First Results from Hybrid Hadronization in Small and Large Systems

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On behalf of the JETSCAPE Collaboration
Overview

• Hadronization Models

• Hybrid Hadronization

• Hybrid Hadronization Implementation

• Space-time Structure

• Qualitative Study of Hybrid Hadronization

• Summary
Hadronization Models

• String fragmentation:
  • Color flux expelled from the QCD vacuum at large distances leads to color flux tubes; results in string-like behavior.
  • Implemented in PYTHIA
  • Quarks in the event are connected with strings, gluons are part of these strings – these strings are then broken to form hadrons.

• Recombination/Quark Coalescence:
  • In a densely populated parton system, quarks can directly recombine into hadrons
  • Successful phenomenology in heavy-ion collisions
    • Baryon/meson ratios
    • Elliptic flow scaling
Hybrid Hadronization Model

• Hybrid Hadronization:
  • A hybrid of the existing models of string fragmentation and recombination.
  • Extrapolates smoothly between vacuum phenomenology of string fragmentation and recombination in a densely populated environment, with a focus on the hadronization of parton showers/jets.

• Motivation: in-medium effects for jet hadronization
  • Hadron chemistry
  • Momentum diffusion
  • Medium flow effects
Hybrid Hadronization – Vacuum

• Algorithm\(^1\) developed and implemented as a part of the JET Collaboration.

• Input: partons from a shower Monte-Carlo.

• Gluons are split into \(q\bar{q}\) pairs. Quarks that are close in coordinate and momentum space could recombine into hadrons.

  • Probability (meson): \(W_{M,n}(y, k) = \frac{v^n}{n!}e^{-v},\quad v = \frac{1}{2}\left(\frac{y^2}{\sigma^2_M} + k^2\sigma^2_M\right)\)

• Gluons are allowed to reform if the decayed pair is still present.

• Holes in strings are naturally repaired using the color flow information.

• Remnant strings are fragmented into hadrons using PYTHIA 8.

\(^1\)K. Han, R. J. Fries, C. M. Ko, Phys. Rev. C 93, 045207 (2016)
Hybrid Hadronization – Medium

• This procedure can be extended to include thermal parton recombination.

• All partons to be considered for hadronization must exist at or outside the surface of the QGP.
  • If there are shower partons inside the QGP, they must either be propagated by the shower MC to the hypersurface, or absorbed by the medium.

• Sampled thermal partons from the medium are added to the list of available partons.

• Apply same recombination MC procedure
  • Allow shower-thermal (sh-th) hadrons
  • Purely thermal hadrons are not included.
Hybrid Hadronization Implementation

• Input
  • Shower & thermal partons – momentum, position, color information

• Recombination
  • Sample probabilities for random quark pairs and triplets to recombine into hadrons, using color flow information from a shower MC

• String Prep
  • Prepare remnant partons on a string-by-string basis for PYTHIA – constructing a fake history for junction containing strings

• PYTHIA invocation
  • Call PYTHIA to perform string fragmentation on remnant strings and handle hadron resonances

• Output
  • Recombined and fragmented hadrons, including space-time information

• Hybrid Hadronization is included in JETSCAPE since v2.0
Example Event

- This is a MATTER jet with a trailing color tag (100).
- Two baryons were recombined.
  - Color flow handling gives unique structures
- This resulted in a junction-antijunction system.
  - Junctions will result in baryons after string fragmentation, resulting in baryon number conservation.
- Strings may need to be modified for PYTHIA
  - A parton was added to pair off the trailing color tag – enforcing color neutrality.
  - A junction was chosen to be recombined, cutting the string
    - Multi-junction systems often present difficulties for PYTHIA (including this one)
Space-time Structure

- Space-time information is important in heavy-ion collisions, including for hadronization!

- The parton shower typically extends further in space-time than the fireball size ( >100 fm/c for 500 GeV jets).

- The example that follows is for MATTER jets in a vacuum & MATTER+LBT jets in a 4 fm QGP brick.
  - Showing both the partonic and hadronic space-time structures.

\[ r = \sqrt{x^2 + y^2} \]

Partons propagate with \( v \sim c \)

Initial parton is at origin when \( t = 0 \)
Results – Vacuum Jets Space-time

Partons shown have virtuality $Q < Q_0 = 1 \text{ GeV}$

Partons propagate with $v \sim c$

$r = \sqrt{x^2 + y^2}$
Results – Vacuum Jets Space-time

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Results – Vacuum Jets Space-time

Partons shown have virtuality $Q < Q_0 = 1$ GeV

Partons propagate with $v \sim c$

$$r = \sqrt{x^2 + y^2}$$
Partons with virtuality $Q < Q_0 = 1$ GeV shown where the temperature $T < T_C$.

Partons propagate with $v \sim c$. 

$r = \sqrt{x^2 + y^2}$
Results – Brick Jets Space-time

Partons propagate with \( v \sim c \)

Partons with virtuality \( Q < Q_0 = 1 \text{ GeV} \)

shown where the temperature \( T < T_C \)
Results – Brick Jets Space-time

Partons with virtuality $Q < Q_0 = 1$ GeV shown where the temperature $T < T_C$
Partons propagate with $v \sim c$

$$r = \sqrt{x^2 + y^2}$$
JETSCAPE Hybrid Hadronization Study

• We consider a QGP brick with a space-like hypersurface with varying sizes.

• The flow velocity of the thermal partons is varied.

• The jet initiating parton is a fixed energy quark, showered with MATTER and LBT, then hadronized with Hybrid Hadronization.

• We look for traditional recombination signals – an enhanced baryon meson ratio & flow.

• Caveat – there are no purely thermal hadrons in the following. Here we wish to study the systematics of Hybrid Hadronization; a comparison to experimental data will follow later.
There are no thermal hadrons – the soft sector cannot be directly compared to data!
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Summary

• Hybrid Hadronization is available in JETSCAPE v2.0 and later.
• Some features shown here are not yet in the public release.
• Study of the space-time structure of jets is important for hadronization.
• There is a strong scaling of medium signatures with the size of the medium.
• There are clear signals for thermal partons imparting flow and increasing baryon production below 10 GeV/c
  • While we did not directly compare to experimental data, they share qualitatively similar trends with the results from this study.
• A tuning of MATTER + HH in vacuum ($e^+e^-$ and $p+p$) is underway.
Backup Slides
Results – Brick Jets Spacetime II
Results – Vacuum Jets Spacetime II

Partonic Spacetime Distribution
500 Gev Quark Jet

Hadronic Spacetime Distribution
500 Gev Quark Jet

N_entries

x_perp (fm)

N_entries

x_perp (fm)
Jet Parton Density

• Distance of quark-antiquark pairs in phase space is the deciding factor for recombination into mesons.

• Example$^1$: Distribution of pair distances in 100 GeV (PYTHIA 6) parton showers in phase space (center of mass frame of the pair):
  • Most of the jet is relatively dense in phase space.
  • Space-time structure for shower partons implemented with formation times $E/Q^2$.
  • There are long tails (~high $z$ partons)

• Perturbative evolution should not lead to dilute showers, otherwise non-perturbative effects are already dominant.

$^1$K. Han, R.J.F., C. M. Ko, Phys. Rev. C 93, 045207 (2016)
Recombination Formalism

- The formula for the recombination probability, as derived from the Wigner function coalescence yield (meson):

\[
\overline{W}_M(y, k) = \int d^3x'_1 d^3k'_1 d^3x'_2 d^3k'_2 \times W_q(x'_1, k'_1) W_{q\bar{q}}(x'_2, k'_2) W_M(y', k').
\]

- Evaluated at equal time in the pair or triplet rest frame.

- Bound state Wigner function derived from harmonic oscillator wave functions (Laguerre polynomials \(L_n\)).

\[
W_n(u) = 2(-1)^n L_n \left( \frac{4u}{\hbar \omega} \right) e^{-2u/\hbar \omega} \quad u = \frac{\hbar \omega}{2} \left( \frac{x^2}{\sigma^2} + \sigma^2 k^2 \right)
\]

- For proper \(q, q\bar{q}\) Wigner functions, need to start from quark wave packets - for which the true shape is not known.

- With Gaussian wave packets, the overlap of wave packets and Wigner function is mathematically straightforward. The probability densities for the \(n\)-th excited states are:

\[
\overline{W}_{M,n}(y, k) = \frac{v^n}{n!} e^{-v} \quad v = \frac{1}{2} \left( \frac{y^2}{\sigma^2} + k^2 \sigma^2_M \right)
\]

- Hadron wave function widths fixed by measured and predicted charge radii.
Recombination Code Flow

• Colored partons that recombination cannot handle (eg, diquarks, color octet hadrons) are passed through as parts of remnant strings.

• Gluons are decayed into q-qbar pairs.

• Quarks are randomly sampled to evaluate recombination probabilities, then this probability is sampled to determine if a hadron is formed.

• If a hadron is formed:
  • An immediate **string repair** is performed.
  • Hadron id is chosen based on quark composition.

• Repeat sampling procedure for all quark pairs/triplets.

• Reform unused q-qbar pairs back into original gluons.
Partons are taken from a shower Monte-Carlo, these must include a valid color structure for reasonable results

- Partons that have interacted with the medium at low virtuality scales (LBT, MARTINI) and thermal partons are assigned a random color

A color correlation matrix is constructed, denoting the probability that a color/anticolor can form a color singlet

- The colors of a single gluon will have a recombination probability of 0
- A color with itself will have a recombination probability of 1
- Uncorrelated colors will have a recombination probability of 1/9

If a meson recombination occurs, this means that the chosen color tags *must* be equal

- All remaining instances of one of those color tags is replaced with the other (arbitrary)
- The color correlation matrix is updated to reflect this change

For a baryon recombination, the color structure will result in the creation or annihilation of a junction

- This preserves baryon number!
Partons are taken from a shower Monte-Carlo, these must include a valid color structure for reasonable results

- Color tags > 0 for partons in vacuum-type strings
- Color tags = 0 for partons that have interacted with the medium at low virtuality scales (LBT, MARTINI) or for thermal partons

A color correlation matrix is constructed, denoting the probability that a color/anticolor can form a color singlet

- The color tags of a single gluon will have a probability of 0
- A color tag with itself (except 0) will have a probability of 1
- Uncorrelated color tags will have a probability of 1/9

If a meson recombination occurs, this means that the chosen color tags *must* be equal

- All remaining instances of one of those color tags is replaced with the other (arbitrary)
- The color correlation matrix is updated to reflect this change

For a baryon recombination, the color tags used will create (or annihilate) a junction

- This preserves baryon number!

Recombinations involving a 0 color tag may need a partner, another color tag 0 parton, that will be assigned a color tag.