Equilibration of Charm Quarks at Ultrarelativistic Energies

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Standard Model of Particle Physics

### Quarks
- **U** (up) | Mass: $2.3 \text{ MeV/c}^2$ | Charge: $2/3$
- **C** (charm) | Mass: $1.275 \text{ GeV/c}^2$ | Charge: $2/3$
- **T** (top) | Mass: $173.07 \text{ GeV/c}^2$ | Charge: $2/3$
- **D** (down) | Mass: $4.8 \text{ MeV/c}^2$ | Charge: $-1/3$
- **S** (strange) | Mass: $95 \text{ MeV/c}^2$ | Charge: $-1/3$
- **B** (bottom) | Mass: $4.18 \text{ GeV/c}^2$ | Charge: $-1/3$

### Leptons
- **E** (electron) | Mass: $0.511 \text{ MeV/c}^2$ | Charge: $-1$
- **M** (muon) | Mass: $105.7 \text{ MeV/c}^2$ | Charge: $-1$
- **T** (tau) | Mass: $1.777 \text{ GeV/c}^2$ | Charge: $-1$
- **Neutrino (e)** | Mass: $<2.2 \text{ eV/c}^2$ | Charge: $0$
- **Neutrino (μ)** | Mass: $<0.17 \text{ MeV/c}^2$ | Charge: $0$
- **Neutrino (τ)** | Mass: $<15.5 \text{ MeV/c}^2$ | Charge: $0$

### Gauge Bosons
- **W** | Mass: $80.4 \text{ GeV/c}^2$ | Charge: $\pm 1$
- **Z** | Mass: $91.2 \text{ GeV/c}^2$ | Charge: $0$

### Bosons
- **Gluon** | Mass: $126 \text{ GeV/c}^2$
- **Higgs boson** | Mass: $126 \text{ GeV/c}^2$
The Quark-Gluon Plasma
The QCD phase diagram
Colliders now and in the future

- **Future Circular Collider (FCC)**
  Circumference: 90 - 100 km
  Energy: 100 TeV (pp) 90-350 GeV (e⁺e⁻)

- **Large Hadron Collider (LHC)**
  **Large Electron-Positron Collider (LEP)**
  Circumference: 27 km
  Energy: 14 TeV (pp) 209 GeV (e⁺e⁻)

- **Tevatron**
  Circumference: 6.2 km
  Energy: 2 TeV (pp)
The Quark-Gluon Plasma

Sequential suppression of charmonium states

(H. Satz: “The Quark-Gluon Plasma”)

\[ T < T_c \]

\[ T_{\psi'} < T < T_{\chi} \]

\[ T > T_{\psi} \]
Charm Quark Equilibration

From kinetic theory (weak coupling):
- Low $\sqrt{s_{NN}}$: Thermal production negligible
- FCC energies: $T_0 = 840$ MeV
- Thermal production efficient


On the other hand:
- $\Gamma_{\text{chem}}^{-1} \sim 10$ fm/c

(Bödeker, Laine, JHEP 2012)

\[ \rightarrow \text{Relevant at LHC} \]
\[ \rightarrow \text{Dominant at FCC} \]

Equilibration $T$ and $V$

- Susceptibilities correspond to conserved charge fluctuations:
  \[
  \chi^2 = \frac{1}{TV} \langle \delta N^2 \rangle
  \]

- Use Charm Quark Number Susceptibilities, order $i$:
  \[
  \chi^i_c(T) = \left. \frac{\partial^i p(T, \bar{\mu})}{\partial \mu^i_c} \right|_{\bar{\mu}=0}
  \]

- Two equations with two unknowns $T$ and $V$:
  \[
  \frac{\langle (\delta N_{c-\bar{c}})^2 \rangle}{\chi^2_c} = TV \quad \text{and} \quad \frac{\chi^4_c}{\chi^2_c / T^2} = \kappa \sigma^2 \equiv \frac{\langle (\delta N_{c-\bar{c}})^4 \rangle}{\langle (\delta N_{c-\bar{c}})^2 \rangle} - 3 \langle (\delta N_{c-\bar{c}})^2 \rangle
  \]
Susceptibilities - lattice and pQCD

Unquenched lQCD only for $T < 0.5$ GeV

(Graf, Bleicher, Steinheimer, Herold, PRC 97 (2018))
Susceptibilities - lattice and pQCD

\[
\left( \frac{\delta N^2}{\langle \rangle^{1/2}} \right)
\]

\[
\kappa \sigma^2
\]

(Graf, Bleicher, Steinheimer, Herold, PRC 97 (2018))
Charm Quark Equilibration

- Thermal Charm Quark Production
- Important at FCC, relevant at LHC
- Possible to explore equilibration $T$, $V$ via susceptibilities
- Future: Additional constraints from higher-order fluctuations