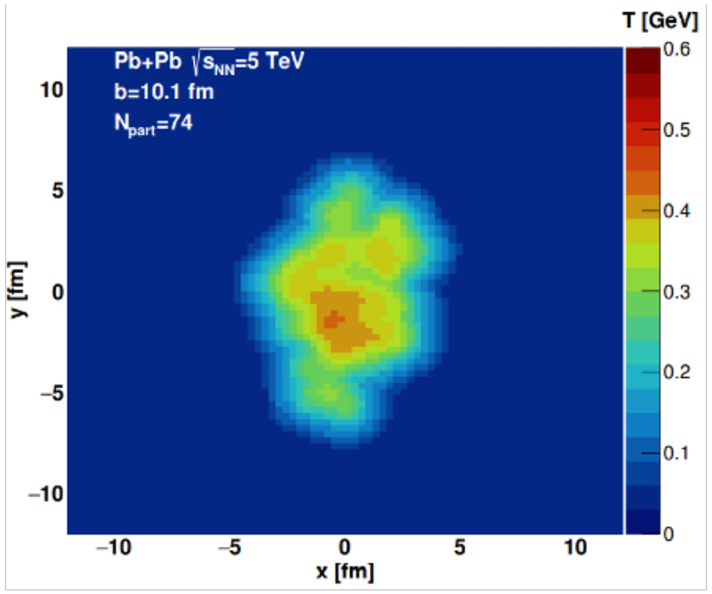
Kinetic Equation

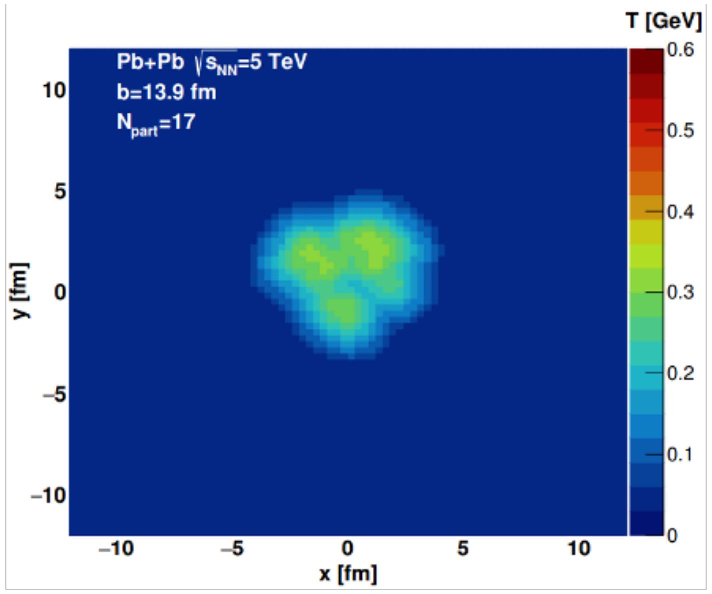
Kinetic freeze-out temperature

H. Sung et al, Phys. Lett B 819 (2019) 136388

0-5% 40-50% 70-80%







The fraction of the volume where initial temperature higher than **156 MeV** is larger than 98% in all three centrality ranges.

Result

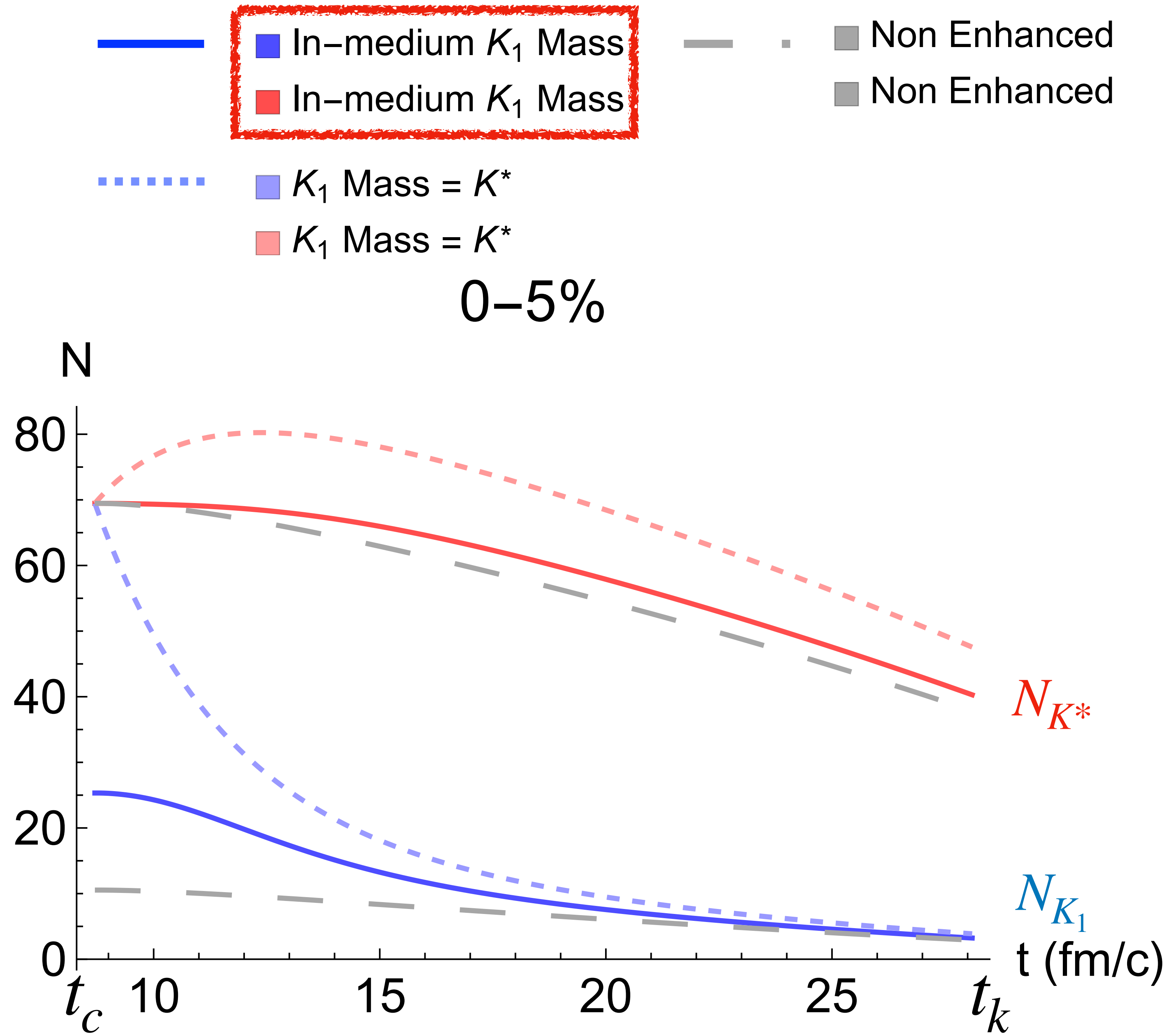
At chemical freeze-out time

Previous work: dotted lines

$m_{K_1}(t_c) = m_{K^*} = 892$ MeV

Current work: solid lines

$m_{K_1}(t_c) = 1.08$ GeV

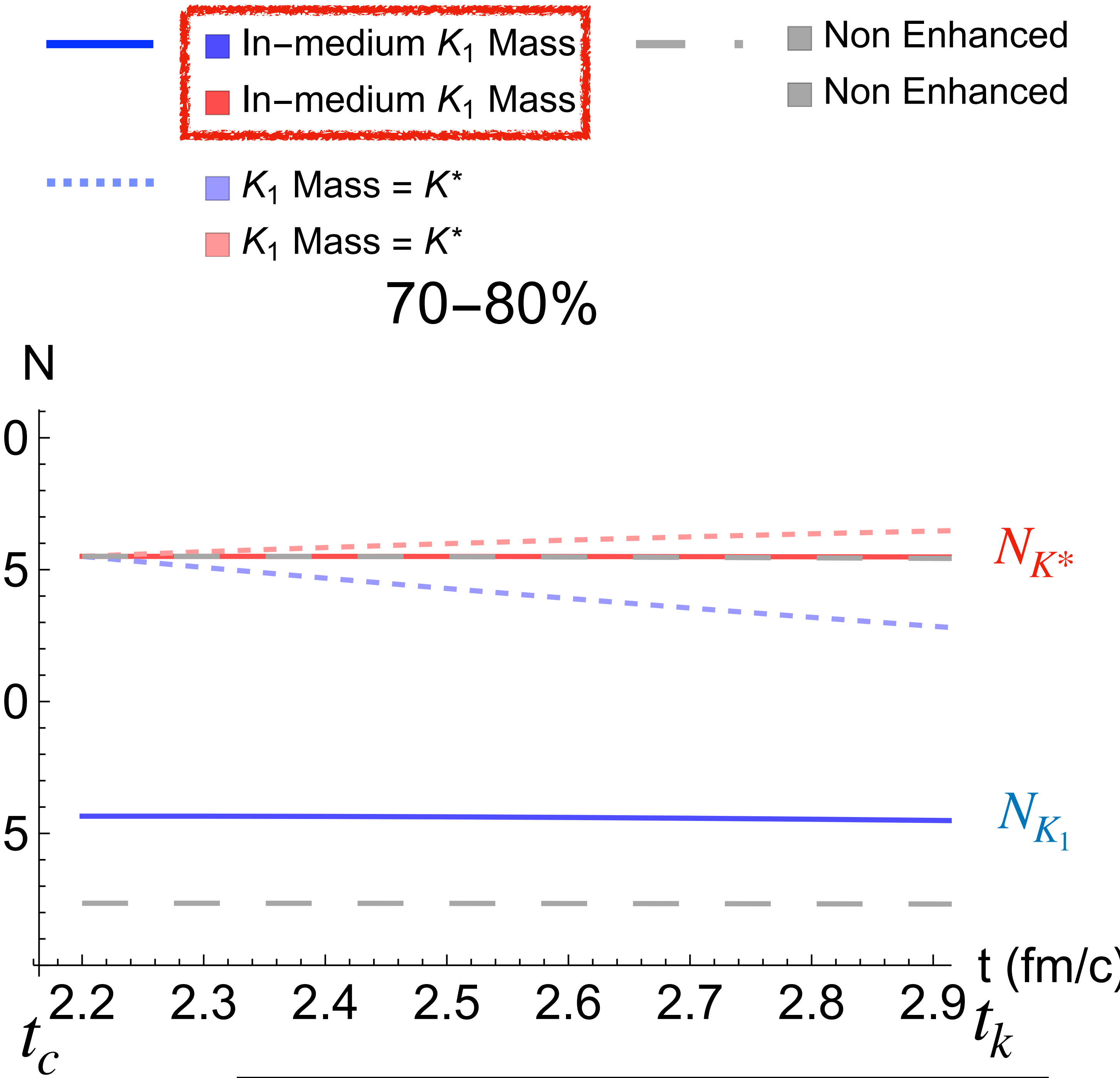


$T_c = 156\,MeV$	t_c (fm/c)	t_k (fm/c)
0- 5%	8.7	28.1
40 – 50%	4.9	13
70 – 80%	2.2	2.9

~ 20 (fm/c)

LHC(Pb+Pb) 5.02 TeV at t_k			
Centrality	0-5 %	40-50	70-80
N_{K^*}	40	8.9	1.5
N_{K_1}	3.2	1.4	0.55
Ratio	0.08	0.15	0.35

Result



At chemical freeze-out time

Previous work: dotted lines

$$m_{K_1}(t_c) = m_{K^*} = 892 \text{ MeV}$$

Current work: solid lines

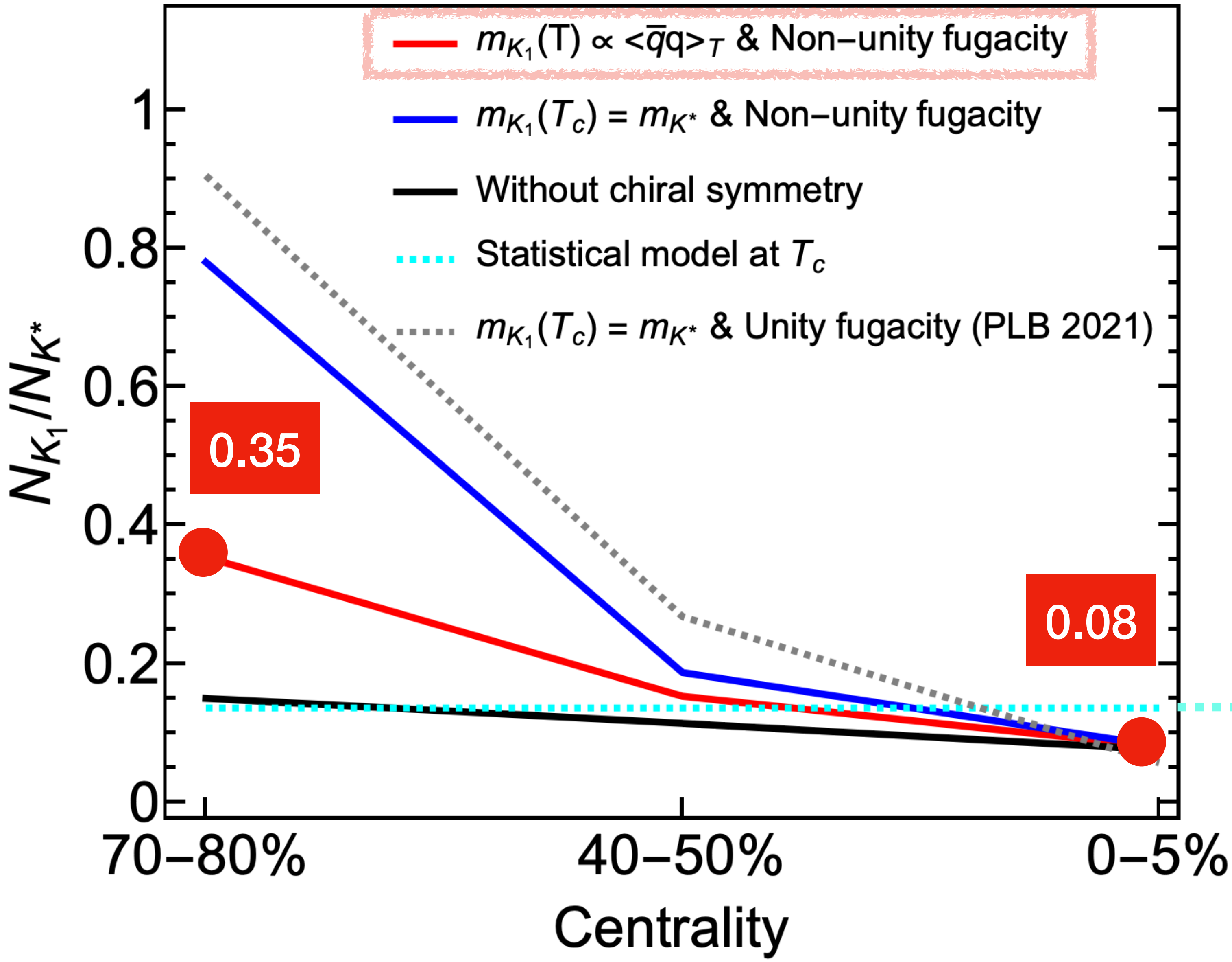
$$m_{K_1}(t_c) = 1.08 \text{ GeV}$$

$T_c = 156\,MeV$	t_c (fm/c)	t_k (fm/c)
0- 5%	8.7	28.1
40 – 50%	4.9	13
70 – 80%	2.2	2.9

< 1 (fm/c)

LHC(Pb+Pb) 5.02 TeV at t_k			
Centrality	0-5 %	40-50	70-80
N_{K^*}	40	8.9	1.5
N_{K_1}	3.2	1.4	0.55
Ratio	0.08	0.15	0.35

Result



H. Sung et al, Phys. Rev. C 109, 044911
arXiv:2310.11434 [nucl-th] (2023)

H. Sung et al, Phys. Lett B 819 (2019) 136388
arXiv:2102.11665 [nucl-th] (2021)

* At (70-80%) centrality

2.5 times greater than statistical model prediction

statistical model: 0.14

LHC(Pb+Pb) 5.02 TeV at t_k			
Centrality	0-5 %	40-50	70-80
N_{K*}	40	8.9	1.5
N_{K_1}	3.2	1.4	0.55
Ratio	0.08	0.15	0.35

Summary

- As centrality decreases, the evidence of K_1 enhancement becomes more prominent.

- K_1 production is about 2.5 times greater than the statistical model prediction in Pb+Pb collisions (70-80%) at $\sqrt{s_{NN}} = 5.02$ TeV.

- Chiral symmetry restoration in heavy-ion collision can be seen from the K_1/K^* ratio.

$$K^{*-} \to \begin{cases} \pi^0 K^- \\ \pi^- \bar{K}^0 \end{cases} , \quad \bar{K}^{*0} \to \begin{cases} \pi^+ K^- \\ \pi^0 \bar{K}^0 \end{cases}$$

$$K_1^- \to \begin{cases} \rho^0 K^- \\ \rho^- \bar{K}^0 \\ \pi^0 K^{*-} \\ \pi^- \bar{K}^{*0} \end{cases} , \quad \bar{K}_1^0 \to \begin{cases} \rho^+ K^- \\ \rho^0 \bar{K}^0 \\ \pi^+ K^{*-} \\ \pi^0 \bar{K}^{*0} \end{cases}$$

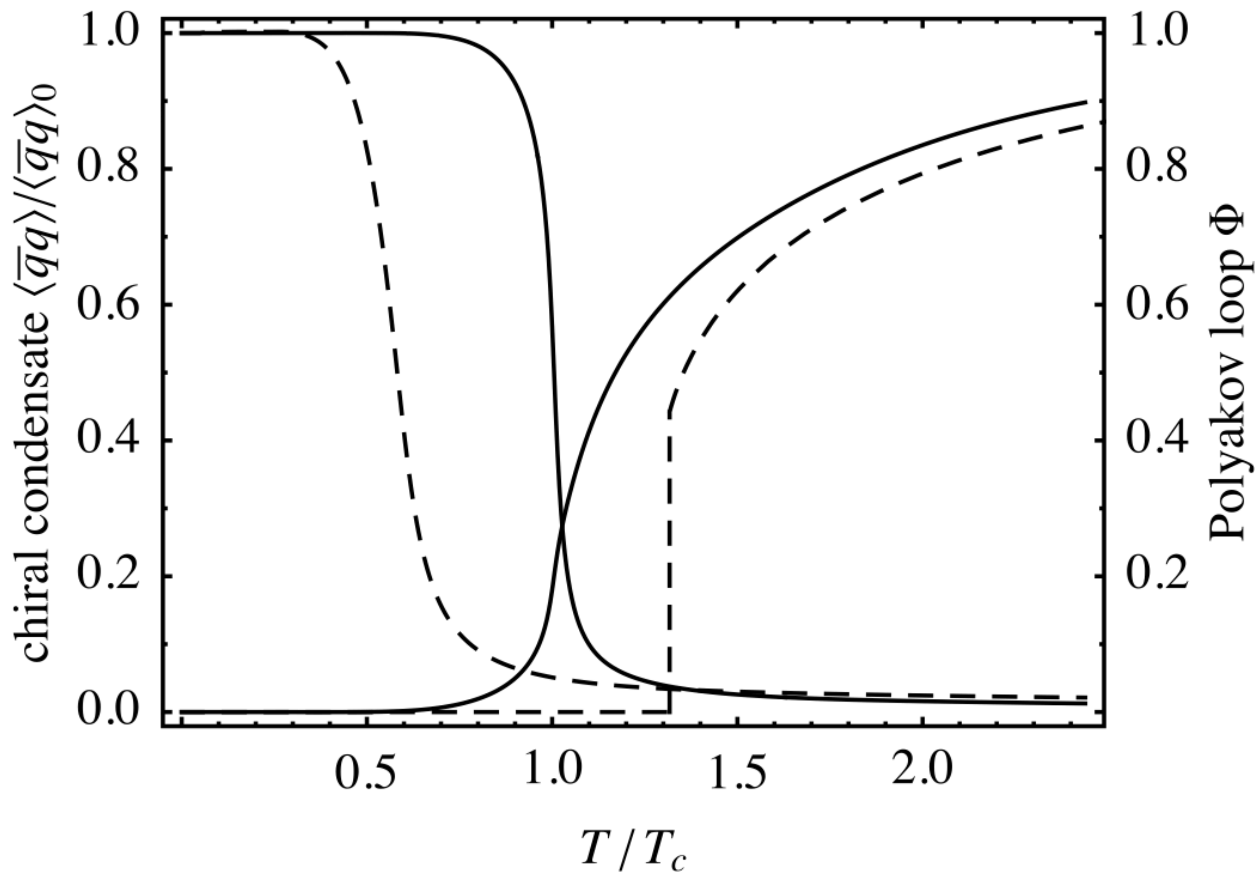
Back up

Quark Condensate

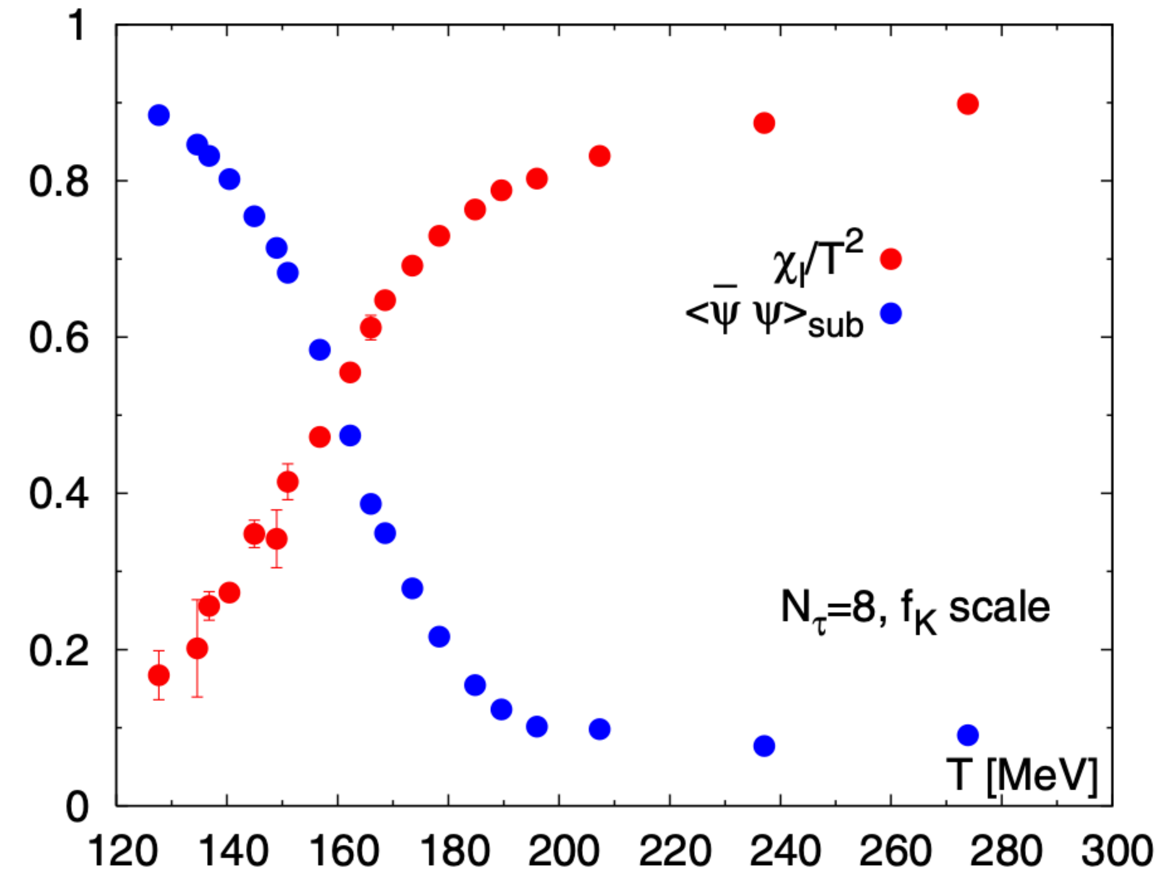
Lattice-QCD result

HotQCD

W. Weise / Progress in Particle and Nuclear Physics 67 (2012) 299–311



P Petreczky 2012 *J. Phys. G: Nucl. Part. Phys.* **39** 093002



$$m^2_{K_1}(T) = m^2_{K*} + \frac{\langle qq \rangle_0}{\langle qq \rangle_T}(m^2_{K_1} - m^2_{K*})$$

$m_{K_1}(t_c) = 1.08$ GeV

$m_{K_1}(t_c) = 1.12$ GeV

K_1/K^*=0.35 (70-80%)

K_1/K^*=0.3 (70-80%)