Charm-Hadron Production in pp & AA Collisions

Min He

Nanjing University of Sci. & Tech., Nanjing, China

Based on recent work done in collaboration with Ralf Rapp of Texas A&M University
Contents

1. Introduction
   - Heavy quark probes & charm hadronization

2. Charm-hadron production in pp
   - SHM augmented with RQM, vs PDG
   - Charm-baryon enhancement

3. Charm-hadron production in AA
   - 2- & 3-body RRM, equilibrium mapping
   - Space-momentum correlations
   - Event-by-event implementations of hydro-Langevin-RRM
   - RQM augmented baryons

4. Results
   - Collectivity pattern: $R_{AA}$, $v_2$ & charm hadro-chemistry: $D_s^+/D^0$, $\Lambda_c^+/D^0$
   - Extraction of charm transport coefficient
Heavy flavor transport in hot QCD matter

- initial production, $\tau \sim 1/2 m_Q$ (pQCD-FONLL, shadowing)
- $c$-quark Brownian diffusion in QGP (T-mat. reso. corr.)
  - low $p_T$ thermalization
  - high $p_T$ e-loss
- $c + q(s) \rightarrow D(Ds)$
- $c + q + q \rightarrow \Lambda_c$
- $D$-meson diffusion in hadronic liquid

- Controled baseline (pQCD), delayed thermalization by $m_Q/T$, tagged probe participating in the full fireball history $\Rightarrow$ spectrum & chemistry modifications

- Transport coeffi., + diffusion/hadronization simulation on top of bulk hydro $\Rightarrow$ Micro & Macro physics combined vs quantum effects
Ds & Λc: Probing charm hadronization

- e⁺e⁻: vacuum fragmentation, costly to excite ssbar-pair or diquark-antidiquark pair from vacuum → Ds and Λc much suppressed
- high-energy pp: likely coalescence for Λc in a quark-rich environment!
- AA: recombination hadronization in QGP → modifying charm hadro-chemistry
Charm-hadron production in pp collisions

- Enhanced \( \Lambda_c^+/D^0 \) w.r.t. pQCD based MC event generators
- Already a puzzle in pp? \( \Rightarrow \) statistical coalescence (SHM) in a quark-rich environment?!

- Standard SHM (with PDG only spectra)\( \Lambda_c^+/D^0 \) ~0.22 too small
- Tension between ALICE (mid-rapidity) vs LHCb (forward-rapidity)?
Charm-hadron production: pp SHM

- PDG: 5 Λ_C^0 (I=0), 3 Σ_C^- (I=1), 8 Ξ_C (I=1/2), 2 Ω_C^- (I=0) → missing baryons?!
- RQM: 18 extra Λ_C^- , 42 extra Σ_C^-, 62 extra Ξ_C, 34 extra Ω_C^- up to 3.5 GeV → supported by lattice PRD 84 (2011) 014025; PoS LAT. 2014 (2015) 084; PLB 737 (2014) 210

- Statistical Hadronization Model (SHM):

\[ n_i = \frac{d_i}{2\pi^2} m_i^2 T H K_2 \left( \frac{m_i}{T_H} \right) \]

Thermal densities of “prompt” ground-state charmed hadrons for hadronization temperatures of \( T_H = 170 \) and 160 MeV (including strong feeddowns) in the PDG and RQM scenarios (assuming 100% BR of Λ_C^- and Σ_C^-'s above the DN threshold into Λ_C^+).

<table>
<thead>
<tr>
<th>( n_i \times 10^{-4} \text{ fm}^{-3} )</th>
<th>( D^0 )</th>
<th>( D^+ )</th>
<th>( D^{++} )</th>
<th>( \Delta^+_c )</th>
<th>( \Xi^{+,0}_c )</th>
<th>( \Omega^0_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG(170)</td>
<td>1.161</td>
<td>0.5098</td>
<td>0.5010</td>
<td>0.3165</td>
<td>0.3310</td>
<td>0.0874</td>
</tr>
<tr>
<td>PDG(160)</td>
<td>0.4996</td>
<td>0.2223</td>
<td>0.2113</td>
<td>0.1311</td>
<td>0.1201</td>
<td>0.0304</td>
</tr>
<tr>
<td>RQM(170)</td>
<td>1.161</td>
<td>0.5098</td>
<td>0.5010</td>
<td>0.3165</td>
<td>0.6613</td>
<td>0.1173</td>
</tr>
<tr>
<td>RQM(160)</td>
<td>0.4996</td>
<td>0.2223</td>
<td>0.2113</td>
<td>0.1311</td>
<td>0.2203</td>
<td>0.0391</td>
</tr>
</tbody>
</table>

- Strong feeddowns of excited states all included: BR=100% to Λ_C^+ for all Λ_C^- & Σ_C^- even above DN (2805 MeV) threshold

- Strangeness supp. \( \gamma_s = 0.6 \)
Charm fragmentations and decays

- FONLL fragmentation of charm quarks into all kinds of charm-hadron relative weight: according to the SHM thermal densities

- Decay simulations of all excited states to ground state $D^0$, $D^+$, $D_s^+$, $\Lambda_C^+$, $\Xi_C$ & $\Omega_C$
Results: pp 5.02 TeV collisions

- Low $p_T$ enhancement from feeddowns of RQM augmented baryons
- Uncertainty band: BR=50%-100% to $\Lambda_C^+$ for $\Lambda_C$ & $\Sigma_C$ above DN (2805 MeV) threshold
Charm-hadron production in AA collisions

- Charm quark diffusion in QGP: T-matrix & Langevin
- 2- & 3-body RRM, equilibrium mapping
- Space-momentum correlations (SMCs)
- Event-by-event implementations of hydro-Langevin-RRM
- Analysis: role of SMCs & RQM augmented baryons
- Results & observables
Langevin + hydro simulation down to $T_C = 170$ MeV
fluid rest frame updates $\rightarrow$ boost to lab frame

- Lattice HQ U-pot. T-matrix resummation

- $p$- and $T$-dependent transport with $D_s(2\pi T) \sim 2$ near $T_{pc}$

- Observed large D-meson $v_2$ ---
  strong coupling of charm with QGP near $T_{pc}$ He, Fries, Rapp
Charm-hadron production in AA collisions

- Charm quark diffusion in QGP: T-matrix & Langevin
- 2- & 3-body RRM, equilibrium mapping
- Space-momentum correlations (SMCs)
- Event-by-event implementations of hydro-Langevin-RRM
- Analysis: role of SMCs & RQM augmented baryons
- Results & observables
Resonance Recombination Model (RRM)

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

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

- Realized by Boltzmann equation Ravagli & Rapp, 2007

\[
p'^{\mu} \partial_\mu f_M(t, \vec{x}, \vec{p}) = -m \Gamma f_M(t, \vec{x}, \vec{p}) + p'^0 \beta(\vec{x}, \vec{p}).
\]

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

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

- Equilibrium limit

\[
f_M(\vec{x}, \vec{p}) = \frac{\gamma p_M}{\Gamma_M} \int \frac{d^3 \vec{p}_1 d^3 \vec{p}_2}{(2\pi)^3} f_q(\vec{x}, \vec{p}_1) f_q(\vec{x}, \vec{p}_2) \times \sigma_M(s) u_{\text{rel}}(\vec{p}_1, \vec{p}_2) \delta^3(\vec{p} - \vec{p}_1 - \vec{p}_2),
\]

- Energy conservation + detailed balance

equilibrium mapping between quark & meson distributions
Generalization to 3-body RRM

- The 1st step: \( q_1(p_1) + q_2(p_2) \rightarrow \text{diquark (} p_{12} \text{)} \)

\[
f_d(\vec{x}, \vec{p}_{12}) = \frac{E_d(\vec{p}_{12})}{\Gamma_d m_d} \int \frac{d^3p_1 d^3p_2}{(2\pi)^3} f_1(\vec{x}, \vec{p}_1) f_2(\vec{x}, \vec{p}_2) \sigma_{12}(s_{12}) v_{\text{rel}}^{12}(\vec{p}_1, \vec{p}_2) \delta^3(\vec{p}_{12} - \vec{p}_1 - \vec{p}_2)
\]

- The 2nd step: \( \text{diquark (} p_{12} \text{)} + q_3(p_3) \rightarrow \text{baryon (} p \text{)} \)

\[
f_B(\vec{x}, \vec{p}) = \frac{E_B(\vec{p})}{\Gamma_B m_B} \int \frac{d^3p_{12} d^3p_3}{(2\pi)^3} f_d(\vec{x}, \vec{p}_{12}) f_3(\vec{x}, \vec{p}_3) \sigma_B(s_{d3}) v_{\text{rel}}^{d3}(\vec{p}_{12}, \vec{p}_3) \delta^3(\vec{p} - \vec{p}_{12} - \vec{p}_3)
\]

\[
= \frac{E_B(\vec{p})}{\Gamma_B m_B} \int \frac{d^3p_1 d^3p_2 d^3p_3}{(2\pi)^6} \frac{E_d(\vec{p}_{12})}{\Gamma_d m_d} f_1(\vec{x}, \vec{p}_1) f_2(\vec{x}, \vec{p}_2) f_3(\vec{x}, \vec{p}_3) \times \sigma_{12}(s_{12}) v_{\text{rel}}^{12}(\vec{p}_1, \vec{p}_2) \sigma_B(s_{d3}) v_{\text{rel}}^{d3}(\vec{p}_{12}, \vec{p}_3) |_{\vec{p}_{12}=\vec{p}_1+\vec{p}_2} \delta^3(\vec{p} - \vec{p}_1 - \vec{p}_2 - \vec{p}_3)
\]

--- baryons formed via “dynamically” generating an intermediate diquark resonance, finally still depending on 3 quark distributions on equal footing

- Meson/baryon invariant spectra on hydrodynamic Cooper-Frye hypersurface at \( T_H=170 \text{ MeV} \)

\[
\frac{dN_{M,B}}{p_T dp_T d\phi_p dy} = \int \frac{p \cdot d\sigma}{(2\pi)^3} f_{M,B}(\vec{x}, \vec{p})
\]
Charm-hadron production in AA collisions

- Charm quark diffusion in QGP: T-matrix & Langevin
- 2- & 3-body RRM, equilibrium mapping
- **Space-momentum correlations (SMCs)**
- Event-by-event implementations of hydro-Langevin-RRM
- Analysis: role of SMCs & RQM augmented baryons
- Results & observables
Space-momentum correlations (SMCs)

- **hydro**: a manifestation of SMCs

\[ f_{q}^{eq}(\vec{x}, \vec{p}) = g_{q}e^{-\frac{p \cdot u(x)}{T(x)}} = g_{q}e^{-\gamma T(x)[m_{T}\cosh(y-\eta) - \vec{p}_{T} \cdot \vec{v}_{T}(x)]/T(x)} \]

**longitudinal boost invariance**: \( y - \eta \)

**transverse SMCs**: \( p_{T} \cdot v_{T} \)

- **hydro-q density**: low (high) \( p_{T} \)-q more concentrated in center (boundary)

**what if neglecting SMCs**: uniformly distributed independent of \( p_{T} \)
as usually done in **conventional instantaneous coalescence models**

\[ f_{c,q}(\vec{x}, \vec{p}) = (2\pi)^{3} \frac{dN_{c,q}}{d^{3}\vec{x}d^{3}\vec{p}} = \frac{(2\pi)^{3}}{VE(\vec{p})} \frac{dN_{c,q}}{p_{T}d\vec{p}d\phi_{q}dy} \quad \& \quad \int p \cdot d\sigma = E(\vec{p})V \]
SMCs: Langevin charm quarks

- Langevin simulation of charm quark diffusion in a hydrodynamically expanding QGP with T-matrix charm thermalization rate
- c-quarks: low (high) \( p_T \)-c more populated in central (outer) region

**Langevin charm quarks**
- \( p_T = 0.0-1.0 \text{ GeV} \), at freezeout \( T_c = 170 \text{ MeV} \)
- \( p_T = 3.0-4.0 \text{ GeV} \), at freezeout \( T_c = 170 \text{ MeV} \)

- SMCs usually neglected in ICMs: uniformly distributed independent of \( p_T \)
- what will be the role of SMCs in recombination/RRM?
Charm-hadron production in AA collisions

- Charm quark diffusion in QGP: T-matrix & Langevin
- 2- & 3-body RRM, equilibrium mapping
- Space-momentum correlations (SMCs)
- Event-by-event implementations of hydro-Langevin-RRM
- Analysis: role of SMCs & RQM augmented baryons
- Results & observables
Charm quark recombination probability

- No. of mesons/baryons formed from a single c-quark of rest frame $p_c^*$

\[
N_M(p_c^*) = \frac{\int \frac{d^3 \vec{p}}{(2\pi)^3} g_q e^{-E(\vec{p}/T_c)}/T_p c E_M(\vec{p})}{m_M \Gamma_M} \sigma(s) \nu_{rel},
\]

\[
N_B(p_c^*) = \frac{\int \frac{d^3 \vec{p}_1 d^3 \vec{p}_2}{(2\pi)^6} g_1 e^{-E(\vec{p}_1)/T_c} g_2 e^{-E(\vec{p}_2)/T_c} E_d(\vec{p}_{12})}{m_d \Gamma_d} \frac{E_d(\vec{p}_{12})}{m_d \Gamma_d} \sigma(s_{12}) \nu_{rel}(\vec{p}_1, \vec{p}_2) \frac{E_B(\vec{p})}{m_B \Gamma_B} \sigma(s_{d3}) \nu_{rel}(\vec{p}_{12}, \vec{p}_{30}).
\]

- Renormalizing $N_M(p_c^*)$ and $N_B(p_c^*)$ by a common factor $\sim 3.6$ for all charmed mesons/baryons such that

\[
\sum_M P_{coal,M}(p_c^* = 0) + \sum_B P_{coal,B}(p_c^* = 0) = 1
\]

--- charm conservation consistently built in, in a (e-by-e) way without spoiling the relative chemical equilibrium realized by RRM

QM19 Wuhan Nov.5,2019
Event-by-event Langevin-RRM simulation

- for a single Langevin c-quark, sample a/two thermal light-q distribution(s)
  \[
  \frac{dN_M}{d\eta} \big|_{\eta=0} = \sum_n \Delta N_M[n] = \sum_n \frac{p \cdot d\sigma(j_0)}{m_M \Gamma_M} \sigma(s) v_{rel}
  \]
  \[
  \frac{dN_B}{d\eta} \big|_{\eta=0} = \sum_{n_1} \sum_{n_2} \Delta N_B[n_1, n_2]
  \]
  \[
  = \sum_{n_1} \sum_{n_2} \frac{p \cdot d\sigma(j_0)}{m_B \Gamma_B} \frac{E_d(P_{12})}{m_d \Gamma_d} \sigma(s_{12}) v_{rel}^{12}(P_{1n_1}, P_{2n_2}) \sigma(s_{d3}) v_{rel}^{d3}.
  \]
  \[
  \vec{p} = \vec{p}_{1n} + \vec{p}_c
  \]
  \[
  \vec{p} = \vec{p}_{1n_1} + \vec{p}_{2n_2} + \vec{p}_c
  \]

- equil. mapping with large transport coeffi. checks out: SMCs incorporated

- equil. mapping: both kinetic & chemical \(\Rightarrow\) observables come out as RRM predictions with realistic T-matrix transport coefficient
Charm-hadron production in AA collisions

- Charm quark diffusion in QGP: T-matrix & Langevin
- 2- & 3-body RRM, equilibrium mapping
- Space-momentum correlations (SMCs)
- Event-by-event implementations of hydro-Langevin-RRM
- Analysis: role of SMCs & RQM augmented baryons
- Results & observables
Direct $D^0$ & $\Lambda_c^+$ production via RRM

- Including SMCs makes the spectra harder & enhances the ratio $\Lambda_c^+/D_0$

- Relatively fast-moving $c$-quarks [$p_T \sim 3-4$ GeV] moving to the outer part of the fireball find higher-density of harder [$p_T \sim 0.6-0.9$ GeV] light quarks for recombination

- An effect entering squared for the recombination production of $\Lambda_c^+$

Stronger thermalization

QM19  Wuhan  Nov.5, 2019
Recombinant vs fragmenting spectra

- **Hydro-Langevin-RRM(+fragmentation):** for all charm-mesons/baryons
  - higher states decay into ground state $D^0$, $D^+$, $D_s^+$, $\Lambda_C^+$

- **SMCs extend the recombinant component toward (quite) higher $p_T$:**
  - RQM augmented higher baryon states’ RRM spectra even harder (also thanks to SMCs)
  - RRM & frag. cross at $p_T \sim 8.5$ (13) GeV for $D^0$ ($\Lambda_C^+$)

- **Helpful for large total $v_2$** (weighted between RRM vs frag. components)
Further interaction in hadronic phase

- Charm-meson/baryon hadronic diffusion coeffi.: empirical cross sections He, Fries, Rapp’12
- Further mild suppression & mild increase in $v_2$
Charm-hadron production in AA collisions

- Charm quark diffusion in QGP: T-matrix & Langevin
- 2- & 3-body RRM, equilibrium mapping
- Space-momentum correlations (SMCs)
- Event-by-event implementations of hydro-Langevin-RRM
- Analysis: role of SMCs & RQM augmented baryons
- Results & observables
D⁰, Dˢ⁺ & Λᶜ⁺ suppression & elliptic flow

- Final total D⁰, Dˢ⁺ & Λᶜ⁺, including feeddowns from all RQM baryons

- T-matrix coefficient*K-factor(=1.6), to compensate for radiative e-loss; uncertainty: BR=50-100% to Λᶜ⁺ for Λᶜ’s & Σᶜ’s above DN (2805 MeV)
Total $\Lambda_c^+/D_0^0$ & $D_s^+/D^0$

- T-matrix coefficient*K-factor(=1.6), to compensate for radiative e-loss; BR=50-100% to $\Lambda_c^+$ for $\Lambda_c$’s & $\Sigma_c$’s above DN (2805 MeV) threshold

- $\Lambda_c^+/D_0$: low $p_T$ RRM equil. limit = SHM pp; intermediate $p_T$ enhancement from RRM with SMCs; high $p_T$ fragmentation pp value; Data (updated RHIC and LHC) trend largely reproduced

- $D_s^+/D^0$ enhancement: recomb. of charm in a strangeness-equilibrated QGP
Summary & outlook

>> Charm-hadron production in pp collisions
- RQM augmented SHM
- Low $p_T$ enhancement of $\Lambda_c^+$ from “missing” charm-baryons

>> Charm-hadron production in AA collisions
- 3-body RRM developed, equilibrium mapping (both kinetic & chemical) ensured by 4-momentum conservation
- Genuine space-momentum correlations (SMCs) enhancing $\Lambda_c^+/D^0$; exact charm conservation implemented on an e-by-e basis
  
  ➔ Both have been challenging within conventional instantaneous coalescence models
- $p_T$-dependent $\Lambda_c^+/D^0$ & $D_s^+/D^0$ enhancement emerge from hydro-Langevin-RRM(+fragmentation) simulations; data trend largely reproduced within BR’s uncertainties
Back-up: pp 200 GeV collisions

- Low pT enhancement from feeddowns of RQM augmented baryons
- Uncertainty band: BR=50-100% to $\Lambda_C^+$ for $\Lambda_C$ & $\Sigma_C$ above DN (2805 MeV) threshold
of Fig. 3. Being convenient to implement in our event-by-event Langevin-RRM simulation, this global renormalization of charm quark coalescence probability does not change the relative difference between the $p_T$ spectra of any two charmed hadrons, therefore not affecting the $p_T$-dependent $\Lambda_c^+/D^0$. This point is in marked contrast to the treatment in [14], where the authors reduced the harmonic oscillator frequency in determining the hadron wave functions and thereby significantly increased the radii of charmed mesons and baryons (relative to the quark model predictions), in order to use up low $p_T$ charm quarks in coalescence; the resulting $\Lambda_c^+/D^0$ was enhanced as a coincidence of using the same reduced frequency parameter for charmed mesons and baryons. The same purpose was achieved in [15] by artificially amplifying the normalization constants of the coalescence Wigner functions (the amplification factor of baryons is the square of that of mesons).
SMCs enhance the $\Lambda_c^+ / D^0$ at $p_T \sim 4.2$ GeV(a)

$p_{Tc} = 3-4$ GeV and light quarks of $p_{Tq} = 0.6-0.9$ GeV are more densely distributed in the outer region of the fireball. Therefore these quarks occupy an effectively smaller (than the whole fireball volume $V_{fb}$) volume $V_{c,\text{eff}}$ and $V_{q,\text{eff}}$ and thus have effectively larger density that can be schematically written as $\Delta N_c(p_{Tc} = 3-4$ GeV$/V_{c,\text{eff}}$ and $\Delta N_q(p_{Tc} = 0.6-0.9$ GeV$)/V_{q,\text{eff}}$.

Consider, e.g., the formation via RRM of $D^0$ and $\Lambda_c^+$ of the same $p_T = 4.2$ GeV. In the most straightforward picture, recombination proceeds by adding the momenta of the participating constituent quarks according to their mass ratio $m_c/m_q = 5$, once they are spatially adjacent. Therefore, charm quarks of $p_{Tc} = 3.0-3.5$ GeV that are already roaming around the outer region of the fireball, will have good chance to recombine with the light quarks of $p_{Tq} = 0.6-0.7$ GeV (remember they are also most likely to show up in the outer region) to form $D^0$ and $\Lambda_c^+$ of (almost) the same $p_T = 4.2$ GeV, roughly following the momentum addition rule $3.5 + 0.7 = 4.2$ GeV and $3.0 + 0.6 + 0.6 = 4.2$ GeV, respectively. Then the RRM production yield of $D^0$ and $\Lambda_c^+$ of the same $p_T = 4.2$ GeV is schematically expressed as
SMCs enhance the $\Lambda_c^+ / D^0$ at $p_T \sim 4.2$ GeV(b)

\[\Delta N_{D^0}(4.2) \sim \frac{\Delta N_c(3.0 - 3.5)}{V_{c,\text{eff}}} \cdot \frac{\Delta N_q(0.6 - 0.7)}{V_{q,\text{eff}}} \quad (8)\]

\[\Delta N_{\Lambda_c^+}(4.2) \sim \frac{\Delta N_c(3.0 - 3.5)}{V_{c,\text{eff}}} \cdot \frac{\Delta N_q(0.6 - 0.7)}{V_{q,\text{eff}}} \cdot \frac{\Delta N_q(0.6 - 0.7)}{V_{q,\text{eff}}} \]

Quarks in the specified $p_T$ interval (i.e., $p_{Tc} = 3.0 - 3.5$ GeV for charm quarks and $p_{Tq} = 0.6 - 0.7$ GeV for light quarks) becomes higher than the case of RRM neglecting space-momentum correlations, where $V_{c/q,\text{eff}}$ is replaced with the whole fireball volume $V_{fb}$ and the densities thus become uniform and smaller. Furthermore, while the higher light quark spatial density is counted only once in $D^0$'s RRM, the square of it comes into the $\Lambda_c^+$'s RRM, leading to a stronger enhancement in $\Lambda_c^+$ spectra and thereby an enhanced $\Lambda_c/D^0$ ratio, relative to the case of RRM without incorporating space-momentum correlations.
Langevin equil. Limit with large coeffi.

![Graphs showing charm quark spectra and v2 with large coefficient.](image)

**Fig. 9.** Langevin charm quark $p_T$ spectra and $v_2$ with large coefficient.
Ds(2\pi T): K=1.6 vs updated SCS T-matrix
Baryon to meson ratio enhancement

- B/M enhanced at intermediate $p_T$ in central AA collisions
- Nicely (straightforwardly) explained by coalescence models Ko, Fries, Hwa
- A direct indication of the working of coalescence hadronization
  
  \[ f_M(p_T) \sim f_q(p_T/2)*f_{\bar{q}}(p_T/2) \quad \text{VS} \quad f_B(p_T) \sim f_q(p_T/3)*f_q(p_T/3)*f_q(p_T/3) \]
Does it carry over to the HF sector?

- A sensitive probe of HQ hadronization via recombination in the presence of deconfined QGP
- A direct measure of the degree of HQ thermalization/interaction strength
RRM: equilibrium mapping

- RRM on hydrofreezeout hypersurface at $T_c$ with $f_{eq(x,p)}^{q} = g_{q} e^{-p \cdot u(x)/T(x)}$

- Equilibrium mapping: ensured by 4-momentum conservation in RRM
  $m_q = 0.3$, $m_s = 0.4$, $m_c = 1.5$, $\Gamma_M \sim 0.1$ GeV, $\Gamma_d \sim 0.2$ GeV, $\Gamma_B \sim 0.3$ GeV
Direct $D^0$ & $\Lambda_c^+$ production via RRM

- Including SMCs makes the spectra harder & enhances the ratio $\Lambda_c^+/D_0$

- Consider RRM formation of $D^0$ (3.5+0.7) & $\Lambda_c^+$ (3.0+0.6+0.6) of $p_T \sim$ 4.2 GeV:
  
  - Enhancement of density of light-q of $p_T \sim$ 0.6-0.7 GeV & c of $p_T \sim$ 3.0-3.5 GeV

\[
\begin{align*}
\Delta N_{D^0}(4.2) & \sim \frac{\Delta N_c(3.0 - 3.5)}{V_{c,\text{eff}}} \cdot \frac{\Delta N_q(0.6 - 0.7)}{V_{q,\text{eff}}} \\
\Delta N_{\Lambda_c^+}(4.2) & \sim \frac{\Delta N_c(3.0 - 3.5)}{V_{c,\text{eff}}} \cdot \frac{\Delta N_q(0.6 - 0.7)}{V_{q,\text{eff}}} \cdot \frac{\Delta N_q(0.6 - 0.7)}{V_{q,\text{eff}}} 
\end{align*}
\]  

--- Rencombinant quark density enhanced vs w/o SMCs: $V_{\text{eff}} < V_{\text{fb}}$

--- Enhanced light-q density entering $D^0$ RRM only once vs twice (squared) for $\Lambda_c^+$ RRM ⇒ the ratio $\Lambda_c^+/D^0$ enhanced!