Monte-Carlo Simulation of Jets in Heavy-Ion Collisions

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Timeline of a heavy-ion collision

- **before collision**: 0 fm/c
- **pre-equilibrium**: $\sim 0.5 \text{ fm/c}$
- **quark-gluon-plasma**: $\sim 3 - 5 \text{ fm/c}$
- **hadronization**
- **hadr. rescattering**: $\sim 10 \text{ fm/c}$
- **freeze-out**
- **detection**

**initial state**
(e.g. color glass condensate)

**thermalization**
(glasma state)

Jet quenching, Hydro, ...

Hadronization models
Hadronic transport

compare theory to experiment
Using probes to learn about the medium

Usual procedure:
Send calibrated probe through medium and detect what comes out.

Unfortunately, the quark-gluon-plasma lives for only $5 \text{ fm}/c \approx 1.6 \times 10^{-23} \text{s}$ or less.
No time to shoot a probe from the outside.
Using probes to learn about the medium

Luckily the collision creates its own probes.

- Photons, dileptons, hard partons

We can study hard (high momentum) probes
- Jets (hadrons created from high momentum partons)
- Electromagnetic probes: Photons, Dileptons
Jet quenching as a probe

Suprise at RHIC. Almost nothing can get through!

Near side jet
Away side jet
Beam direction

\( \Delta \phi \)

\( \frac{1}{N_{\text{trigger}}} \frac{dN}{d(\Delta \phi)} \)


STAR p+p 200GeV

Björn Schenke (BNL)
Jet quenching as a probe

Surprise at RHIC. Almost nothing can get through!

Near side jet
Away side jet
Beam direction

\[ \Delta \phi \]

Away side peak vanishes

\[ \frac{1}{N_{\text{trigger}}} \frac{dN}{d(\Delta \phi)} \]

STAR p+p 200GeV
STAR Au+Au central 200GeV
Jet quenching as a probe

Suprise at RHIC. Almost nothing can get through!

\[ R_{AA} = \frac{\text{yield in A+A collision}}{\text{normalized yield in p+p collision}} \]

transverse momentum

factor 5 suppression
Jet Production

High transverse momentum $\rightarrow$ Large momentum transfer $Q$

$\rightarrow \alpha_s(Q) \ll 1$

Jet production is perturbative.
Jet Production

Cross section for hadron production:

\[ \frac{d\sigma}{dt} = \int_{abcd} f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \frac{d\sigma_{ab\rightarrow cd}}{dt} D_{vac}(z_c, Q_{frag}) \]
Jet Production

Include medium modifications in heavy-ion collisions.

\[
\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \\
\times \frac{d\sigma_{ab\rightarrow cd}}{dt} \mathcal{P}(x_c \rightarrow x'_c|T, u^\mu) D_{\text{vac}}(z'_c, Q_{\text{frag}})
\]
Monte-Carlo simulation of jet quenching

- Low momentum part of the medium is well described by hydrodynamics
- Interactions of hard partons with the medium from perturbative QCD (thermal field theory)

Using this, we want to create the best possible interface between fundamental theory and experiment: Monte-Carlo simulations!
Modular algorithm for relativistic treatment of heavy ion interactions

Modular Algorithm for Relativistic Treatment of heavy Ion Interactions

MARTINI takes care of all components in

\[
\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \times \frac{d\sigma_{ab\to cd}}{dt} \mathcal{P}(x_c \to x'_c|T, u^\mu) D_{\text{vac}}(z'_c, Q_{\text{frag}})
\]
Jet production and evolution in MARTINI

**Geometry**

\[
\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \\
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\]

**Glauber model:** Sample Woods-Saxon distributions
Determine positions of initial hard scatterings

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Image of a diagram showing the distribution of points within a geometric shape, labeled as beam.
Jet production and evolution in MARTINI

Parton distributions in the nuclei and initial scattering

\[ \frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} f_{a/A}(x_a, Q)f_{b/B}(x_b, Q) \times \frac{d\sigma_{ab\rightarrow cd}}{dt} \mathcal{P}(x_c \rightarrow x'_c|T, u^\mu) D_{\text{vac}}(z'_c, Q_{\text{frag}}) \]

- Use vacuum event generator (PYTHIA) to generate partons with high transverse momenta
- Nuclear effects included (EKS98 or EPS09)
- Vacuum shower done with PYTHIA
Jet production and evolution in MARTINI

Medium evolution

\[
\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \times \frac{d\sigma_{ab\rightarrow cd}}{dt} \mathcal{P}(x_c \rightarrow x'_c|T, u^\mu) D_{\text{vac}}(z'_c, Q_{\text{frag}})
\]

MARTINI evolves partons in a background medium

- Medium from hydrodynamics
- Interactions of hard partons with the medium from perturbative QCD
- Monte-Carlo method to evolve the partons
Hadronization

\[
\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \\
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\]

Assume partons hadronize outside the medium:

**Same fragmentation as in vacuum (Lund model in PYTHIA).**

... are also studying different fragmentation methods.
Medium Evolution: Processes in Martini

**Inelastic (AMY)**

Collinear emission


**Elastic**

Transverse momentum transfer is included (important later)


**Conversion**

**Photon emission/conversion**
Pion production in Cu+Cu collisions

Dashed: pure hydro simulation
Solid: MARTINI result


Pion production in Au+Au collisions

Pion spectra

\( R_{AA} \)


Experimental data: S.S. Adler et al. (PHENIX), Phys. Rev. C76, 034904 (2007); Kieran Boyle (PHENIX) at PANIC 2005;
Studying individual jets

So far we have studied single inclusive observables: e.g. the number of certain particles as a function of their momenta.

Now let us look at properties of individual jets.

Rough definition: A jet is a concentrated bunch of hadrons with large transverse momentum seen in the detector. The exact definition will depend on the algorithm used to find the jets among all detected particles.
Studying individual jets

Finding jets in heavy-ion collisions has been difficult.

Need to find this ...

... in this

STAR event display
Studying individual jets

Usually, jets in heavy-ion events at RHIC are a lot less obvious.
Dijet event at LHC (slide from Brian Cole, QM2011)
Jet finding algorithms

Sophisticated jet finding algorithms have been developed. FASTJET in particular.

**$k_T$ algorithm**
- starts from merging low $p_T$ particles close in phase space
- irregular jet shapes
- large areas $> \pi R^2$

**anti-$k_T$ algorithm**
- starts from merging high $p_T$ particles close in phase space
- roughly circular jet shapes
- areas $\sim \pi R^2$
Jet finding algorithms

Reconstructed jets should not be sensitive to the following:

- Insensitive to soft splittings: Infrared save.
- Insensitive to collinear splittings: Collinear save.

Illustration by G. Salam
**anti-$$k_T$$** is best for heavy-ions

**Backreaction**: “How much a jet changes when immersed in a background”

Less smearing of the jets’ momenta due to underlying event

Finding jets in MARTINI and experiment

One great thing about a Monte-Carlo simulation like MARTINI:
We can use the exact same analysis tools as the experiments:
Most direct link between theory and experiment.

Use FASTJET’s anti-$k_T$ with the same settings as e.g. ATLAS.

The clustering depends on the distance between two four momenta:

$$d_{ij} = \min\left(\frac{1}{k_{T_i}^2}, \frac{1}{k_{T_j}^2}\right) \left(\frac{(\phi_i - \phi_j)^2 + (y_i - y_j)^2}{R^2}\right)$$

Four-momenta close to each other are added; final jets determined.

Main parameter: $R$ controls the extension of the jet.
Find jets, determine yield $dN/dA_j$, where

$$A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

is the asymmetry of the dijet, with $E_{Ti}$ the transverse energy of jet $i$.

$R = 0.4$
$E_{T1} > 100 \text{ GeV}$
$E_{T2} > 25 \text{ GeV}$
$\Delta \phi = |\phi_1 - \phi_2| > \pi/2$

C. Young, B. Schenke, S. Jeon, C. Gale, arXiv:1103.5769
Results: Dijet asymmetry at LHC

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Results: Dijet asymmetry at LHC

Modification of the back-to-back alignment: Distribution in $\Delta \phi$.

<table>
<thead>
<tr>
<th>$\Delta \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p+p$ PYTHIA+fastjet</td>
</tr>
<tr>
<td>Pb+Pb MARTINI+fastjet</td>
</tr>
<tr>
<td>ATLAS pp</td>
</tr>
<tr>
<td>ATLAS Pb+Pb, 0-10%</td>
</tr>
</tbody>
</table>

Radiative + elastic

No significant modification.
Part with differences at low $\Delta \phi$ makes up less than 5% of all dijets. Explained by combinatorics. Second jet missing, uncorrelated jet used.

C. Young, B. Schenke, S. Jeon, C. Gale, arXiv:1103.5769
Mechanism: Two contributions

Elastic collisions kick soft radiated gluons out of the cone.

Fragmentation $p_T$ from Lund fragmentation.

At each string breaking the $q$ and $\bar{q}$ receive opposite and compensating $p_T$ kicks according to a Gaussian distribution.

The softer the partons, the larger the angle for the same $p_T$ kick.
This result is in line with the observation by CMS that the asymmetry is balanced by soft out-of-cone particles.
Comparing to CMS results

\[ R = 0.5 \]
\[ E_{T1} > 120 \text{ GeV} \]
\[ E_{T2} > 50 \text{ GeV} \]
\[ \Delta \phi = |\phi_1 - \phi_2| > \frac{2\pi}{3} \]

CMS uses a cone algorithm but quotes agreement with anti-\( k_T \).

![Graph showing comparison of Pb+Pb MARTINI+fastjet, CMS Pb+Pb 0-10% data](image)

C. Young, B. Schenke, S. Jeon, C. Gale, arXiv:1103.5769
Experimental data: CMS Collaboration, arXiv:1102.1957
Summary and Conclusions

- Evolution of high momentum partons is described perturbatively in Monte-Carlo simulation with hydrodynamic background.
- Jets are reconstructed as in the experiments (FASTJET).
- Dijet asymmetry is well described by combined radiative and elastic perturbative QCD processes.
- Modification of back-to-back alignment agrees with experiment.
- Mechanism:
  Soft small angle radiation is bent out of cone by elastic kicks from the medium and fragmentation $p_T$.
- Further detailed studies are on the way: fragmentation functions, missing $p_T$...
Test case: Jet evolution in brick of QGP at constant temperature

Compare MARTINI result to solution of rate equation

\[ T = \text{const.} \]
**Quark** $E_{\text{ini}} = 20$ GeV, $L = 2$ fm, $T = 200$ MeV
Brick results in **MARTINI** are the same as for McGill-AMY as we know it. They have to be because that’s what we put in.

So nothing **new** to worry about here...