Chiral Phase Transition in Lattice Quantum Chromodynamics

Signatures of Chiral Symmetry Restoration

Adel Bensaoula

Supervisor: Dr. Rene Bellwied

Department of Physics
University of Houston

June 2024

Motivation

- Understanding strongly interacting matter at extreme conditions (High-T and High-μ_B) is crucial for mastery over QCD at all regimes.
- Validating theoretical models that describe QCD at high energies.
- Chiral Symmetry Restoration $\rightarrow$ Experimental confirmation of the **Quark-Gluon Plasma**.

Overview

1. Introduction

Quantum Chromodynamics (QCD)

Going over the fundamentals (*Again...*)

- Quantum Chromodynamics (QCD) is the theory of strongly interacting matter.
- Describes the binding of **Quarks** mediated by **Gluons** into bound states $\rightarrow$ **Hadrons** which come in $q\bar{q}$ (Mesons) or qqq (Baryons[1]) states.
- Color Charge (QCD) $\xleftrightarrow{\text{analogous}}$ Electric Charge (QED). However;
  - Three **color** charges instead of one!
  - Color confinement; Strength rises with distance!
  - Asymptotic Freedom; interaction weakens at High Energies.

Next, A *brief* overview of Phase Transitions ...

[1] Multi-quark states with > 3 Quarks remain to be experimentally confirmed but are, however, theoretically possible. They may also constitute of a molecular baryon-meson or baryon-baryon state.

Quantum Chromodynamics (QCD)

Going over the fundamentals (*Again...*)

- Quantum Chromodynamics (QCD) is the theory of strongly interacting matter.
- Describes the binding of **Quarks** mediated by **Gluons** into bound states $\rightarrow$ **Hadrons** which come in $q\bar{q}$ (Mesons) or qqq (Baryons[1]) states.
- Color Charge (QCD) $\xleftrightarrow{\text{analogous}}$ Electric Charge (QED). However;
  - Three color charges instead of one!
  - Color confinement; Strength rises with distance!
  - Asymptotic Freedom; interaction weakens at High Energies.

Next, A *brief* overview of Phase Transitions ...

[1] Multi-quark states with > 3 Quarks remain to be experimentally confirmed but are, however, theoretically possible. They may also constitute of a molecular baryon-meson or baryon-baryon state.

Quantum Chromodynamics (QCD)

Going over the fundamentals (*Again...*)

- Quantum Chromodynamics (QCD) is the theory of strongly interacting matter.
- Describes the binding of **Quarks** mediated by **Gluons** into bound states $\rightarrow$ **Hadrons** which come in $q\bar{q}$ (Mesons) or qqq (Baryons[1]) states.
- Color Charge (QCD) $\xleftrightarrow{\text{analogous}}$ Electric Charge (QED). However;
  - Three **color** charges instead of one!
  - Color confinement; Strength rises with distance!
  - Asymptotic Freedom; interaction weakens at High Energies.

Next, A *brief* overview of Phase Transitions ...

[1] Multi-quark states with > 3 Quarks remain to be experimentally confirmed but are, however, theoretically possible. They may also constitute of a molecular baryon-meson or baryon-baryon state.

Overview on Phase Transitions

- A **Phase Transition** (PT) is the transformation of a thermodynamic system[2] from one phase to another. Properties of the medium exhibiting a phase transition often change **discontinuously** as a result of **external conditions**.
- An **Order Parameter** is a physical observable that is able to distinguish between two distinct phases.
- We follow the *Ehrenfest* Phase Transition Classification based on the behavior of the Free Energy as a function of other thermodynamic variables:
  - First Order Phase Transition; *First Derivative* discontinuity with respect to a thermodynamic variable.
  - Second Order Phase Transition; *Second Derivative* divergence and discontinuity and power law behavior of $\frac{|T_c - T|}{T_c}$ at T_c.
  - Analytic Crossover; Smooth change from one phase to another, characterized by a *peak* in susceptibility.

[2] We usually limit ourselves to equilibrium phase transitions by looking at the behavior of the Free Energy, meaning, both phases are in mechanical, thermal and chemical equilibrium.

Overview on Phase Transitions

- A **Phase Transition** (PT) is the transformation of a thermodynamic system[2] from one phase to another. Properties of the medium exhibiting a phase transition often change **discontinuously** as a result of **external conditions**.
- An **Order Parameter** is a physical observable that is able to distinguish between two distinct phases.
- We follow the *Ehrenfest* Phase Transition Classification based on the behavior of the Free Energy as a function of other thermodynamic variables:
  - First Order Phase Transition; *First Derivative* discontinuity with respect to a thermodynamic variable.
  - Second Order Phase Transition; *Second Derivative* divergence and discontinuity and power law behavior of $\frac{|T_c - T|}{T_c}$ at T_c.
  - Analytic Crossover; Smooth change from one phase to another, characterized by a *peak* in susceptibility.

[2] We usually limit ourselves to equilibrium phase transitions by looking at the behavior of the Free Energy, meaning, both phases are in mechanical, thermal and chemical equilibrium.

Overview on Phase Transitions

- A **Phase Transition** (PT) is the transformation of a thermodynamic system[2] from one phase to another. Properties of the medium exhibiting a phase transition often change **discontinuously** as a result of **external conditions**.
- An **Order Parameter** is a physical observable that is able to distinguish between two distinct phases.
- We follow the *Ehrenfest* Phase Transition Classification based on the behavior of the Free Energy as a function of other thermodynamic variables:
  - First Order Phase Transition; *First Derivative* discontinuity with respect to a thermodynamic variable.
  - Second Order Phase Transition; *Second Detivative* divergence and discontinuity and power law behavior of $\frac{|T_c - T|}{T_c}$ at T_c.
  - Analytic Crossover; Smooth change from one phase to another, characterized by a *peak* in susceptibility.

[2] We usually limit ourselves to equilibrium phase transitions by looking at the behavior of the Free Energy, meaning, both phases are in mechanical, thermal and chemical equilibrium.

QCD Phase Diagram

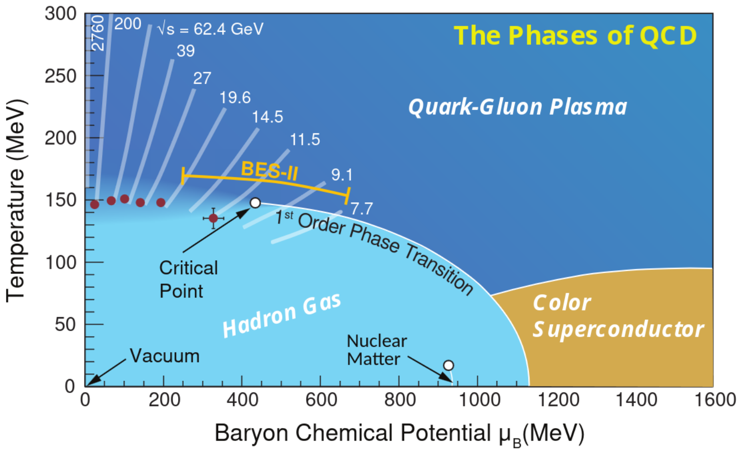

Figure 1: A schematic QCD phase diagram in the thermodynamic parameter space spanned by the temperature T and baryonic chemical potential μ_B. The corresponding (center-of-mass) collision energy ranges for different accelerator facilities, especially the RHIC beam energy scan program, are indicated in the figure. Figure adapted from [Bzd+20]

Lattice Gauge Theory and QCD

- **Lattice QCD** (LQCD) is a non-perturbative approach to studying strongly interacting matter.
- Quarks are represented by lattice points and Gluons are the links between them!
- The relative *strength* of the links can be adjusted.
- **However!** *cost* $\propto \left(\frac{L}{a}\right)^4 \frac{1}{a} \frac{1}{m_\pi^2 a}$; with $\left(\frac{L}{a}\right)^4$ being the lattice specs and $\frac{1}{a} \frac{1}{m_\pi^2 a}$ being the *critical slow-down parameter*.

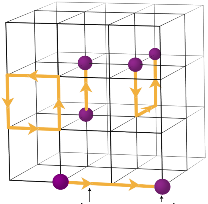

Figure 2: Lattice QCD discretization illustration. Quark fields lie on the grid points, and gluon are represented by links connecting two points[Bi +20]

Lattice Gauge Theory and QCD

- **Lattice QCD** (LQCD) is a non-perturbative approach to studying strongly interacting matter.
- Quarks are represented by lattice points and Gluons are the links between them!
- The relative *strength* of the links can be adjusted.
- **However!** $cost \propto \left(\frac{L}{a}\right)^4 \frac{1}{a} \frac{1}{m_\pi^2 a}$; with $\left(\frac{L}{a}\right)^4$ being the lattice specs and $\frac{1}{a} \frac{1}{m_\pi^2 a}$ being the *critical slow-down parameter*.

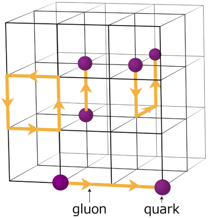

Figure 2: Lattice QCD discretization illustration. Quark fields lie on the grid points, and gluon are represented by links connecting two points[Bi +20]

Lattice Gauge Theory and QCD

- **Lattice QCD** (LQCD) is a non-perturbative approach to studying strongly interacting matter.
- Quarks are represented by lattice points and Gluons are the links between them!
- The relative *strength* of the links can be adjusted.
- **However!** *cost* $\propto \left(\frac{L}{a}\right)^4 \frac{1}{a}\frac{1}{m_\pi^2 a}$; with $\left(\frac{L}{a}\right)^4$ being the lattice specs and $\frac{1}{a}\frac{1}{m_\pi^2 a}$ being the *critical slow-down parameter*.

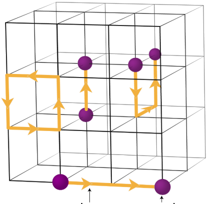

Figure 2: Lattice QCD discretization illustration. Quark fields lie on the grid points, and gluon are represented by links connecting two points[Bi +20]

Lattice Gauge Theory and QCD

- **Lattice QCD** (LQCD) is a non-perturbative approach to studying strongly interacting matter.
- Quarks are represented by lattice points and Gluons are the links between them!
- The relative *strength* of the links can be adjusted.
- **However!** $cost \propto \left(\frac{L}{a}\right)^4 \frac{1}{a}\frac{1}{m_\pi^2 a}$; with $\left(\frac{L}{a}\right)^4$ being the lattice specs and $\frac{1}{a}\frac{1}{m_\pi^2 a}$ being the *critical slow-down parameter*.

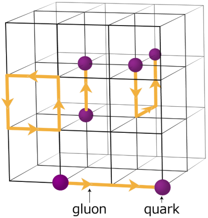

Figure 2: Lattice QCD discretization illustration. Quark fields lie on the grid points, and gluon are represented by links connecting two points[Bi +20]

Thermal LQCD

- Temperature evolution $\Longleftrightarrow$ Time evolution
  - $T^{-1} = a_t N_t$
- $\frac{a_T}{a_s} \ll 1$
- (Anti-)Periodic boundary conditions on the (Fermionic) Bosonic degrees of freedom.[3]
- $\beta = \frac{6}{g^2}$ varies T.[4]

[3] This ensures correct spin statistics.

[4] Increasing β drives the correlation length to diverge in units of lattice spacing, thus increasing the temperature.

Thermal LQCD

- Temperature evolution $\iff$ Time evolution
  - $T^{-1} = a_t N_t$
- $\frac{a_T}{a_s} \ll 1$
- (Anti-)Periodic boundary conditions on the (Fermionic) Bosonic degrees of freedom.[3]
- $\beta = \frac{6}{g^2}$ varies T.[4]

[3] This ensures correct spin statistics.

[4] Increasing β drives the correlation length to diverge in units of lattice spacing, thus increasing the temperature.

Thermal LQCD

- Temperature evolution $\Longleftrightarrow$ Time evolution
  - $T^{-1} = a_t N_t$
- $\frac{a_T}{a_s} \ll 1$
- (Anti-)Periodic boundary conditions on the (Fermionic) Bosonic degrees of freedom.[3]
- $\beta = \frac{6}{g^2}$ varies T.[4]

[3] This ensures correct spin statistics.

[4] Increasing β drives the correlation length to diverge in units of lattice spacing, thus increasing the temperature.

Thermal LQCD

- Temperature evolution $\Longleftrightarrow$ Time evolution
  - $T^{-1} = a_t N_t$
- $\frac{a_T}{a_s} \ll 1$
- (Anti-)Periodic boundary conditions on the (Fermionic) Bosonic degrees of freedom.[3]
- $\beta = \frac{6}{g^2}$ varies T.[4]

[3] This ensures correct spin statistics.

[4] Increasing β drives the correlation length to diverge in units of lattice spacing, thus increasing the temperature.

Thermal LQCD

- Temperature evolution $\Longleftrightarrow$ Time evolution
  - $T^{-1} = a_t N_t$
- $\frac{a_T}{a_s} \ll 1$
- (Anti-)Periodic boundary conditions on the (Fermionic) Bosonic degrees of freedom.[3]
- $\beta = \frac{6}{g^2}$ varies T.[4]

[3] This ensures correct spin statistics.
[4] Increasing β drives the correlation length to diverge in units of lattice spacing, thus increasing the temperature.

2. The Limits of QCD

Limits of the QCD Lagrangian

What is the Pure Gauge Limit of QCD?

$m_q \to \infty$

- Only **gluonic** degrees of freedom!
- Z_3 Symmetry of QCD; 1^{st} Order PT.
- **Polyakov Loop** $\langle L(\vec{r}) \rangle$; Order Parameter.

What is the Chiral limit of QCD?

$m_q \to 0$

- **Chiral Symmetry** spontaneously broken.
- **Chiral Condensate** $\langle \Psi\bar{\Psi} \rangle$; Order Parameter; 2^{nd} Order PT.

Real World!

$m_q \neq 0$; small for u, d, s

- **Chiral Symmetry** explicitly broken by finite quark masses.
- Z_3 Symmetry explicitly broken by presence of quarks.
- Transition is **Analytic Crossover**.

Limits of the QCD Lagrangian

What is the Pure Gauge Limit of QCD?

$m_q \to \infty$

- Only **gluonic** degrees of freedom!
- Z_3 Symmetry of QCD; 1^{st} Order PT.
- **Polyakov Loop** $\langle L(\vec{r}) \rangle$; Order Parameter.

What is the Chiral limit of QCD?

$m_q \to 0$

- **Chiral Symmetry** spontaneously broken.
- **Chiral Condensate** $\langle \Psi \bar{\Psi} \rangle$; Order Parameter; 2^{nd} Order PT.

Real World!

$m_q \neq 0$; small for u, d, s

- **Chiral Symmetry** explicitly broken by finite quark masses.
- Z_3 Symmetry explicitly broken by presence of quarks.
- Transition is **Analytic Crossover**.

Limits of the QCD Lagrangian

What is the Pure Gauge Limit of QCD?

$m_q \rightarrow \infty$

- Only **gluonic** degrees of freedom!
- Z_3 Symmetry of QCD; 1^{st} Order PT.
- **Polyakov Loop** $\langle L(\vec{r})\rangle$; Order Parameter.

What is the Chiral limit of QCD?

$m_q \rightarrow 0$

- **Chiral Symmetry** spontaneously broken.
- **Chiral Condensate** $\langle \Psi\bar{\Psi}\rangle$; Order Parameter; 2^{nd} Order PT.

Real World!

$m_q \neq 0$; small for u, d, s

- **Chiral Symmetry** explicitly broken by finite quark masses.
- Z_3 Symmetry explicitly broken by presence of quarks.
- Transition is **Analytic Crossover**.

Honarable mention: The Z3 Symmetry Breaking of Pure Gauge QCD

$$m_l \to \infty \qquad \Rightarrow \qquad m_l \neq 0$$

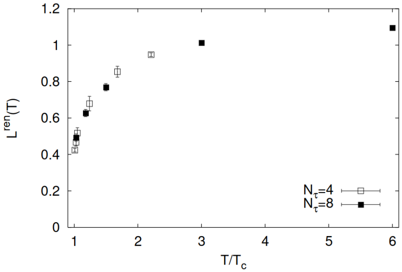

Figure 3: Heavy Quark Anti-Quark Renormalized Polyakov loop as a function of temperature.[Kac+02]

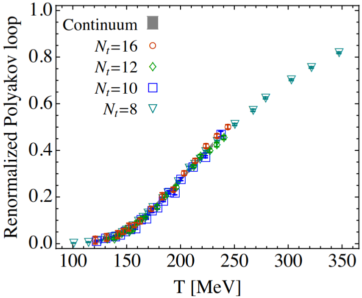

Figure 4: Renormalized Polyakov loop as a function of the temperature with Physical Quark Masses.[Bor+10]

Our Focus: The Chiral Phase Transition in the Chiral Limit

$$m_l \to 0 \quad \Rightarrow \quad m_l \neq 0$$

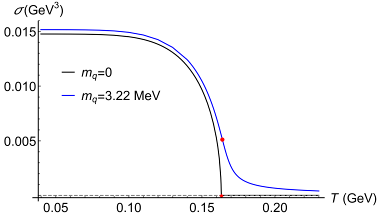

Figure 5: Chiral condensate σ as a function of temperature T in the chiral limit ($m_q = 0$, the black curves) and with the physical quark mass ($m_q = 3.22$, the blue curve). The red circles represent the critical point (T_c) of the second order phase transition and the crossover point (T_{cp}), which is identified as the fastest decreasing point of σ, i.e., $d^2\sigma/d^2T\Big|_{T=T_{cp}}$. Numerically, we get $T_c = 0.163 GeV$ and $T_cp = 0.164 GeV$[Cao+21]

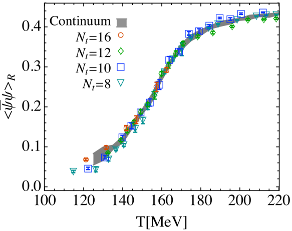

Figure 6: Renormalized Chiral Condensate $\langle\Psi\bar{\Psi}\rangle_R$ defined in eq.(1)[Bor+10]

$$\langle\Psi\bar{\Psi}\rangle_R = -(\langle\Psi\bar{\Psi}\rangle_{l,T} - \langle\Psi\bar{\Psi}\rangle_{l,0})\frac{m_l}{X} \quad (1)$$

$$with \quad l = u, \ d$$

The Chiral Susceptibility $\chi_{\Psi\bar{\Psi}}$

$$\chi_{\Psi\bar{\Psi}} \sim -\frac{\partial F}{\partial m_l} \tag{2}$$

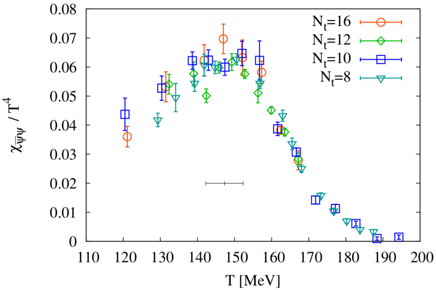

Figure 7: Re-normalized Chiral susceptibility as a function of the temperature normalized with $1/T^4$. The horizontal error bar marks the temperature of the peak in the continuum. The peak position is sensitive to the details of the normalization, which is a manifestation of the broadness of the transition range.[Bor+10]

Key Takeaways on the Chiral Phase Transition

- Defining the Light Quark Susceptibility $\chi_{\Psi\bar{\Psi}}$ in eq. (2)[Bor+10], we get observe a divergence + Power Law behavior at the Chiral limit indicative of a 2^{nd} order PT.
- In the case of $m_l \neq 0$ This is replaced by an **Analytic Crossover** marked by a peak in the Light Quark Susceptibility $\chi_{\Psi\bar{\Psi}}$.
- Though Chiral Symmetry is explicitly broken with the physical quark masses, we still expect a *partial* restoration at a high enough energy regime.

3. Chiral Symmetry Observables

But First, Resonances as Probes for the Medium

But just what are *Resonances*?

- Unsable excited states characterized by a pole position[5] in the complex s-plane.

$$\sqrt{s_R} = M_R - i\frac{\Gamma_R}{2}$$

- with M_R being the rest mass and $\Gamma_R/2$ being the Lifetime.
- Coupled to multiple decay channels.

E.g: $\Delta(1232)$ Resonance decay channels

$$\begin{aligned}
\Delta^{++} &\rightarrow p + \pi^{+} \\
\Delta^{+} &\rightarrow p + \pi^{0} \\
\Delta^{0} &\rightarrow p + \pi^{-} \\
\Delta^{0} &\rightarrow n + \pi^{0} \\
\Delta^{-} &\rightarrow n + \pi^{-}
\end{aligned}$$

[5] Model Independent

Experimental Observables (I)

- **Chiral Symmetry** implies that every Isospin multiplet has a mass degenerate *parity partner*[6]. However, $m_l \neq 0$ explicitly breaks this symmetry thus making them no longer degenerate.
  E.g:

$$J^{\pi} = 1^{-} \ (vector) \quad m_{\rho} = 0.77 \ Gev$$
$$J^{\pi} = 1^{+} \ (axial \ vector) \quad m_{a_1} = 1.23 \ GeV$$

- Experimental Evidence that **Chiral Symmetry is not realized** at hadronic phase!

- **What happens at the Analytic Crossover?**

  Chiral Symmetry Restoration $\Rightarrow$ Parity Partner Mass Degeneracy[7]

Mass Modification!

[6] State with the same Mass, Quantum Numbers and Opposite Parity.
[7] Parital.

Experimental Observables (I)

- **Chiral Symmetry** implies that every Isospin multiplet has a mass degenerate *parity partner*[6]. However, $m_l \neq 0$ explicitly breaks this symmetry thus making them no longer degenerate.
  E.g:

$$J^{\pi} = 1^{-} \ (vector) \quad m_{\rho} = 0.77 \ Gev$$

$$J^{\pi} = 1^{+} \ (axial \ vector) \quad m_{a_1} = 1.23 \ GeV$$

- Experimental Evidence that **Chiral Symmetry is not realized** at hadronic phase!

- **What happens at the Analytic Crossover?**

  Chiral Symmetry Restoration $\Rightarrow$ Parity Partner Mass Degeneracy[7]

Mass Modification!

[6] State with the same Mass, Quantum Numbers and Opposite Parity.
[7] Parital.

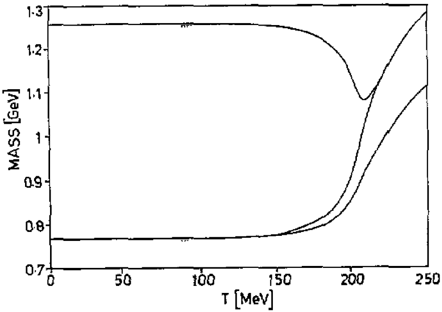

Figure 8: Temperature dependence of vector and axial-vector meson masses. The upper Curve corresponds to a_1, the middle one is ρ and the lower one is ω. [BR95]

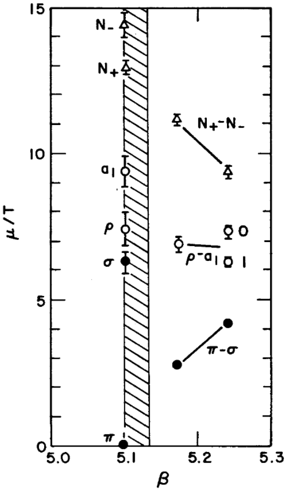

Figure 9: Screening masses, expressed in units of the temperature, as extrapolated to the chiral limit. [DK87]

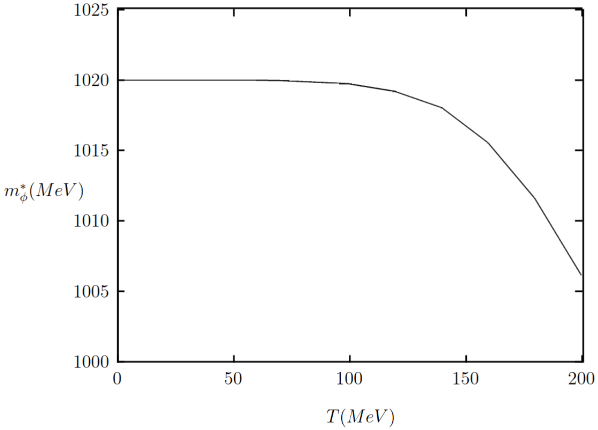

Figure 10: ϕ meson mass dependence on temperature. [Bha+97]

Experimental Observables (II)

- **Increased Interaction rates**: $\rightarrow$ Modification of the spectral width.
  - Expected enhancement in production mechanisms in the presence of the medium.

- **Resonance Overlap** $\rightarrow$ Increase in the density of states of Resonances.

Width Broadening!

Experimental Observables (II)

- **Increased Interaction rates**: $\rightarrow$ Modification of the spectral width.
  - Expected enhancement in production mechanisms in the presence of the medium.
- **Resonance Overlap** $\rightarrow$ Increase in the density of states of Resonances.

Width Broadening!

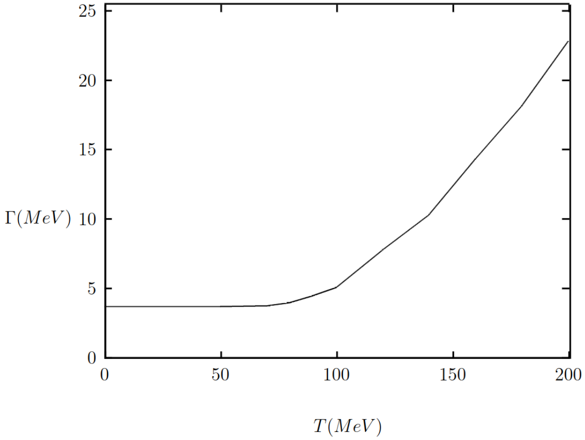

Figure 11: ϕ meson width dependence on temperature. [Bha+97]

Experimental Observables (III)

- **Off-mass shell decay** $\rightarrow$ Main decay channel rate reduction.
  - What happens once we're below the **Energy Threshold** of the main decay channel?

$$\text{E.g:} \qquad m_{\Delta}(T)|_{T \rightarrow T_c} \neq m_N + m_{\pi}$$

- **Decay Channel** $\rightarrow$ Secondary decay channel enhancement.
  - Can we disentangle a Temperature dependence in Γ_S/Γ_P due to the presence of the medium?

Branching Ratio Modification!

Experimental Observables (III)

- **Off-mass shell decay** $\rightarrow$ Main decay channel rate reduction.
    - What happens once we're below the **Energy Threshold** of the main decay channel?

$$\text{E.g:} \qquad m_\Delta(T)|_{T\rightarrow T_c} \neq m_N + m_\pi$$

- **Decay Channel** $\rightarrow$ Secondary decay channel enhancement.
    - Can we disentangle a Temperature dependence in Γ_S/Γ_P due to the presence of the medium?

Branching Ratio Modification!

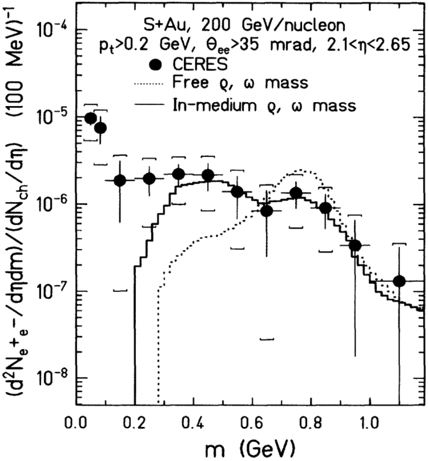

Figure 12: Dilepton invariant mass spectra from calculations with free (dotted histogram) and in-medium (solid histogram) vector meson masses. [LKB95]

More Observables, *Same Signature*

Mass Shifting

$\Updownarrow$

Width Broadening

$\Updownarrow$

Branching Ratio Modification

4. Experimental Analysis

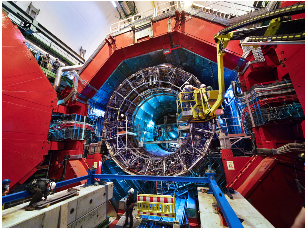

Figure 13: ALICE at CERN.

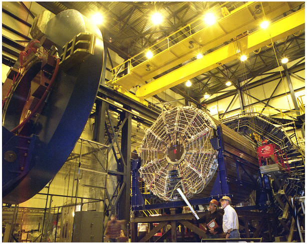

Figure 15: STAR at RHIC.

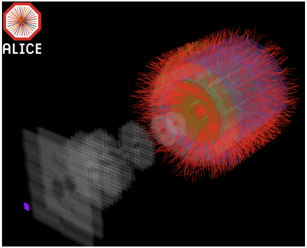

Figure 14: ALICE Event Display for RUN3 Data.

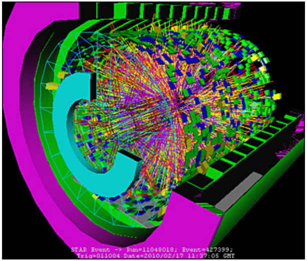

Figure 16: STAR Event Display for RUN20.

Relativistic Heavy-Ion Collisions

Probing matter at the most extreme conditions!

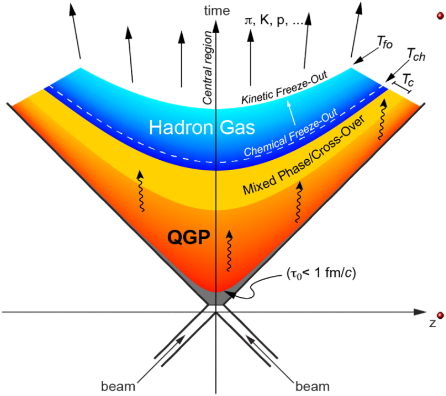

Figure 17: Evolution of a Relativistic Heavy Ion Collision.

Ready, Set, *Measure*! Right?

Right ... ?

Relativistic Heavy-Ion Collisions

Probing matter at the most extreme conditions!

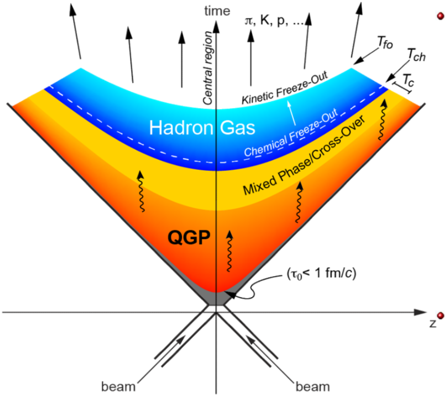

Figure 17: Evolution of a Relativistic Heavy Ion Collision.

Ready, Set, *Measure*! Right?
Right ... ?

The Good, the **Bad** and the *Ugly*

Surely, it can't be that bad ... Consider the case of the $a_1(1260)$ Meson.

- Two decay channels $\rightarrow \gamma\pi$ and $\rightarrow \rho\pi$.
- Width Broadening driven by Chiral Symmetry Restoration?

Harder to distinguish without $\rho - \pi$ correlations ...

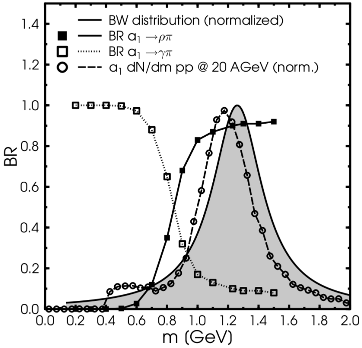

Figure 18: Mass dependent branching ratios for the a_1 meson with the two exit channel of $\gamma\pi$ and $\rho\pi$ as calculated from UrQMD.[VB08]

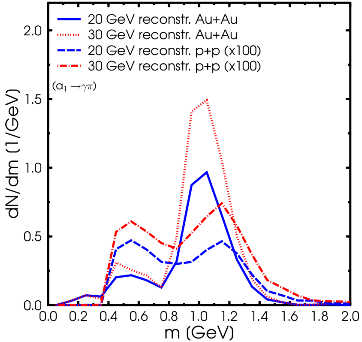

Figure 19: Mass distribution of a1 mesons which can be reconstructed in $\gamma\pi$ correlations in nucleus-nucleus and proton-proton collisions at 20 and 30 GeV. [VB08]

The Good, the **Bad** and the *Ugly*

Surely, it can't be THAT Ugly ... Consider the case of the $\phi(1020)$ Meson.

- Abundant Production at different energies!
- A **hadronic** decay $\rightarrow K^+K^-$ and a leptonic decay $\rightarrow e^+e^-$.
- Noticable deviation in branching ratio due to Chiral Symmetry Restoration?

May be inconclusive since the $\phi(1020)$ **greatly** outlives the QGP ...

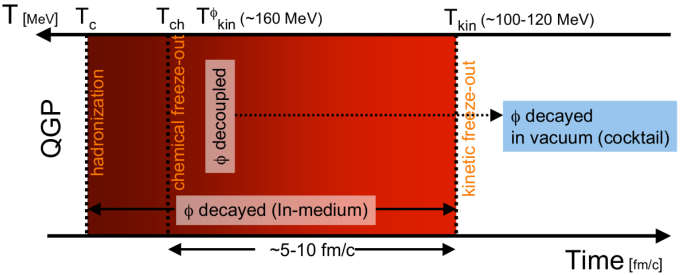

Figure 20: Diagram showcasing the decay of the ϕ through the evolution of the QGP.

The Good, the Bad and the Ugly

Is there even hope for our approach at this point?
Maybe ...

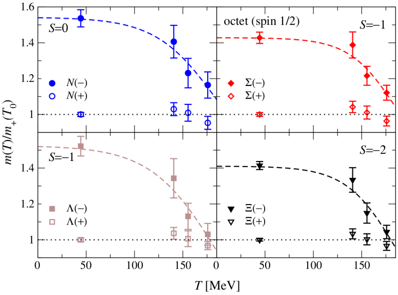

Figure 21: Temperature dependence of the octet ground state masses. [Aar+19]

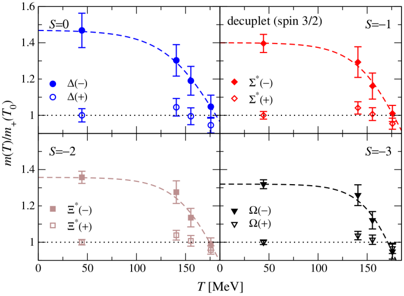

Figure 22: Temperature dependence of the decuplet ground state masses. [Aar+19]

Ξ ($J^\pi = 3/2^\pm$) Excited Baryon Parity Partners

- Starting with the Positive Chiral Partner $\Xi(1530)$
  - $M_{\Xi(1530)^0} = 1531.6 \pm 0.4 MeV$ $M_{\Xi(1530)^-} = 1534.4 \pm 1.1 MeV$
  - $\tau \sim 20\ fm/c$
  - Decay Modes: $\Xi\pi$ and $\Xi\gamma$
- Now, for the **Negative** Chiral Partner $\Xi(1820)$
  - $M_{\Xi(1820)} = 1823 \pm 5 MeV$
  - $\tau \sim \mathbf{10\ fm/c}$
  - Measured Decay Modes: $\Lambda\bar{K}$, $\Sigma\bar{K}$.
  - Not much is known about the $\Xi(1820)$ ...

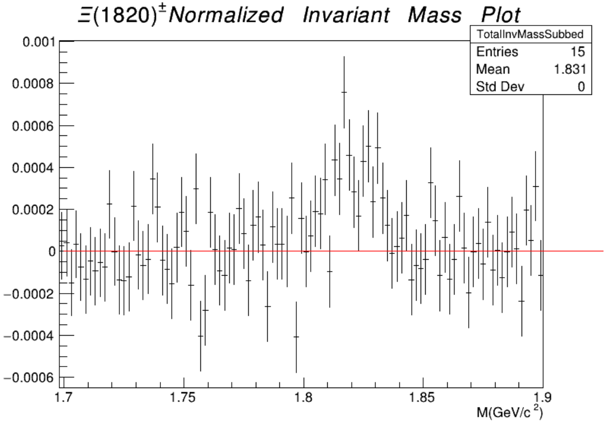

Figure 23: Invariant mass plot produced through background subtraction from $\sim$ 400 million events (collisions).

5. Conclusion

Conclusion

- The Chiral Phase transition is a model independent PT in the Low - μ_B regime.
  - $\rightarrow$ Rich phenomenon with many experimental observables, some mentioned in previous talk(s).
  - $\rightarrow$ Key in understanding the nature of confinement in the energy regime.
  - $\rightarrow$ Direct observation of dynamical mass generation.
- Modification in the Resonance Mass Spectrum *smoking gun* Signature of this PT.
- **Strong** evidence for the existence and production of the Quark-Gluon Plasma!
- **Most important aspect ...** it would be pretty cool :)

Conclusion

- The Chiral Phase transition is a model independent PT in the Low - μ_B regime.
  - $\rightarrow$ Rich phenomenon with many experimental observables, some mentioned in previous talk(s).
  - $\rightarrow$ Key in understanding the nature of confinement in the energy regime.
  - $\rightarrow$ Direct observation of dynamical mass generation.
- Modification in the Resonance Mass Spectrum *smoking gun* Signature of this PT.
- **Strong** evidence for the existence and production of the Quark-Gluon Plasma!
- **Most important aspect ...** it would be pretty cool :)

Thank You

References I

[Aar+19] Gert Aarts et al. "Hyperons in thermal QCD: A lattice view". In: *Phys. Rev. D* 99 (7 Apr. 2019), p. 074503. DOI: 10.1103/PhysRevD.99.074503. URL: https://link.aps.org/doi/10.1103/PhysRevD.99.074503.

[Bha+97] Abhijit Bhattacharyya et al. "In-medium effects on the ϕ meson". In: *Phys. Rev. C* 55 (3 Mar. 1997), pp. 1463–1466. DOI: 10.1103/PhysRevC.55.1463. URL: https://link.aps.org/doi/10.1103/PhysRevC.55.1463.

[Bi +20] Bi, Yujiang et al. "Lattice QCD GPU Inverters on ROCm Platform". In: *EPJ Web Conf.* 245 (2020), p. 09008. DOI: 10.1051/epjconf/202024509008. URL: https://doi.org/10.1051/epjconf/202024509008.

[Bor+10] Szabolcs Borsányi et al. "Is there still any T_c mystery in lattice QCD? Results with physical masses in the continuum limit III". In: *Journal of High Energy Physics* 2010.9 (Sept. 2010). ISSN: 1029-8479. DOI: 10.1007/jhep09(2010)073. URL: http://dx.doi.org/10.1007/JHEP09(2010)073.

[BR95] A Bhattacharyya and S Raha. "Temperature dependence of hadron masses: I. Results from an extended linear sigma model". In: *Journal of Physics G: Nuclear and Particle Physics* 21.6 (June 1995), p. 741. DOI: 10.1088/0954-3899/21/6/004. URL: https://dx.doi.org/10.1088/0954-3899/21/6/004.

[Bzd+20] Adam Bzdak et al. "Mapping the phases of quantum chromodynamics with beam energy scan". In: *Physics Reports* 853 (Apr. 2020), pp. 1–87. ISSN: 0370-1573. DOI: 10.1016/j.physrep.2020.01.005. URL: http://dx.doi.org/10.1016/j.physrep.2020.01.005.

[Cao+21] Xuanmin Cao et al. "Thermal properties of light mesons from holography". In: *Journal of High Energy Physics* 2021.8 (Aug. 2021). ISSN: 1029-8479. DOI: 10.1007/jhep08(2021)005. URL: http://dx.doi.org/10.1007/JHEP08(2021)005.

[DK87] Carleton E. Detar and John B. Kogut. "Measuring the Hadronic Spectrum of the Quark Plasma". In: *Phys. Rev. D* 36 (1987), p. 2828. DOI: 10.1103/PhysRevD.36.2828.

[Kac+02] O Kaczmarek et al. "Heavy quark–antiquark free energy and the renormalized Polyakov loop". In: *Physics Letters B* 543.1–2 (Sept. 2002), pp. 41–47. ISSN: 0370-2693. DOI: 10.1016/s0370-2693(02)02415-2. URL: http://dx.doi.org/10.1016/S0370-2693(02)02415-2.

[LKB95] G. Q. Li, C. M. Ko, and G. E. Brown. "Enhancement of Low-Mass Dileptons in Heavy Ion Collisions". In: *Phys. Rev. Lett.* 75 (22 Nov. 1995), pp. 4007–4010. DOI: 10.1103/PhysRevLett.75.4007. URL: https://link.aps.org/doi/10.1103/PhysRevLett.75.4007.

[VB08] Sascha Vogel and Marcus Bleicher. "a_1 meson being a difficult messenger for the restoration of chiral symmetry". In: *Physical Review C* 78.6 (Dec. 2008). ISSN: 1089-490X. DOI: 10.1103/physrevc.78.064910. URL: http://dx.doi.org/10.1103/PhysRevC.78.064910.