Hybrid Hadronization

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What is Hybrid Hadronization?

- Take two existing hadronization models and merge them to create something with a wider range of applicability.
Quark Recombination

- Signature of quark recombination processes are seen in dense systems (nucleus-nucleus collisions, beam of fixed target experiments)

- Enhanced baryon/meson ratios, elliptic flow scaling with quark number, strangeness enhancement (e.g. $D_s$ vs $D$, $B_s$ vs $B$).
Compare To String Fragmentation

- Lund string fragmentation picture

- Extremely successful phenomenology $e^+e^-, p+p$

- Shortcomings of individual models:
  - Long distance behavior not properly described in recombination models; confinement not enforced.
  - Color flow needed for string fragmentation not readily available in in-medium shower MC; no cross talk of shower and thermal partons

Two Sides Of The Same Coin?

- QQ potential:

- Strong force ~ Coulomb at short distances, string behavior at large distances

- How to make this work for nuclear collisions? Put the Coulomb part back and add quark recombination to string fragmentation

Kaczmarek et al. (2007)
Partons in Monte Carlos (e.g. JETSCAPE)

- How we describe a parton depends on its virtuality $Q$, the ambient medium, and its energy (with respect to a suitable reference)

<table>
<thead>
<tr>
<th>Ambient medium</th>
<th>Large virtuality $Q$ (typically FS after hard process)</th>
<th>Large energy*</th>
<th>Hadronization ($T &lt; T_c$; $Q$, $E$ small)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T &lt; T_c$ or vacuum</td>
<td>Radiation $\rightarrow$ Shower (e.g. PYTHIA, MATTER)</td>
<td>* wrt next neighbors in phase space non-perturbative treatment $\rightarrow$ strings</td>
<td>String breaking</td>
</tr>
<tr>
<td>$T &gt; T_c$ or sufficiently dense system</td>
<td>Radiation $\rightarrow$ In-medium Shower (e.g. MATTER)</td>
<td>* wrt surrounding medium in-medium scattering (e.g. LBT, MARTINI)</td>
<td>Recombination ($T = T_c$)</td>
</tr>
</tbody>
</table>

- Virtuality usually drops faster $\rightarrow$ steps above are typically sequential.
- A single jet in A+A typically is a blend of several of these situations.
Hybrid Hadronization

- Hybrid hadronization has two well-defined limits:
  - Dilute systems $\rightarrow$ String fragmentation
  - Dense systems $\rightarrow$ Quark recombination
- Extrapolate smoothly in between, based on probabilities calculated with realistic potentials.
- Monte Carlo implementation suitable for event generators.

- Recombination Step: Developed for the JET Collaboration
  
  K. Han, RJF., C. M. Ko, Phys. Rev. C 93, 045207 (2016)

- (Remnant) string formation

- String fragmentation: standard PYTHIA
Steps in Monte Carlo Implementation

- Implementation for jets in an event generator

- Force gluon decay

- Recombine

- Remnant strings

- String Decay

- Jets in QGP: add sampled thermal quarks on the $T=T_c$ hypersurface

K. Han, RJF., C. M. Ko, Phys. Rev. C 93, 045207 (2016)
Hybrid Hadronization

- Distance of quark-antiquark pairs in phase space (in their local rest frame) determines the recombination probability.

- Earlier studies with PYTHIA 6 showers: “dense” jet bulk with long tails (mostly large-$z$)

K. Han, RJF., C. M. Ko, Phys. Rev. C 93, 045207 (2016)
Recombination Probabilities

- Calculate probabilities for quark wave packets to form mesons or baryons. Wigner formalism to include space-time information:

\[ \overline{W} = \int d^3x_1 d^3p_1 \int d^3x_2 d^3p_3 \, W_a(x_1, p_1)W_b(x_2, p_2)W_M(\Delta x, \Delta p) \]

- Bound state Wigner function from harmonic oscillator wave functions

\[ W_n(u) = 2(-1)^nL_n\left(\frac{4u}{\hbar\omega}\right) e^{-2u/\hbar\omega} \]

\[ u = \frac{\hbar\omega}{2} \left( \frac{x^2}{\sigma^2} + \sigma^2 k^2 \right) \]

- For the probabilities to be positive definite, need proper q, qbar wave packets. Not provided by shower MCs.

- Assume Gaussian wave packets of certain width for simplicity. The probability densities for the \( n \)-th excited states (position \( y \), momentum \( k \)) are

\[ \overline{W}_{M,n}(y, k) = \frac{u^n}{n!} e^{-v} \]

\[ v = \frac{1}{2} \left( \frac{y^2}{\sigma^M_n^2} + k^2 \sigma^2_M \right) \]

K. Han, RJF., C. M. Ko, Phys. Rev. C 93, 045207 (2016)
Monte Carlo Implementation

- Old JET collaboration code: could only handle limited string configurations.
- Reproduced PYTHIA 6 results in vacuum
- 2018: complete rewrite of the code in C++ for JETSCAPE → v3.0
- Can now handle complex string configurations (junctions and multi-junction systems, full p+p events with MPIs etc.)
Hybrid Hadronization Example

- Example: complete p+p 200 GeV event (generated by PYTHIA 6)
- Two “jets” plus underlying event and beam remnants
Hybrid Hadronization Example

- Cartoon: Same event with added thermal partons

- Sample thermal partons from a hydro code at $T=T_c$.
  - In JETSCAPE: MUSIC hydro
Some Results: p+p

- p+p: preliminary results from v3.0 applied to PYTHIA 8 showers compared to PYTHIA 8 with string fragmentation only.

- No space-time information used in PYTHIA 8 → likely overestimate recombination contribution at intermediate momenta.

- No tuning yet.
Some Results: A+A

- MATTER showers with v3.0 ($\hat{q} = 1 \text{ GeV}^2/\text{fm}$)
  - MUSIC hydro event
  - Not tuned to data

- Shower-thermal recombination increases nucleon production at intermediate momenta as expected.
- Caveat: thermal bulk not added!

No bulk hadrons in this calculation
Hadronization: Conclusion and Outlook

- Hybrid Hadronization: Combine aspects of string fragmentation and quark recombination.
- MC implementation: Use recombination as a first stage before PYTHIA string fragmentation.
- Challenge: Incomplete information. Ideally we need color flow and space-time information.

Future developments:
- JETSCAPE 2.0; code will become publicly available.
- Tune vacuum part to data (using MATTER?)
Announcement

2\textsuperscript{nd} JETSCAPE Winter School and Workshop

January 9-13, 2019

Texas A&M University
Backup
Recombination Processes

- Atomic physics: recombination of protons and electrons into hydrogen + photons

- Nuclear/particle physics: recombination of quarks into mesons and baryons?

  WMAP: Afterglow of photons from the recombination event 300,000 years after the Big Bang (CMB).
Old Results

[K. Han, RJF., C. M. Ko, Phys. Rev. C 93, 045207 (2016)]
Hard and Semi-Hard Hadronization

- Vacuum jets embedded in a background computed with fluid dynamics

![Diagram of vacuum jets embedded in a background computed with fluid dynamics](image)
Some Results: A+A

\[ \text{MATTER+HybridHad v3.0} \]