Quark-Gluon Plasma: from QCD thermodynamics to heavy ion phenomenology

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Part 1: QCD thermodynamics

- QCD: general
- QCD: thermodynamics
- DSE calculation: CEP, phase diagram

Part 2: QGP phenomenology

- Heavy ion collisions
- Heavy flavor probe
- A non-perturbative formalism: microscopic dynamics + macroscopic simulations
Quantum ChromoDynamics

\[ \mathcal{L}_{QCD} = \bar{q}(i\partial + gA - \hat{m}_q)q - \frac{1}{4}G_{a\mu\nu} \]

- color confinement
- asymptotic freedom

2004 Nobel Prize

\[ \alpha_s(Q) = 0.1189 \pm 0.0010 \]

QCD
QCD vacuum & chiral symmetry

◆ u/d quark higgs mass (electronweak symmetry breaking)
5-10 MeV → (approximate) chiral symmetry

\[ \mathcal{L}_{\text{QCD}} = (\bar{u}_L, \bar{d}_L) i\mathcal{D} \left( \frac{u_L}{d_L} \right) + (\bar{u}_R, \bar{d}_R) i\mathcal{D} \left( \frac{u_R}{d_R} \right) + \mathcal{O}(m_q) - \frac{1}{4} G^2_{a\mu\nu} \]

◆ But ... \( \bar{q}q \) attraction ⇒ condensates fill QCD vacuum

\[ \langle 0 | \bar{q}q | 0 \rangle = \langle 0 | \bar{q}_Lq_R + \bar{q}_Rq_L | 0 \rangle \approx 5 \text{ fm}^{-3} \]

◆ Spontaneous/dynamical chiral symmetry breaking

\[ \text{SU}(2)_L \otimes \text{SU}(2)_R \rightarrow \text{SU}(2)_V \]

Profound Consequences:

• effective quark-mass: mass generation from nothing
account for 98% visible mass

\[ m_q \approx 300 \text{ MeV} \rightarrow m(\text{proton}) \approx 3 \times m_q \approx 1 \text{ GeV} \]

• massless Goldstone bosons: \( \pi \) \( m_{\text{pion}} = 140 \) MeV

• “chiral partners” split: \( \Delta M \approx 0.5 \) GeV
At finite temperature/density ...

◆ confinement → deconfinement
◆ chiral symmetry restoration
A theoretical study of chiral phase transition: quark number suscept. vs CEP

- Quark number susceptibility:
  response of number density against chemical potential

\[
\langle \psi^+ \psi \rangle = \langle \bar{\psi}_i (\gamma_4)_{ij} \psi_j \rangle = (-) N_c N_f \int \frac{d^4 p}{(2\pi)^4} tr \gamma [G(p, \mu) \gamma_4].
\]

\[
\frac{\partial G(p, \mu)}{\partial \mu} = (-) G(p, \mu) \frac{\partial G^{-1}(p, \mu)}{\partial \mu} G(p, \mu),
\]

- Ward identity:

\[
(-) \Gamma_4(p, 0; \mu) = \frac{\partial G^{-1}(p, \mu)}{\partial \mu}
\]

- related to zero-momentum (spacelike) limit of the vector-vector vacuum polarization

\[
\chi(T, \mu) = (-) N_c N_f T \sum_{n=-\infty}^{+\infty} \int \frac{d^3 p}{(2\pi)^3} tr \gamma [G(\tilde{p}_n) \Gamma_4(\tilde{p}_n, 0) G(\tilde{p}_n) \gamma_4]
\]

\[
\tilde{p}_n = (\vec{p}, \omega_n + i\mu)
\]

The total momentum \( P=0 \)

dressed quark propagator

dressed quark-photon vertex
Dyson-Schwinger & Bethe-Salpeter

◆ Coupled integral equations relating all Green functions of a QFT

◆ Tractable truncation schemes: rainbow-ladder

\[ P_{\mu} \Gamma_{5\mu}(k; P) = S^{-1}(k_+) i \gamma_5 + i \gamma_5 S^{-1}(k_-) \]

AV-WTI respected, key for DCSB

DSE, quark gap equation

\[ G^{-1}(p) = Z_2(i \gamma \cdot p + m_{\text{bar}}) + \frac{4}{3} \int_{q}^{\Lambda} 4\pi \alpha(p-q) D_{\mu\nu}^{\text{free}}(p-q) \gamma_\mu G(q) \gamma_\nu, \]

BSE, qqbar bound state equation

\[ \left[ \Gamma_{\pi}^i (k; P) \right]_{tu} = \int_{q}^{\Lambda} \left[ S(q + P/2) \Gamma_{\pi}^i (q; P) S(q - P/2) \right]_{sr} K_{t'u}^{rs}(q, k; P) \]

S-wave (pseudoscalar, vector) light mesons well addressed Roberts2003,2011
DSE-BSE calculations (finite T & \(\mu\))

**DSE, quark gap equation**

\[
G^{-1}(p_k, m) = i\gamma \cdot p_k + \frac{4}{3} T \sum_{n=-\infty}^{+\infty} \int \frac{d^3 p}{(2\pi)^3} g^2 D_{\mu\nu}^{\text{eff}}(p_k - q_n) \gamma_{\mu} G(q_n, m) \gamma_{\nu}.
\]

model gluon propagator, constrained by vacuum observables

\[
g^2 D_{\mu\nu}^{\text{eff}}(\vec{p}_k - \vec{q}_n) = \delta_{\mu\nu} D_0 f_0(\vec{p}_k^2) f_0(\vec{q}_n^2).
\]

\[
G^{-1}(\vec{p}_k) = i\gamma \cdot \vec{p} A(\vec{p}_k^2) + i\gamma_4 \omega_k C(\vec{p}_k^2) + B(\vec{p}_k) B(\vec{p}_k) = m + b(T, \mu) f_0(\vec{p}_k^2)
\]

dynamically generated mass

# at low T, Re b experiences an abrupt decrease at some \(\mu\) --- 1st order transition

# at high T, Re b tends to evolve smoothly with \(\mu\) --- crossover

# what happens in between?, 1st order line ends at some CEP? --- to be verified

**BSE, inhomogeneous**

\[
\Gamma_4(\vec{p}_k, 0) = \gamma_4 - \frac{4}{3} T \sum_{n=-\infty}^{+\infty} \int \frac{d^3 q}{(2\pi)^3} g^2 D_{\rho\sigma}^{\text{eff}}(\vec{p}_k - \vec{q}_n) \gamma_\rho G(\vec{q}_n) \Gamma_4(\vec{q}_n, 0) G(\vec{q}_n) \gamma_\sigma.
\]

\[
\Gamma_\mu(p, 0) = \alpha_1(p^2) \gamma_\mu + \alpha_2(p^2) \gamma \cdot p p_\mu - \alpha_3(p^2) i p_\mu.
\]

in vacuum

\[
\Gamma_4(\vec{p}_k, 0) = \alpha(\vec{p}_k^2) \gamma_4 - i \beta(\vec{p}_k^2) \omega_k.
\]

in-medium

The 2nd term crucial to search for the CEP, c.f. Ward Identity in P6
Locating CEP in the phase diagram

Ehrenfest: susceptibilities diverge at 2\textsuperscript{nd} order phase transition, CEP is a 2\textsuperscript{nd} transition points

A diverging cusp emerges along the \( \mu_{\text{CEP}} = 164 \text{MeV} \) line at \( T_{\text{CEP}} = 117 \text{MeV} \) --- CEP location!

M.He, et al, 2009

Recent experimental (PRL98, 092301 & 0708.3512) & lattice estimate (PRD71, 114014) CEP(\( T \sim 165-170 \text{MeV} \), \( \mu \sim 150-180 \text{MeV} \))

crossover

1\textsuperscript{st} order transition

comparable to recent C.D.Roberts, PRL2011; NJL-type models (PRD77, 096001 ...) universally predict \( \mu_{\text{CEP}} \sim 300 \text{MeV} \)
Can the QGP be created in lab? How?

T.D. Lee: *In order to study the question of ‘vacuum’, we must turn to a different direction: we should investigate some ‘bulk’ phenomena by distributing high energy over a relatively large volume.*” (1975)

*S. Borsanyi et al., JHEP 1011, 077 (2010)*
Big vs little bang: heavy ion collision

- Time:
  - $10^{-32}$ sec: big bang
  - $10^{-30}$ sec: EW transition
  - $10^{-5}$ sec: confinement
  - $10^{-3}$ sec: nucleosynthesis
  - $10^{12}$ sec: first atoms

- Diagram:
  - Freeze-Out
  - QGP
  - Hadron Gas
  - Beam
  - Initial state
  - Pre-equilibrium
  - QGP and hydrodynamic expansion
  - Hadronization
  - Hadronic phase and freeze-out

- Time scale:
  - 0.1 fm/c
  - 1 fm/c
  - 10 fm/c
RHIC @BNL: A bird’s-eye view

$\nu = 0.99995 \cdot c = 186,000 \text{ miles/sec}$

$\text{Au + Au at 200 GeV}$
QGP: perfect fluid & probes

**Collective flow:**
hydrodynamic expansion, lowest eta/s
\[ T^{\mu \nu} = (\varepsilon + p)u^\mu u^\nu - p g^{\mu \nu} \]
\[ \partial_\mu T^{\mu \nu}(x) = 0 \]

**Jet quenching:**
high \( p_T \) partons lose energy through gluon radiation when traversing QGP

**J/ψ suppression:**
Debye screening of color force weakens c-cbar binding \( \rightarrow \) dissolve in QGP

**Electromagnetic probe:**
thermal EM radiation enhancement; vector meson in-medium broadening

**Open heavy flavor:**
heavy flavor quenching and transport
\( \rightarrow \) Does charm flow or not?
Toward a complete description of Heavy Flavor Transport in Medium

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Outline

1. Introduction:
   • Heavy quark probe for hot & dense matter

2. HQ probe: a strongly coupled framework
   • Transport coefficient
   • HQ diffusion in QGP: Langevin + hydro simulation
   • Hadronization: coalescence vs fragmentation
   • D-meson diffusion in hadronic phase
   • $R_{AA}$ & $v_2$: thermalization & quenching

3. Summary
Introduction: HQ probe

- primordial hard production + number conserved
- thermalization delayed

\[ \tau_Q \approx \frac{m_Q}{T}, \tau_q \approx 6 \tau_q \geq \tau_{QGP} \]

Heavy quarks make a direct probe of the medium

- HQ energy loss:
  - gluon radiation: dead cone suppression
  - elastic scattering: efficient low \( p_T \) thermalization

\[ p_{th} \sim \sqrt{3m_QT} \gg T \sim q_{tr} \]

\[ \frac{\partial f}{\partial t} = \gamma \frac{\partial (pf)}{\partial p} + D \frac{\partial^2 f}{\partial p^2} \]

\( \gamma \sim \int |T_{qq}|^2 (1 - \cos \theta) f^q \)

\( D = \gamma m_Q T \)
Introduction: elastic collision (cond)

◆ **pQCD elastic collisions** B. Combridge, 1978

![Diagram](image1)

Various weakly coupled (pQCD) scenarios for HQ transport:
Moore & Teaney, 2005; Gossiaux & Aichelin, 2008; Alberico et al., 2011; J. Uploff et al., 2010; ...

Running coupling, Debye screening, K-factor?

◆ **Resonant scattering: non-perturbative** van Hees, Greco & Rapp, 2005, 2006

![Diagram](image2)

Strongly coupled scenario
A strongly coupled framework: HQ

Medium/hydro

HQ relaxation rate
- T-matrix: resonance

Hadronization: fragmentation vs Resonance Recombination

D/B: hadronic diffusion

D/B: semi-leptonic decay

Initial distribution

D/B relaxation rate
**HQ relaxation rate: T-matrix**

\[ T = V + V_T \]

- **static approximation**
  \[ q_0 \approx \frac{\bar{q}^2}{2m_Q} \ll \bar{q} \]

- **lattice potential:** Kaczmarek, 2008
  \[ U = F - T \frac{\partial F}{\partial T} \]

- **open/hidden heavy flavor** vacuum spectroscopy reproduced: Riek & Rapp, 2010

- **heavy quarkonia** (bound states)
- **heavy quark transport** (scattering states)

**Resummation & Unitarization**

**Common basis & mutual constraints**
HQ relaxation rate: T-matrix (cont.)

- **T-matrix resummation** ➔ color singlet and anti-triplet broad Feshbach resonances up to ~1.5 $T_c$

- this resonance correlation will be reiterated in our hadronization-coalescence model

- **T-matrix relaxation rate**: a factor ~4-5 larger than LO pQCD at $T=1.2 \, T_c$

- **T-dependence**: screening potential vs light parton density; $p$-dependence: less contribution from threshold Feshbach resonance as $p$ increases
Medium evolution: improved AZHYDRO

- lattice EoS + pre-equilibrium flow + compact initial density profile $s(x,y) \sim n_{BC}(x,y)$
- multistrange hadrons $\phi, \Xi, \Omega$ probably freeze out earlier STAR, PRC79, 2009
- multi-strange particles’ spectra and $v_2$ fitted at $T_{ch} = 160$ MeV
  bulk particles’ spectra and $v_2$ fitted at $T_{kin} = 110$ MeV

M. He, R.J. Fries, R. Rapp, in preparation
HQ initial distribution

- Initial $p_t$ spectrum: PYTHIA parametrization
- $B \rightarrow e$ starts to dominate over $D \rightarrow e$ at $p_t \sim 5$ GeV

- Initial spatial distribution: Glauber binary collision density $n_{BC}(x,y)$

\[
\frac{d^2 N_e}{d p_T^2} = C \frac{(p_T + A)^2}{(1 + p_T / B)^\alpha}
\]

\[
\frac{\sigma_{b\bar{b}}}{\sigma_{c\bar{c}}} = 4.9 \times 10^{-3}
\]
A strongly coupled framework: HQ

Medium/hydro

HQ relaxation rate
T-matrix: resonance

HQ Langevin diffusion

Hadronization: fragmentation vs Resonance Recombination

D/B: hadronic diffusion
D/B relaxation rate

Initial distribution

D/B: semi-leptonic decay
Langevin simulation of HQ diffusion

Langevin + hydro simulation down to $T_c=170$ MeV
fluid rest frame updates $\rightarrow$ boost to lab frame

$\begin{align*}
\frac{dx}{dt} &= \frac{p}{E}, \\
\frac{dp}{dt} &= -\Gamma(p)p + \sqrt{2D(p + dp)} dt \rho
\end{align*}$

- quenching: early stage when medium particles’ density is high
- $v_2$: develops at later stage when the medium particles’ $v_2$ is large

(a) charm quark
(b) bottom quark

$\begin{align*}
\text{Au + Au, } \sqrt{s_{NN}}=200 \text{ GeV, } b=7.24 \text{ fm}
\end{align*}$
A strongly coupled framework: HQ

- HQ relaxation rate
  - T-matrix: resonance
- HQ Langevin diffusion
- Initial distribution
- Hadronization: fragmentation vs Resonance Recombination
- D/B: hadronic diffusion
- D/B: semi-leptonic decay
- D/B relaxation rate
Hadronization: Resonance Recombination

◆ Hadronization = Resonance formation \( c\bar{q} \rightarrow D \)

\[ p^\mu \partial_\mu f_M(t, \vec{x}, \vec{p}) = -m \Gamma f_M(t, \vec{x}, \vec{p}) + p^0 \beta(\vec{x}, \vec{p}). \]

\( \beta(\vec{x}, \vec{p}) = \int \frac{d^3 p_1 d^3 p_2}{(2\pi)^6} f_q(\vec{x}, \vec{p}_1) f_{\bar{q}}(\vec{x}, \vec{p}_2) \times \sigma(s) v_{\text{rel}}(\vec{p}_1, \vec{p}_2) \delta^3(\vec{p} - \vec{p}_1 - \vec{p}_2) \)

\[ \sigma(s) = g_\sigma \frac{4\pi}{k^2} \frac{(\Gamma m)^2}{(s - m^2) + (\Gamma m)^2} \]

◆ Equilibrium limit

◆ Energy conservation + detailed balance

\[ f_M^{\text{eq}}(\vec{p}) = \frac{E_M(\vec{p})}{m \Gamma} \int d^3 x \beta(\vec{x}, \vec{p}) \]

\( \rightarrow \) consistent with T-matrix findings of resonance correlations towards \( T_c \)

◆ Realized by Boltzmann equation Ravagli & Rapp, 2007
Equilibrium Quark $\rightarrow$ Equilibrium Meson

◆ Kolb-Heinz AZHYDRO: space-momentum correlation at freezeout included, excellent equilibrium mapping achieved; boost invariance preserved
c.f. M. He, R. J. Fries & R. Rapp, 2010

$\Rightarrow$ RRM has correct equilibrium limit (compared to instantaneous coalescence models) & facilitates the description of the transition from low $p_T$ (equilibrium) to intermediate $p_T$ (kinetic) region in heavy-light quark recombination
Hadronization: coal. vs frag.

- charm quark coal. prob. based on scattering rate: $D(z) = \delta(z-1)$
- supplemented by $P_{\text{coal}}(p_t) = \tau_{\text{res}}\gamma_Q(p_t)$

- flow bump more prominent from c to D & shifted to higher \( p_T \)
- At \( p_T \sim 1.5-4.5 \text{ GeV} \), coalescence adds momentum to D, \( R_{\text{AA}} \) increases from c to D

- Coalescence acts as an extra interaction, driving D-spectrum closer to equilibrium

- At low \( p_T, R_{\text{AA}} \) gets a larger dip, than charm; flow depletion on D, captured by c-q RRM
**Hadronization: coal. vs frag. (cond.)**

- **coal. vs frag.** : relatively normalized with the calculated coal. prob.

\[
\frac{dN_D^{total}}{dyd^2p_T} = \frac{dN_D^{coal}}{dyd^2p_T} + \frac{dN_D^{frag}}{dyd^2p_T}
\]

\[
R_{AA}(p_T, b) = \frac{dN^{AA}}{2\pi p_T dp_T dy} \left/ \frac{N_{coll}(b)}{2\pi p_T dp_T dy} \right.
\]

- **space-momentum correlation** built up via Langevin + hydro for HQ & q from hydro environment fully implemented in RRM

- **RRM** admits equilibrium mapping between quark and meson distributions, thus able to capture the remarkable flow effect via heavy-light coalescence

- **coalescence**: adds \(v_2\) from the light quarks to D meson

- **at higher** \(p_T\), coal. yields to frag.: preserves the HQ \(v_2\) from c \(\rightarrow\) D
A strongly coupled framework: HQ

HQ relaxation rate
T-matrix: resonance

HQ Langevin diffusion

Hadronization: fragmentation vs Resonance Recombination

D/B: hadronic diffusion

D/B: semi-leptonic decay

Initial distribution

D/B relaxation rate

Medium/hydro
Charm diffusion: pion gas

- D&D₀*, D* & D₁': chiral partners, large pion s-wave decay width ~300 MeV, Fuchs, et al., 2006; BELLE Colla., 2004; also verified by Chiral Unitarized Approach

- D + pion → resonance → D + pion: $A_{1/2} = \sum_{j=0,1,2} \frac{8\pi\sqrt{s}}{k} \frac{(2j+1)}{(2j_1+1)(2j_2+1)} \frac{-\sqrt{s}\Gamma_j^{D\pi}}{s-M_j^2+i\sqrt{s}\Gamma_j^{\text{tot}}}$
Charm diffusion: hadronic resonance gas

- D + K, eta, rho, omega, K*, N, Delta, empirical s-wave cross sections based on ChUA: Lutz et al., 2004, 2006; E. Oset et al., 2007

- A ~ 0.1 /fm at T = 180 MeV, comparable to the non-perturbative T-matrix calculation of charm quark thermal relaxation rate in QGP

- Expected modification of D-spectrum at RHIC: \(1 - \exp(-A\Delta\tau_{had}) \approx 20\%\)

- Spatial diffusion coefficient \(D_s = T/(mA)\), surprisingly close to T-matrix result for charm quark in QGP: quark-hadron duality?!

- AdS/CFT: Gubser 2006

- pQCD (alpha=0.4)
**Charm diffusion: HRG → \eta/s**

- **Transport coefficient**: \( \eta/s = (1/5 \sim 1/2)D_s \); Danielewicz & Gyulassy, 1985
- **\( D_c \) translates into** \( \eta/s = (2-5)/4\pi \) at \( T=180 \) MeV, comparable to J.N-Hostler 2009

- Both exhibit a minimum across the quark-hadron transition
- The charm diffusion coefficient provides us with another perspective of looking into the transport properties of sQGP/dense matter
A strongly coupled framework: HQ

- HQ relaxation rate
  - T-matrix: resonance

- HQ Langevin diffusion
- Initial distribution

- Hadronization: fragmentation vs Resonance Recombination

- D/B: hadronic diffusion
- D/B: semi-leptonic decay

- Medium/hydro

- D/B relaxation rate
D/B hadronic phase Langevin diffusion

- flow bump somewhat shifted
- spectrum quenching continues, but largely counteracted by the hardening effect of large hadronic flow → RAA not change much

- $v_2$ amplified by ~30%
- though bulk $v_2$ does not quite grow in hadronic phase, D-meson continues to thermalize and pick up $v_2$ from the medium
**D/B hadronic phase Langevin diffusion**

- Flow bump somewhat shifted
- Spectrum quenching continues, but largely counteracted by the hardening effect of large hadronic flow $\rightarrow$ RAA not change much
- $v_2$ amplified by $\sim 30$
- Though bulk $v_2$ does not quite grow in hadronic phase, D-meson continues to thermalize and pick up $v_2$ from the medium

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**Graphs**

(a) $R_{AA}^D$ vs $p_T$ for Au + Au, $\sqrt{s_{NN}}=200$ GeV, $b=7.24$ fm.

(b) $v_2$ vs $p_T$ for Au + Au, $\sqrt{s_{NN}}=200$ GeV, $b=7.24$ fm.
A strongly coupled framework: HQ

- HQ relaxation rate
  - T-matrix: resonance

- HQ Langevin diffusion

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- D/B: hadronic diffusion

- D/B relaxation rate

- D/B: semi-leptonic decay

Medium/hydro
Non-photonic decay electrons

Monte-Carlo simulation, free quark decay $c(b) \rightarrow s(c) + e + \nu$, $m_b=5.28$, $m_c=1.87$, $m_s=0.5$, $m_e=0.0005$ GeV; inclusive branching ratios: $c$:11.5% ; $b$: 10.4%

Matrix elements $\langle |M|^2 \rangle \propto (p_s \cdot p_\nu)(p_c \cdot p_e)$ and $\langle |M|^2 \rangle \propto (p_c \cdot p_e)(p_b \cdot p_\nu)$

Hadronic form factors little effect, checked

$\sigma_{b\bar{b}}/\sigma_{c\bar{c}} = 4.9 \times 10^{-3}$ (Page9)
Summary & Conclusion

◆ A **strongly coupled** framework for HQ diffusion + hadronization (Hydro + Langevin + RRM) + D/B hadronic diffusion presented

◆ The role of **resonance correlation** emphasized:
  
  (a). resonance contribution (**Q-q T-matrix** calculation) to heavy quark thermal relaxation
  
  (b). **c-q Resonance Recombination** to describe the coalescence hadronization
  
  (c). D* resonances in hadronic phase

◆ **Medium flow’s** effect (via RRM ) on heavy-meson observables highlighted


  M. He, R. J. Fries & R. Rapp, in preparation

◆ charm hadronic diffusion: **quark-hadron duality?!**

  Reference: M. He, R. J. Fries & R. Rapp, PLB701, 445  (2011)

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**Charm Does Flow!**

Thanks for attention!
Backup 1: charm quark Langevin diffusion equilibrium

c-quark $v_2$ at $e_c=0.722263$, $T_c=0.170$, $b=7.24$

$\alpha_0=0.13, \alpha_2=0.004, \kappa=4.2, m_c=1.7$

- direct hydro calculation
- nBC(x,y)-initial, $\Gamma_c=10.0$
Backup 2: D-meson RRM equilibrium

D-meson at $e_c=0.722263$, $T_c=0.170$, $b=7.24$
$\alpha_0=0.13, \alpha_2=0.004, \kappa=4.2, m_c=1.7, m_q=0.3,$
$m_D=2.1, \Gamma_D=0.1$, unif.init.spatial distr.

- direct hydro calculation
- nBC(x,y)-initial, $\Gamma_c=10.0$
Backup 3: D-meson hadronic phase

Langevin diffusion equilibrium

Graphs showing the distribution of D-meson production as a function of $p_T$ with parameters $e_{\text{dec}}=0.1094$, $T_{\text{dec}}=0.110$, $b=7.24$, $\alpha_0=0.13$, $\alpha_2=0.004$, $\kappa=4.2$, $m_c=1.7$, $m_q=0.3$, $m_D=2.1$, $\Gamma_D=0.1$, and $\Gamma_{\text{c}}=10.0 + \Gamma_D=10.0$. The graphs compare the direct hydro calculation with the initial nBC(x,y).
Backup 4: c/b coal.prob. based on scattering rate

◆ Aim: formulate coal.prob. consistent with RRM

◆ Quark scattering rate (vs thermal relaxation rate): \( \gamma_Q = n <\sigma v_{rel}> \)

Breit-Wigner resonant cross section to reproduce color singlet contribution to relaxation rate \( \Rightarrow \) scattering rate \( \Rightarrow \) boosted to lab frame at the end of Langevin simulation: \( \gamma_Q = \gamma_Q(p_t) \)

◆ Charm quark scattering time: \( \tau_Q = 1/\gamma_Q \). Within this time duration, we can form a D-meson/resonance through c-qbar resonant scattering (RRM). If the resonance formation time allowed by the system evolution (mixed phase duration) \( \tau_{res} > \tau_Q \), \( \Rightarrow \) \( P_{coal}(p_t) = 1 \); otherwise, \( P_{coal}(p_t) = \tau_{res} \gamma_Q(p_t) \)
Backup 5: c/b coal.prob. based on scattering rate (continued)

![Graph showing the scattering rate for a specific model with a legend indicating the model types and parameters](image)

- For c-quark, $T_c = 170$ MeV
- For b-quark, $T_c = 170$ MeV

**System Properties**
- Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $b = 7.24$ fm
Backup 6: New hydro fits: multistrange particles’ spectra
Backup 7: New hydro fits: bulk particles’ spectra

![Graphs showing particle spectra](image)
Backup 8: New hydro fits: multistrange and bulk particles’ $v_2$
LHC Overview

Large Hadron Collider
CERN, Geneva: 2007 Start

- $pp \sqrt{s} = 14\,\text{TeV}$
- $L = 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$
- 27 km Tunnel in Switzerland & France

CMS
- pp, general purpose; HI

Atlas
- 5000+ Physicists
- 250+ Institutes
- 60+ Countries

ALICE: HI

LHCb: B-physics

Challenges: Analyze petabytes of complex data cooperatively
Harness global computing, data & network resources