HF Production and Dynamics in AMPT

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INT Program INT-17-1b
Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks
May 1 - June 8, 2017

May 4, 2017
Outline

• Where are heavy flavours in the AMPT model?
• Anisotropic parton escape: review
• Anisotropic parton escape: flavour dependence
• Future heavy flavour work with AMPT
• Summary
A Multi-Phase Transport AMPT was constructed as a comprehensive model for heavy ion collisions. It aims to evolve the system from initial condition to final observables; conserve energy/momentum/flavour/charge of each event, include particle productions of different flavours at different $P_T$ & $y$, keep non-equilibrium features and dynamics (e.g. intrinsic fluctuations and correlations).

It is also a test-bed of different ideas:

- **Discovery of the triangular flow $v_3$**
  - Alver & Roland, PRC 81 (2010)

- **Longitudinal (de)correlations of flows**
  - Pang et al. PRC 91 (2015), EPJA52 (2016)

- **Flow may be dominated by anisotropic parton escape**
  - He et al. PLB753 (2016); ZWL et al. NPA 956 (2016)

So we are working to extend AMPT to heavy flavours, in order to simultaneously study light flavours, heavy flavours including their interactions.
Where are heavy flavours (Q) in the current AMPT model?

Structure of AMPT v2.xx (String Melting version)

A+B → HIJING1.0:
Minijet partons, excited strings, spectator nucleons

Generate parton space-time → Strings melt to q & qbar via intermediate hadrons

Partons freeze out → ZPC (parton cascade)

Hadronization (Quark Coalescence)

Extended ART (hadron cascade)

Hadrons freeze out (at a global cut-off time); then strong-decay most remaining resonances

Final particle spectra

Heavy hadrons in final spectra

Initial Q/Qbar production

2 ↔ 2 elastic scatterings

Coalescence to heavy hadrons (D, D_s, D*, Λ_c, B, ...)

Where are heavy flavours (Q) in the current AMPT model?
The escape mechanism: review

Liang He, Terrence Edmonds, ZWL, Feng Liu, Denes Molnar, Fuqiang Wang: PLB 753 (2016): Anisotropic parton escape is the dominant source of azimuthal anisotropy in transport models. ZWL et al. NPA 956 (2016) for Quark Matter 2015: Elliptic anisotropy $v_2$ may be dominated by particle escape instead of hydrodynamic flow.

Background:

- **Transport models** at large-enough cross section will approach hydrodynamics.

It has been generally believed that:

- Early hydro-type collective flow in sQGP converts initial spatial anisotropy into final momentum-space $v_n$.

- For low-$P_T$ particles in high-energy heavy ion collisions, since both hydrodynamics and transport models can describe $v_n$ data, the mechanism of $v_n$ development in transport models (*via particle interactions*) is in principle the same as in hydrodynamics (*via pressure gradients*).
The escape mechanism: review

Small systems: again, both hydrodynamics and transport can describe flow.

Bozek and Broniowski, PLB 718 (2013) using e-by-e viscous hydrodynamics.

Bzdak and Ma, PRL 113 (2014) using AMPT (String Melting version).

Puzzle for small systems such as p+Pb or d+Au:

- Mean free path may be comparable to the system size; is hydrodynamics still applicable to such small systems?
- Transport and hydrodynamics should be different here, could they also be different for large systems?
The escape mechanism: review

We have followed the complete parton collision history and evaluate its effect on parton $v_2$ in AMPT.

**Ncoll**: number of collisions suffered by a parton

3 parton populations at any given $N_{coll}$:

- **freezeout partons**: freeze out after exactly $N_{coll}$ collisions;
- **active partons**: will collide further; freeze out after $>N_{coll}$ collisions;
- **all partons**: sum of the above two populations (i.e. all partons that have survived $N_{coll}$ collisions).

He et al. PLB753 (2016)
At $N_{\text{coll}}=0$: all partons: $v_2=0$ by symmetry (as they include all initial partons); they contain 2 parts: escaped/freeezeout: $v_2 \approx 4.5\%$, active: $v_2 < 0$.

At $N_{\text{coll}}=1$: active partons at $N_{\text{coll}}=0$ collide once each & become all partons at $N_{\text{coll}}=1$: $v_2 \approx 0$

This process repeats itself at higher $N_{\text{coll}}$ (with fewer partons), eventually all partons freezeout/hadronize. $<v_2> = \text{weighed average of the freezeout partons’ } v_2$. 
The escape mechanism: review

At \( N_{\text{coll}} = 0 \):
escaped partons: \( v_2 \approx 4.5\% \),
this is **purely** due to
anisotropic escape probability
(response to geometrical shape only, no contribution from collective flow)

At \( N_{\text{coll}} \geq 1 \):
escaped partons: \( v_2 > 0 \)
due to
anisotropic escape probability & (anisotropic) **collective flow**.

How to separate the two contributions?
We design a **Random-\( \phi \) Test**

In event-averaged picture of elliptic flow:
The escape mechanism: review

\( v_2 \) from the **Random-\( \phi \) Test**: purely from the escape mechanism

He et al. PLB753 (2016)

\[ \begin{array}{cccc}
\text{Au}+\text{Au} & 3.9\% & 2.7\% & 69\% \\
\text{d}+\text{Au} & 2.7\% & 2.5\% & 93\% \\
\end{array} \]

\(<v_2>_{\text{normal}} & <v_2>_{\text{random-\( \phi \)}} \quad \text{Ratio} \quad <N_{\text{coll}}> \quad \sim \text{fraction from pure escape} \quad 4.6 \text{ (modest)} \quad 1.2 \text{ (low)} \end{array} \)
The escape mechanism: review

ZWL et al. NPA 956 (2016)

Anisotropic particle escape is dominant for $v_2$ in small systems & even for $v_2$ in semi-central AuAu at RHIC.

At very large $\sigma$ or $\langle N_{coll} \rangle$, hydrodynamic collective flow will be the dominant contribution of $v_2$.

MPC: the same qualitative conclusion as AMPT despite many differences (parton initial condition, cross section & $d\sigma/dt$, formation time, parton-subdivision)

$\frac{v_2}{2} \text{ ratio} \sim \text{fraction from pure escape}$

\[ \begin{array}{c}
\text{AuAu (b=7.3fm)} \\
\text{AMPT} \\
\text{AMPT random } \varphi \\
\text{MPC} \\
\text{MPC random } \varphi
\end{array} \]

\[ \begin{array}{c}
\sigma (\text{mb}) \\
0 \\
10 \\
20 \\
30 \\
40 \\
50 \\
60
\end{array} \]

\[ \begin{array}{c}
\langle v_2 \rangle \text{ random/} \langle v_2 \rangle \\
2 \\
4 \\
6 \\
8 \\
10
\end{array} \]
The escape mechanism: review

Implications:

• The escape mechanism helps to explain similar anisotropic flows observed in small and large systems: since both are dominated by same mechanism *(anisotropic escape probability)*

• The driving force for $v_2$ at low & high $P_T$ is qualitatively the same since both are dominated by *anisotropic probability of interactions* before escape (scatterings/kicks for low $P_T$ & energy loss for high $P_T$)

• At low/modest opacity/\(<\text{Ncoll}\>): *transport and hydrodynamics are different.*

The escape mechanism dominates $v_n$ at low to modest opacity/\(<\text{Ncoll}\)>; hydro-type collective flow dominates $v_n$ at very high opacity/\(<\text{Ncoll}\>.

Which is the case for A+B collisions at RHIC & LHC?
The escape mechanism: flavour dependence

Our previous results are for ALL quarks @200 GeV.

**Does the escape mechanism work differently for different flavours?**
**or**
**Does collective flow work differently for different flavours?**

We now use string melting AMPT to analyze light (u/d), strange, charm quarks in p+Pb@5TeV, Au+Au@200GeV, Pb+Pb@2.76TeV.

H.L. Li, ZWL, F.Q. Wang, in preparation;
first result on pPb in H.L. Li, ZWL, F.Q. Wang, J Phys Conf Ser 779 (2017)
The escape mechanism: flavour dependence

Elastic parton scatterings only:

\[ q_i q_j \rightarrow q_i q_j, \quad q_i \bar{q}_j \rightarrow q_i \bar{q}_j, \quad qQ \rightarrow qQ, \ldots \]

Caveat: here we use the same cross section for all flavours:

Parton cross section based on \( gg \rightarrow gg \) in leading-order pQCD:

\[
\frac{d\sigma_{gg}}{dt} \sim \frac{9\pi\alpha_s^2}{2s^2} \left( 3 - \frac{ut}{s^2} - \frac{us}{t^2} - \frac{st}{u^2} \right)
\]

\[
\sim \frac{9\pi\alpha_s^2}{2} \left( \frac{1}{t^2} + \frac{1}{u^2} \right) \sim \frac{9\pi\alpha_s^2}{2t^2}
\]

A screening mass \( \mu \) regulates the divergence:

\[
\frac{d\sigma_{gg}}{dt} \sim \frac{9\pi\alpha_s^2}{2(t - \mu^2)^2}
\]

\[
\rightarrow \sigma_{gg} = \frac{9\pi\alpha_s^2}{2\mu^2} \frac{1}{1 + \mu^2/s}
\]

3mb cross section is used since it reproduces \( \pi/K/p \) \( v2(P_T) \)

ZWL, PRC 90 (2014) G.L. Ma & ZWL, PRC 93 (2016)
The update of summary

Fig. 1: Partons v2 as function of number of collisions.

1, Quarks v2 as function of ncoll and significantly depends on mass and collisions system.

2, Hydrodynamic type flow has more contribution for charm v2 comparing to light quark v2.

Providing simulation results (the expected and surprised results)

Fig. 2 (Providing the quarks v2)

<table>
<thead>
<tr>
<th>No</th>
<th>pt cut</th>
<th>pPb b=0 fm</th>
<th>AuAu b=6.6-8.1 fm</th>
<th>PbPb b=8 fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>&lt;Ncoll&gt;</td>
<td>3.279%</td>
<td>0.002%</td>
<td>7.292%</td>
</tr>
<tr>
<td>&lt;Ncoll&gt;=normal</td>
<td>v2 Rndm</td>
<td>2.392%</td>
<td>0.03%</td>
<td>2.931%</td>
</tr>
<tr>
<td>v2 Norm</td>
<td>4.468%</td>
<td>0.03%</td>
<td>4.784%</td>
<td>0.06%</td>
</tr>
<tr>
<td>v2 Rndm/v2 Norm</td>
<td>72.9%</td>
<td>63%</td>
<td>42.5%</td>
<td>47.4%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C-Quark</th>
<th>&lt;Ncoll&gt;</th>
<th>3.203%</th>
<th>0.008%</th>
<th>2.852%</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Ncoll&gt;=normal</td>
<td>v2 Rndm</td>
<td>1.894%</td>
<td>0.009%</td>
<td>1.214%</td>
</tr>
<tr>
<td>v2 Norm</td>
<td>4.784%</td>
<td>0.03%</td>
<td>3.885%</td>
<td>0.06%</td>
</tr>
<tr>
<td>v2 Rndm/v2 Norm</td>
<td>59.1%</td>
<td>47.4%</td>
<td>26.5%</td>
<td>22%</td>
</tr>
</tbody>
</table>

Mass ordering in v2(Ncoll):

v2c < v2s < v2ud at small Ncoll,
reversed at large Ncoll.
The escape mechanism: flavour dependence

Mass ordering in the Ncoll distribution for all 3 systems:

\(<\text{Ncoll}\>^c > <\text{Ncoll}\>^s > <\text{Ncoll}\>^{ud}\)

Related to the initial (momentum &) spatial distribution

\(R_\perp: \text{transverse radius}\)
The escape mechanism: flavour dependence

Random-ϕ for light quarks only
(Normal charm: they keep their collective flow):
large reduction of charm $v_2$ (like the random-ϕ test)

light quark collective flow is essential for charm $v_2$
The escape mechanism: flavour dependence

Space-momentum correlation: 
\[ \beta_\perp = \left\langle \frac{\vec{r}_\perp \cdot \vec{p}}{r_\perp p} \right\rangle \]

He et al. PLB753 (2016)

\[ \sim \text{transverse flow velocity} \]

\[ AMPT \text{ Au+Au (b=7.3 fm)} \]

Strong r-p correlation

\[ \sim \text{Collective flow} \]
The escape mechanism: flavour dependence

Space-momentum correlation: 
\[ \beta_\perp = \frac{\left< \frac{\mathbf{r}_\perp \cdot \mathbf{p}}{r_\perp p} \right>}{\left< \frac{r_\perp p}{r_\perp p} \right>} \]

He et al. PLB753 (2016)

Strong r-p correlation

Random-\(\phi\) test:
finite r-p correlation

r-p correlation purely from escape mechanism, not from collective flow

\( \sim \) Collective flow

Collective flow is destroyed
The escape mechanism: flavour dependence

Space-momentum correlation:

Random-\(\phi\) light / Normal charm:
all partons_charm’s correlation \(\sim 0\):
\[\Rightarrow\] charm cannot “flow” without light quark flow
\(\text{(although charm still interacts a lot with random-}\phi\text{ light quarks)}\).
The escape mechanism: flavour dependence

Analysis is done for 3 systems:

- Au+Au 200 GeV b:6.6-8.1 fm
- Pb+Pb 2.76 TeV 8 fm
- p+Pb 5 TeV 0 fm
The escape mechanism: flavour dependence

\[ v_2(P_T): \text{mass ordering at low } P_T \]
this is partly responsible for
the mass ordering of hadron \(v_2\)

H.L. Li et al. PRC 93 (2016); arXiv:1604.07387
### The escape mechanism: flavour dependence

<table>
<thead>
<tr>
<th>No pt cut</th>
<th>pPb b=0fm</th>
<th>AuAu b=6.6-8.1fm</th>
<th>PbPb b=8fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>light</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;Ncoll&gt;= 2.02</td>
<td>&lt;Ncoll&gt;= 4.5</td>
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<tr>
<td></td>
<td>&lt;v2&gt;Rndm= 2.392%</td>
<td>&lt;v2&gt;Rndm= 2.931%</td>
<td>&lt;v2&gt;Rndm= 3.214%</td>
</tr>
<tr>
<td></td>
<td>&lt;v2&gt;Norm= 3.279%</td>
<td>&lt;v2&gt;Norm= 4.468%</td>
<td>&lt;v2&gt;Norm= 7.562%</td>
</tr>
<tr>
<td></td>
<td>&lt;v2&gt;Rndm/&lt;v2&gt;Norm=72.9%</td>
<td>&lt;v2&gt;Rndm/&lt;v2&gt;Norm=65.6%</td>
<td>&lt;v2&gt;Rndm/&lt;v2&gt;Norm=42.5%</td>
</tr>
<tr>
<td>s-quark</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;Ncoll&gt;= 2.54</td>
<td>&lt;Ncoll&gt;= 5.45</td>
<td>&lt;Ncoll&gt;= 11.14</td>
</tr>
<tr>
<td></td>
<td>&lt;v2&gt;Rndm= 1.894%</td>
<td>&lt;v2&gt;Rndm= 2.266%</td>
<td>&lt;v2&gt;Rndm= 2.23%</td>
</tr>
<tr>
<td></td>
<td>&lt;v2&gt;Norm= 3.203%</td>
<td>&lt;v2&gt;Norm= 4.784%</td>
<td>&lt;v2&gt;Norm= 8.424%</td>
</tr>
<tr>
<td></td>
<td>&lt;v2&gt;Rndm/&lt;v2&gt;Norm=59.1%</td>
<td>&lt;v2&gt;Rndm/&lt;v2&gt;Norm=47.4%</td>
<td>&lt;v2&gt;Rndm/&lt;v2&gt;Norm=26.5%</td>
</tr>
<tr>
<td>c-quark</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;Ncoll&gt;= 4.23</td>
<td>&lt;Ncoll&gt;= 8.6</td>
<td>&lt;Ncoll&gt;= 15.48</td>
</tr>
<tr>
<td></td>
<td>&lt;v2&gt;Rndm= 1.214%</td>
<td>&lt;v2&gt;Rndm= 0.8455%</td>
<td>&lt;v2&gt;Rndm= 0.6724%</td>
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<tr>
<td></td>
<td>&lt;v2&gt;Norm= 2.139%</td>
<td>&lt;v2&gt;Norm= 3.885%</td>
<td>&lt;v2&gt;Norm= 7.923%</td>
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<tr>
<td></td>
<td>&lt;v2&gt;Rndm/&lt;v2&gt;Norm=56.8%</td>
<td>&lt;v2&gt;Rndm/&lt;v2&gt;Norm=22%</td>
<td>&lt;v2&gt;Rndm/&lt;v2&gt;Norm=8.5%</td>
</tr>
</tbody>
</table>

The escape mechanism:
- flavour dependence
- System size/energy
- Less from escape / more from collective flow
The escape mechanism: flavour dependence

$\Delta \phi$: change of azimuth due to one collision (the Ncoll-th collision):

Mass ordering on parton deflection angle: it takes more collisions to deflect a heavier quark, so light quark flow & strong light-charm interaction are essential to generate significant charm $v_2$. 

$\langle \Delta \phi \rangle$
The escape mechanism: flavour dependence

\[ \frac{\langle v_2 \rangle_{\text{random-ϕ}}}{\langle v_2 \rangle_{\text{normal}}} \text{ ratio} \]
\[ \sim \text{fraction from pure escape:} \]

<table>
<thead>
<tr>
<th></th>
<th>dAu@200GeV b=0 fm</th>
<th>pPb@5TeV b=0 fm</th>
<th>AuAu@200GeV b=6.6-8.1 fm</th>
<th><a href="mailto:PbPb@2.76TeV">PbPb@2.76TeV</a> b=8 fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>u/d</td>
<td>93% (all quarks)</td>
<td>72.9%</td>
<td>65.6%</td>
<td>42.5%</td>
</tr>
<tr>
<td>s</td>
<td>59.1%</td>
<td>47.4%</td>
<td>26.5%</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>56.8%</td>
<td>21.8%</td>
<td>8.5%</td>
<td></td>
</tr>
</tbody>
</table>

v2 of charm quarks in AuAu@RHIC-200GeV & PbPb@LHC:
mostly comes from collective flow (not the escape mechanism).

⇒ heavy quarks are more sensitive probes of collective flow & the medium.

Esha, Md. Nasim & Huang, JPG44 (2017)

v2 of light quarks:
escape mechanism is more important for AuAu@RHIC, pPb@LHC and smaller/lower-energy systems;
hydro-type collective flow is more important for PbPb@LHC although with significant contribution from the escape mechanism.
Future heavy flavour work with AMPT

Up-to-date proton parton distribution function & nuclear shadowing needed for heavy flavors and high-\(P_T\)

*ongoing with L. Zheng, S.S. Shi, C. Zhang at CCNU*

Include gluons & inelastic parton interactions

- Include gluons in string melting initial condition in addition to quarks/antiquarks

- Include 2-2 inelastic parton reactions:
  \[ gg \leftrightarrow ssbar / ccbar, qqbar \leftrightarrow ssbar / ccbar, \ldots \]

- Include gluons in a coalescence/recombination model with energy momentum conservation

For high \(P_T\):

- Parton radiative energy loss

*planned*
AMPT aims to serve as a comprehensive transport model for heavy ion collisions: event-by-event from initial condition to final observables; include particle productions and interactions at different $y$ & $P_T$; conserve energy/momentum/flavour/charge (ongoing work) of each event; keep non-equilibrium dynamics & intrinsic fluctuations/correlations.

We have followed the complete parton collision history to study $v_2$ of light/strange/charm quarks in AMPT:

$v_2$ of charm quarks in AuAu@200GeV & PbPb@2.76TeV mostly comes from collective flow (not the escape mechanism), indicating that heavy quarks are more sensitive probes of the medium.

$v_2$ of light quarks at AuAu@200GeV & pPb@LHC come mostly from the escape mechanism, but at PbPb@2.76TeV comes more from collective flow (although still with significant fraction from the escape mechanism).

We are working to improve AMPT on heavy flavours, to simultaneously study light flavours, heavy flavours including their interactions.