Jet substructure modifications in a QGP from multi-scale description of jet evolution with JETSCAPE

Yasuki Tachibana
for the JETSCAPE Collaboration

Aix-Les-Bains, October 3rd 2018
JETSCAPE

- Package of MC event generator for heavy ion collision
  - Current version, JETSCAPE 1.0 available at https://github.com/JETSCAPE
  - General, modular and highly extensible

**JETSCAPE Event Generator**

- Initial geometry of Nucleus-Nucleus collision
- Initial Soft Density distribution
- Hard Particle Production
- Viscous Fluid dynamics of QGP
- Multi-stage Jet Shower Evolution
- Hard & Semi-hard Hadronization
- Cooper-Frye Sampling
- Hadronic Cascade

STAT part (future release)

Talk by R. Soltz (Tue)
• Package of MC event generator for heavy ion collision
  - Current version, JETSCAPE 1.0 available at https://github.com/JETSCAPE
  - General, modular and highly extensible

JETSCAPE Event Generator

Multi-stage Jet Shower Evolution

Viscous Fluid dynamics of QGP

Hard & Semi-hard Hadronization

Cooper-Frye Sampling

Hadronic Cascade

Initial geometry of Nucleus-Nucleus collision

Hard Particle Production

Initial Soft Density distribution

STAT part (future release)
Multi-stage jet evolution in JETSCAPE

- Multi-scale description of parton shower

  In-vacuum

  Large- $Q$

  Small- $Q$

  $Q^2$: virtuality (off-shellness)

- Virtuality ordered splitting in vacuum
Multi-stage jet evolution in JETSCAPE

- **Multi-scale description of parton shower**  Majumder, Putschke(16), JETSCAPE(17)

  - Virtuality ordered splitting in vacuum

  - Large- $Q$

    - Small- $Q$

  $Q^2$: virtuality (off-shellness)
Multi-stage jet evolution in JETSCAPE

- **Multi-scale description of parton shower**  
  Majumder, Putschke(16), JETSCAPE(17)

- Virtuality ordered splitting in vacuum
- Large-$Q$ → Medium effect on the top of in-vacuum splitting

$Q^2$: virtuality (off-shellness)
Multi-stage jet evolution in JETSCAPE

- Multi-scale description of parton shower  
  Majumder, Putschke(16), JETSCAPE(17)

- Virtuality ordered splitting in vacuum

- Large-$Q$  
  Medium effect on the top of in-vacuum splitting

$Q^2$: virtuality (off-shellness)
Multi-stage jet evolution in JETSCAPE

- Multi-scale description of parton shower
  - Virtuality ordered splitting in vacuum
  - Large-$Q$ Medium effect on the top of in-vacuum splitting
  - Small-$Q$, Large-$E$ Splitting driven almost purely by medium effect

$Q^2$: virtuality (off-shellness)
Multi-stage jet evolution in JETSCAPE

- Multi-scale description of parton shower  Majumder, Putschke(16), JETSCAPE(17)

- In-medium

- Virtuality ordered splitting in vacuum
- Large- $Q$  → Medium effect on the top of in-vacuum splitting
- Small-$Q$, Large-$E$  → Splitting driven almost purely by medium effect
- Small-$Q$, Small-$E$  → Energy-momentum diffusion into medium

$Q^2$: virtuality (off-shellness)
Multi-stage jet evolution in JETSCAPE

- **Multi-scale description of parton shower**
  
  - Virtuality ordered splitting in vacuum
  - Large- $Q$  → Medium effect on the top of in-vacuum splitting
  - Small- $Q$, Large- $E$  → Splitting driven almost purely by medium effect
  - Small- $Q$, Small- $E$  → Energy-momentum diffusion into medium

No single model can describe all stages of jet evolution
Multi-stage jet evolution in JETSCAPE

- Jet energy loss modules and their transition in JETSCAPE

Virtuality separation scale: $Q_0$

### Large-$Q (> Q_0)$
- **MATTER**
  - Majumder(13), Kordell, Majumder(17), Cao, Majumder(17)
  - Radiation dominated
  - Virtuality ordered splitting
  - Higher Twist Formalism

### Small-$Q ( < Q_0)$
- **LBT**
  - Wang, Zhu(13), Luo, et al.(15,18)
  - Large-$E$
  - Scattering dominated
  - On-shell parton transport
  - Higher Twist Formalism

- **MARTINI**
  - Cao, et al.(16,17), He, et al.(18)
  - Small-$E$
  - Diffusion into medium
  - AMY Formalism

- **AdS/CFT**
  - Schenke, Gale, Jeon(09), Park, Jeon, Gale(17, 18)
  - $\mathcal{N} = 4$ super Yang-Mills
  - Chesler, Rajagopal(14, 15)
  - Pablos, et al.(15, 16, 17)
Multi-stage jet evolution in JETSCAPE

- Jet energy loss modules and their transition in JETSCAPE

Virtuality separation scale: $Q_0$

Switching between modules for parton by parton

**Large-$Q$ ($> Q_0$)**

- **MATTER**
  - Majumder(13), Kordell, Majumder(17), Cao, Majumder(17)
  - Radiation dominated
  - Virtuality ordered splitting
  - Higher Twist Formalism

**Small-$Q$ ($< Q_0$)**

**Large-$E$**

- **LBT**
  - Wang, Zhu(13), Luo, et al.(15,18)
  - Cao, et al.(16,17), He, et al.(18)
  - Scattering dominated
  - On-shell parton transport
  - Higher Twist Formalism

**MARTINI**

- Schenke, Gale, Jeon(09), Park, Jeon, Gale(17, 18)
  - AMY Formalism

**Small-$E$**

- **AdS/CFT**
  - Chesler, Rajagopal(14, 15)
  - Pablos, et al.(15, 16, 17)
  - Diffusion into medium
  - $\mathcal{N} = 4$ super Yang-Mills

Virtuality separation scale: $Q_0$
Jet evolution simulation with JETSCAPE

● **Jet substructure observables**
  - Jet shape (angular structure)
  - Fragmentation function (momentum distribution)
  - Sensitive to details of jet energy propagation and dissipation
    
    \[
    \text{jet } R_{AA}, \text{ single hadron } R_{AA}, \text{ jet } v_2, \text{ hadron } v_2
    \]

● **Purpose of this study**
  - Demonstrate results from multi-stage jet evolution in JETSCAPE
  - Comparison among different module settings
    (MATTER+LBT, MATTER+MARTINI, MATTER+AdS/CFT, etc.)
  - Fine tuning of parameters both for pp and for AA are not done yet
Jet evolution simulation with JETSCAPE

- Settings in simulations (PbPb 2.76 TeV)

Jet

QGP fluid
Jet evolution simulation with JETSCAPE

- Settings in simulations (PbPb 2.76 TeV)
  - MATTER, LBT: Recoil ON
  - MARTINI, AdS/CFT: No medium response (to be implemented in future)

Jet

QGP fluid
Jet evolution simulation with JETSCAPE

- **Settings in simulations (PbPb 2.76 TeV)**

  - **Jet**
    - MATTER, LBT: *Recoil ON*
    - MARTINI, AdS/CFT: No medium response (to be implemented in future)
    - **Virtuality separation scale:** $Q_0 = 2$ GeV

- **QGP fluid**
**Settings in simulations (PbPb 2.76 TeV)**

- **Jet**
  - MATTER, LBT: Recoil ON
  - MARTINI, AdS/CFT: No medium response (to be implemented in future)
  - Virtuality separation scale: $Q_0 = 2 \text{ GeV}$
  - **Initial condition from TRENTo+Pythia (MPI, ISR: ON)**
    Moreland, Bernhard, Bass(14)

- **QGP fluid**
Settings in simulations (PbPb 2.76 TeV)

- **Jet**
  - MATTER, LBT: *Recoil ON*
  - MARTINI, AdS/CFT: No medium response (to be implemented in future)
  - Virtuality separation scale: $Q_0 = 2$ GeV
  - Initial condition from TREATo+Pythia (MPI, ISR: ON)
    Moreland, Bernhard, Bass(14)
  - **Lund Hadronization**

- **QGP fluid**
Settings in simulations (PbPb 2.76 TeV)

Jet

- MATTER, LBT: **Recoil ON**
  - MARTINI, AdS/CFT: No medium response (to be implemented in future)
- Virtuality separation scale: $Q_0 = 2\,\text{GeV}$
- Initial condition from TRENTo+Pythia (MPI, ISR: ON)
  Moreland, Bernhard, Bass(14)
- Lund Hadronization
- **In pp, MATTER vacuum shower down to** $Q = 1\,\text{GeV}$

QGP fluid
Jet evolution simulation with JETSCAPE

Settings in simulations (PbPb 2.76 TeV)

Jet

- MATTER, LBT: **Recoil ON**
  - MARTINI, AdS/CFT: No medium response (to be implemented in future)
- Virtuality separation scale: $Q_0 = 2\,\text{GeV}$
- Initial condition from TRENTo+Pythia (MPI, ISR: ON)
  - Lund Hadronization
- In pp, MATTER vacuum shower down to $Q = 1\,\text{GeV}$

QGP fluid

- 2+1D, event-averaged (data table)
Jet evolution simulation with JETSCAPE

Settings in simulations (PbPb 2.76 TeV)

Jet

- MATTER, LBT: Recoil ON
  MARTINI, AdS/CFT: No medium response (to be implemented in future)
- Virtuality separation scale: $Q_0 = 2$ GeV
- Initial condition from TRENTo+Pythia (MPI, ISR: ON)
  
  Moreland, Bernhard, Bass(14)
- Lund Hadronization
- In pp, MATTER vacuum shower down to $Q = 1$ GeV

QGP fluid

- 2+1D, event-averaged (data table)

- TRENTo initial condition+free-streaming
  
  Liu, Shen, Heinz(15)
Jet evolution simulation with JETSCAPE

**Settings in simulations (PbPb 2.76 TeV)**

**Jet**

- MATTER, LBT: **Recoil ON**
  - MARTINI, AdS/CFT: No medium response (to be implemented in future)
- Virtuality separation scale: $Q_0 = 2\text{ GeV}$
- Initial condition from TRENTo+Pythia (MPI, ISR: ON)
  Moreland, Bernhard, Bass(14)
- Lund Hadronization
- In pp, MATTER vacuum shower down to $Q = 1\text{ GeV}$

**QGP fluid**

- 2+1D, event-averaged (data table)
- TRENTo initial condition+free-streaming
  Liu, Shen, Heinz(15)
- **VISHNU** (viscous hydro calculation)
  Shen, Qiu, Song, Bernhard, Bass, Heinz(16)
Jet evolution simulation with JETSCAPE

Settings in simulations (PbPb 2.76 TeV)

Jet

- MATTER, LBT: Recoil ON
  MARTINI, AdS/CFT: No medium response (to be implemented in future)
- Virtuality separation scale: \( Q_0 = 2 \text{ GeV} \)
- Initial condition from TRENTo+Pythia (MPI, ISR: ON)
  Moreland, Bernhard, Bass(14)
- Lund Hadronization
- In pp, MATTER vacuum shower down to \( Q = 1 \text{ GeV} \)

QGP fluid

- 2+1D, event-averaged (data table)
- TRENTo initial condition+free-streaming
  Liu, Shen, Heinz(15)
- VISHNU (viscous hydro calculation)
  Shen, Qiu, Song, Bernhard, Bass, Heinz(16)
Jet Shape

\[ \rho(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[ \frac{1}{p_T^{\text{jet}}} \sum_{\text{trk} \in (r-\delta r/2, r+\delta r/2)} p_T^{\text{trk}} \right] \]

\[ r = \sqrt{(\eta_{p} - \eta_{\text{jet}})^2 + (\phi_{p} - \phi_{\text{jet}})^2} \]

- Parameters in Pythia8.230 are default
- CMS from PLB 730 (2014) 243

**pp baseline**

JETSCAPE, pp 2.76 TeV, anti-\(k_T\) \(R = 0.3, p_T^{\text{jet}} > 100\) GeV, \(0.3 < |\eta_{\text{jet}}| < 2.0, p_T^{\text{trk}} > 1\) GeV

\( \rho_{pp}(r) \)

- CMS (smeared for PbPb 0-10%)
- MATTER(vacuum)
- Pythia8.230

\( \rho_{MC}(r)/\rho_{\text{EXP}}(r) \)

- MATTER(vacuum)
- Pythia8.230

Note: Self-normalized observable
Jet Shape

\[ \rho(r) = \frac{1}{N_{jet}} \sum_{jet} \left[ \frac{1}{p_T^{jet}} \sum_{\text{trk} \in (r-\delta r/2, r+\delta r/2)} p_T^{\text{trk}} \right] \]

\( r = \sqrt{(\eta_p - \eta_{\text{jet}})^2 + (\phi_p - \phi_{\text{jet}})^2} \)

note: self-normalized observable

**pp baseline**

JETSCAPE, pp 2.76 TeV, anti-\( k_T \) \( R = 0.3, p_T^{\text{jet}} > 100 \text{ GeV}, 0.3 < |\eta_{\text{jet}}| < 2.0, p_T^{\text{trk}} > 1 \text{ GeV} \)

Need further parameters tuning, very similar behavior to default Pythia8

*Parameters in Pythia8.230 are default CMS from PLB 730 (2014) 243

Y. Tachibana for the JETSCAPE Collaboration, Hard Probes 2018, Aix-Les-Bains
Jet Shape

\[ \rho(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[ \frac{1}{p_T^{\text{jet}}} \frac{\sum_{\text{trk} \in (r-\delta r/2, r+\delta r/2)} p_T^{\text{trk}}}{\delta r} \right] \]

\[ (r = \sqrt{(\eta_p - \eta^{\text{jet}})^2 + (\phi_p - \phi^{\text{jet}})^2}) \]

note: self-normalized observable

PbPb/pp

JETSCAPE, 2.76 TeV, PbPb : 0-5 %, anti-\( k_T \) \( R = 0.3 \), \( p_T^{\text{jet}} > 100 \) GeV, \( 0.3 < |\eta^{\text{jet}}| < 2.0 \), \( p_T^{\text{trk}} > 1 \) GeV

CMS from PLB 730 (2014) 243
Jet Shape

\[ \rho(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[ \frac{1}{p_T^{\text{jet}}} \frac{\sum_{\text{trk} \in (r-\delta r/2, r+\delta r/2)} p_T^{\text{trk}}}{\delta r} \right] \]

\[ (r = \sqrt{(\eta_p - \eta_{\text{jet}})^2 + (\phi_p - \phi_{\text{jet}})^2}) \]

note: self-normalized observable

**PbPb/pp**

JETSCAPE, 2.76 TeV, PbPb: 0-5%, anti-\( k_T \) \( R = 0.3, p_T^{\text{jet}} > 100 \text{ GeV}, 0.3 < |\eta_{\text{jet}}| < 2.0, p_T^{\text{trk}} > 1 \text{ GeV} \)

Enhancement around the edge of jet cone due to recoils in LBT

Y. Tachibana for the JETSCAPE Collaboration, Hard Probes 2018, Aix-Les-Bains
Jet Shape

\[ \rho(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[ \frac{1}{p_T^{\text{jet}}} \frac{\sum_{\text{trk} \in (r-\delta r/2, r+\delta r/2)} p_T^{\text{trk}}}{\delta r} \right] \]

\[ (r = \sqrt{(\eta_p - \eta_{\text{jet}})^2 + (\phi_p - \phi_{\text{jet}})^2}) \]

Note: self-normalized observable

\[ \rho_{\text{PbPb}}(r)/\rho_{pp}(r) \]

JETSCAPE, 2.76 TeV, PbPb : 0-5%, anti-\(k_T\) \(R = 0.3, p_T^{\text{jet}} > 100\) GeV, \(0.3 < |\eta_{\text{jet}}| < 2.0, p_T^{\text{trk}} > 1\) GeV

CMS from PLB 730 (2014) 243

Y. Tachibana for the JETSCAPE Collaboration, Hard Probes 2018, Aix-Les-Bains
Jet Shape

\[ \rho(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[ \frac{1}{p_T^{\text{jet}}} \frac{\sum_{\text{trk} \in (r-\delta r/2, r+\delta r/2)} p_T^{\text{trk}}}{\delta r} \right] \]

\( r = \sqrt{(\eta_p - \eta^{\text{jet}})^2 + (\phi_p - \phi^{\text{jet}})^2} \)

note: self-normalized observable

PbPb/\text{pp}

JETSCAPE, 2.76 TeV, PbPb : 0-5 %, anti-\(k_T\) \(R = 0.3, p_T^{\text{jet}} > 100\) GeV, \(0.3 < |\eta^{\text{jet}}| < 2.0, p_T^{\text{trk}} > 1\) GeV

Medium effect during virtuality ordered splitting cannot be seen
\[ D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{trk}}}{dz} \quad (z = \frac{p_{\text{trk}}^T}{p_{\text{jet}}^T}) \]

**pp baseline**

JETSCAPE, 2.76 TeV, \( pp \), anti-\( k_T \), \( R = 0.4 \), \( 100 < p_{\text{jet}}^T < 398 \) GeV, \( 0 < |Y_{\text{jet}}| < 2.1 \), \( p_{\text{trk}}^T > 1 \) GeV

*Parameters in Pythia8.230 are default*

ATLAS from EPJ C77 (2017) 379

Fragmentation Function

Y. Tachibana for the JETSCAPE Collaboration, Hard Probes 2018, Aix-Les-Bains
Fragmentation Function

\[ D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{trk}}}{dz} \quad (z = \frac{p_T^{\text{trk}}}{p_T^{\text{jet}}}) \]

JETSCAPE, 2.76 TeV, pp, anti-\( k_T \) \( R = 0.4 \), \( 100 < p_T^{\text{jet}} < 398 \) GeV, \( 0 < |Y_{\text{jet}}| < 2.1, p_T^{\text{trk}} > 1 \) GeV

\( \text{pp baseline} \)

*Parameters in Pythia8.230 are default

ATLAS from EPJ C77 (2017) 379

Deviation at high-\( z \), need further tunings

Y. Tachibana for the JETSCAPE Collaboration, Hard Probes 2018, Aix-Les-Bains
\[ D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{trk}}}{dz} \]

\[ z = \frac{p_{\text{trk}}}{p_{\text{jet}}} \]

\textbf{PbPb/pp}

JETSCAPE, 2.76 TeV, PbPb: 0-5\% \text{, } \text{anti-}k_T \text{ } R = 0.4, 100 < p_{\text{jet}}^\text{jet} < 398 \text{ GeV}, 0 < |Y_{\text{jet}}| < 2.1, p_{\text{trk}}^\text{trk} > 1 \text{ GeV}

ATLAS from EPJ C77 (2017) 379
\[ D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{trk}}}{dz} \quad (z = p_{\text{trk}}^T / p_{\text{jet}}^T) \]

**Fragmentation Function**

**PbPb/pp**

JETSCAPE, 2.76 TeV, PbPb : 0-5%, \( \text{anti-}k_T \) \( R = 0.4 \), \( 100 < p_{\text{jet}}^T < 398 \) GeV, \( 0 < |Y_{\text{jet}}| < 2.1 \), \( p_{\text{trk}}^T > 1 \) GeV

![Graph showing fragmentation function](image)

*Small-\( z \) enhancement due to recoils in LBT*
Fragmentation Function

\[ D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{trk}}}{dz} \left( z = \frac{p_{\text{trk}}}{p_{\text{jet}}} \right) \]

PbPb/pp

JETSCAPE, 2.76 TeV, PbPb : 0-5 %, anti-\(k_T\) \(R = 0.4\), 100 < \(p_{\text{jet}}\) < 398 GeV, 0 < \(|Y_{\text{jet}}|\) < 2.1, \(p_{\text{trk}} > 1\) GeV

ATLAS from EPJ C77 (2017) 379

\[ \frac{D_{\text{PbPb}}}{{D_{\text{pp}}}}(z) \]
Fragmentation Function

\[ D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{trk}}}{dz} \left( z = \frac{p_{\text{trk}}}{p_{\text{jet}}} \right) \]

\[ \text{PbPb/pp} \]

JETSCAPE, 2.76 TeV, PbPb: 0-5%, anti-\( k_T \) \( R = 0.4 \), \( 100 < p_{\text{jet}}^T < 398 \) GeV, \( 0 < |Y_{\text{jet}}| < 2.1 \), \( p_{\text{trk}}^T > 1 \) GeV

Medium effect during virtuality ordered splitting at large-\( z \).
Summary

- **Multi-stage jet evolution in JETSCAPE**
  - Switching between different energy loss modules by virtuality of partons
    - Large-$Q$: virtuality ordered splitting (MATTER)
    - Small-$Q$: on-shell transport or strong coupling (LBT, MARTINI or AdS/CFT)

- **Jet substructure from multi-scale description of jet shower**
  - Significant contribution from recoil effect in LBT
  - Medium effect during virtuality ordered splitting
    - Jet shape: small
    - Fragmentation function: sizable at large-$z$
Rigorous analysis

- Further parameters tuning both for pp and for AA
- Other observables (more sensitive to details of jet evolution)

Updates

- Recoils in MARTINI and medium response in AdS/CFT
- Hydro back reaction to deposited energy and momentum from jet
- Other modules and their combinations
• Presentations from JETSCAPE Collaboration

- “Bayesian extraction of $\hat{q}$ with a multi-stage jet evolution approach” by Ron Soltz (Tuesday)

- “Multi-stage jet evolution through QGP using the JETSCAPE framework: inclusive jets, correlations and leading hadrons” by Chanwook Park (Thursday)

- “JETSCAPE 1.0: The first software release of the JETSCAPE collaboration” by Joern Putschke (Poster)

- “p+p physics with the JETSCAPE 1.0 framework” by Rainer Fries (Poster)

Thanks to all collaborators!
Backup
Jet Shape

\[ \rho(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[ \frac{1}{p_T^{\text{jet}}} \sum_{\text{trk} \in (r-\delta r/2, r+\delta r/2)} p_T^{\text{trk}} \right] \]

\[ (r = \sqrt{(\eta_p - \eta_{\text{jet}})^2 + (\phi_p - \phi_{\text{jet}})^2}) \]

note: self-normalized observable

PbPb/pp

JETSCAPE, 2.76 TeV, PbPb: 0-5 %, anti-\( k_T \) \( R = 0.3, p_T^{\text{jet}} > 100 \) GeV, 0.3 < |\( \eta_{\text{jet}} \) | < 2.0, \( p_T^{\text{trk}} > 1 \) GeV

CMS from PLB 730 (2014) 243

\( \rho(r)/\rho_{pp}(r) \)

pp baseline dependence
Jet Shape

\[ \rho(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[ \frac{1}{p_T^{\text{jet}}} \sum_{\text{trk}\in(r-\delta r/2,r+\delta r/2)} p_T^{\text{trk}} \right] \]

- \( r = \sqrt{(\eta_p - \eta^{\text{jet}})^2 + (\phi_p - \phi^{\text{jet}})^2} \)

*Parameters in Pythia8.230 are default

CMS from PLB 730 (2014) 243

JETSCAPE, 2.76 TeV, PbPb: 0-5%, anti-\( k_T \) \( R = 0.3, p_T^{\text{jet}} > 100 \text{ GeV}, 0.3 < |\eta^{\text{jet}}| < 2.0, p_T^{\text{trk}} > 1 \text{ GeV} \)

\[ \rho_{\text{PbPb}}(r) \]

\[ \rho_{\text{MC}}(r)/\rho_{\text{EXP}}(r) \]

Note: self-normalized observable

Y. Tachibana for the JETSCAPE Collaboration, Hard Probes 2018, Aix-Les-Bains