Modeling of jet quenching in heavy ion collisions

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Outline

Jet definition
  Jet finding algorithms
  Background

Jet production
  Factorisation
  Nuclear PDFs

Jet sub-structure
  Resumming collinear logarithms
  Colour coherence & angular ordering
  Jet sub-structure variables & grooming

Jet quenching
  Key experimental results
  Theoretical considerations
  Medium response
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What is a jet?

A jet is

- a **collimated** spray of hadrons.
- result of fragmentation of an **energetic quark or gluon**.
Jet algorithms

- A jet is defined by the algorithm and its parameters used to reconstruct jets.
- Jets are proxies for a hard partons and NOT equivalent to hard partons.
- Two classes of jet finding algorithms:
  - Cone algorithms
  - Sequential recombination algorithms
- Jet algorithms should be *infra-red and collinear safe*, i.e. result must not change when
  - Adding a soft particle
  - Splitting a particle into two collinear ones
Sequential recombination algorithms: the $k_\perp$ class

The distance measure

$$d_{ij} = \min \left( p_{\perp,i}^{2p}, p_{\perp,j}^{2p} \right) \frac{\Delta R^2}{R^2} \quad \text{and} \quad d_{iB} = p_{\perp,i}^{2p}$$

- $p = 1$: $k_\perp$ algorithm

- $p = 0$: Cambridge/Aachen algorithm
  - Dokshitzer, Leder, Moretti, Webber, JHEP 9708 (1997) 001

- $p = -1$: anti-$k_\perp$ algorithm
  - Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

The algorithm

1. compute minimum of all $d_{ij}$ and $d_{iB}$
2. if minimum is a $d_{iB}$, declare object $i$ to be a jet and remove it
   else combine object $i$ and $j$
3. repeat from point 1 until no objects left
Background

- background gets clustered into jets
- ideal situation: flat background – can be subtracted
Background

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- More realistic: fluctuating background – can be subtracted on average, have to unfold
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  - shape has to be known
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- modulated background
  - can be subtracted
  - shape has to be known
- fluctuating modulated background: subtract & unfold
Subtracting background

Two strategies:
- cluster jets and subtract observable-by-observable
- subtract background on entire event, then cluster jets

Example for observable subtraction: Area subtraction

\[ p_{\perp}^{(\text{corr})} = p_{\perp}^{(\text{meas})} - \rho A_J \]

- \( A_J \): jet area
  - distribute very soft 'ghost particles' with known density in event
  - cluster jets
  - number of ghosts in jet gives jet area
- \( \rho \): average background \( p_{\perp} \) density
  - estimate \( \rho \) outside hard jets
  - have to find unbiased estimator

Subtracting background

Example for event subtraction: SoftKiller

- divide event into tiles
- introduce $p_\perp$ cut such that half of the tiles are empty
- $p^{(\text{cut})}_\perp = \text{median}_{i \in \text{tiles}} \left\{ p^{(\text{max})}_\perp, i \right\}$

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Factorisation of jet production cross section

- energetic quarks and gluons are produced in hard scattering processes
- factorisation of the cross section:

\[ \sigma(P_1, P_2) = \sum_{i,j} \int_0^1 dx_1 \, dx_2 \, f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}_{ij}(x_1 P_1, x_2 P_2, \alpha_s, Q^2) \]

- \( \hat{\sigma}_{ij} \): partonic cross section
  - has perturbative expansion in \( \alpha_s \)
  - known: NNLO for di-jets, NLO for up to \( \sim 5 \) jets
  - short distance physics: insensitive to nature of incoming hadrons
    i.e. no nuclear modifications

- \( f_i(x, Q^2) \): parton distribution function
  - nuclear pdf fits available
Nuclear PDFs: EPPS16

▶ bound proton PDF defined as

\[ f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2)f_i^p(x, Q^2) \]

▶ bound neutron PDF from isospin symmetry

▶ \( Q^2 \) dependence: DGLAP with 2-loop splitting functions

▶ parametrise \( R_i^A \) and fit for chosen free proton PDF (in this case CT14NLO)
Nuclear PDFs: nCTEQ15

- Nuclear PDF defined as

\[ f_i^{(A,Z)}(x, Q^2) = \frac{Z}{A} f_i^{p/A}(x, Q^2) + \frac{A-Z}{A} f_i^{n/A}(x, Q^2) \]

- Bound neutron PDF from isospin symmetry
- \( Q^2 \) dependence: DGLAP evolution
- Parametrise and fit bound proton PDF \( f_i^{p/A} \)
- NLO PDF
Nuclear PDFs

\[
R^{Pb}_{W}(x, Q^2 = 10 \text{ GeV}^2)
\]

Nuclear PDFs

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jets have characteristic sub-structure dictated by QCD radiation

in collinear limit QCD cross sections factorise:

\[ d\sigma_{n+1} \approx d\sigma_n \frac{dQ^2}{Q^2} \frac{d\phi}{2\pi} \frac{dz}{2\pi} \frac{\alpha_s}{P_{ba}(z)} \]

Altarelli-Parisi splitting functions:

\[
\begin{align*}
    P_{qq} &= C_F \frac{1 + z^2}{1 - z} \\
    P_{gq} &= C_F \frac{1 + (1 - z)^2}{z} \\
    P_{gg} &= C_A \frac{(1 - z(1 - z))^2}{z(1 - z)} \\
    P_{qg} &= T_R \left( z^2 + (1 - z)^2 \right)
\end{align*}
\]
Collinear logarithms

- naive “radiation probability”

\[
\Pi_1 \equiv \frac{\sigma_{n+1}}{\sigma_n} = \int_{Q_0^2}^{Q_{\text{max}}^2} \frac{dQ^2}{Q^2} \int_{z_{\text{min}}}^{1} dz \frac{\alpha_s}{2\pi} P_{ba}(z) \approx \frac{\alpha_s}{2\pi} \ln^2 \left( \frac{Q_{\text{max}}^2}{Q_0^2} \right)
\]

- \(\Pi_1 > 1\) for sufficiently hard processes \(\rightarrow \Pi_1\) is not a probability

- have to resum

  can be done analytically and explicitly in Monte Carlo event generators

- straightforward iteration:

\[
\Pi_n \approx \frac{1}{n!} \frac{\alpha_s^n}{(2\pi)^n} \ln^{2n} \left( \frac{Q_{\text{max}}^2}{Q_0^2} \right)
\]
The Sudakov form factor

- no-emission probability: Sudakov form factor

\[ \Delta(Q_{\text{max}}^2, Q^2) = \exp \left( - \int_{Q^2}^{Q_{\text{max}}^2} \frac{dQ^2}{Q^2} \int_{z_{\text{min}}}^{1} dz \frac{\alpha_s}{2\pi} P_{ba}(z) \right) = \exp \left( - \int_{Q^2}^{Q_{\text{max}}^2} dQ^2 P_{\text{em}}(Q^2) \right) \]

- basis for Monte Carlo implementation
- parton showers resum collinear logs to leading log accuracy with some sub-leading terms
Resumming collinear logarithms

### Initial state evolution

- **Jet definition**
- **Jet production**
- **Jet sub-structure**
- **Jet quenching**

**Resumming collinear logarithms**

**Initial state evolution**

- **in principle initial state evolution the same as in final state**
- **but: both ends of evolution fixed**
- **must account for probability to resolve parton at larger $x = zx'$**

\[
P_{\text{em}}^{(\text{is})}(x, Q^2) = \frac{1}{Q^2} \int dz \frac{\alpha_s}{2\pi} P_{ba}(z) \frac{x' f_a(x', Q^2)}{xf_b(x, Q^2)}
\]

- **hard to implement in forward evolution**
  - have to reach flavour and $t_{\text{max}}$ set by hard process
- **evolve backwards from hard process towards incoming hadron**

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Modeling jet quenching

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Multiple emissions

- splitting probability depends only on starting scale
- splitting process can be iterated
- leading contribution from strongly ordered histories
  \[ Q_1^2 \gg Q_2^2 \gg Q_3^2 \gg Q_4^2 \text{ and } Q_2^2 \gg Q_2'^2 \]

- evolution variable: to leading log accuracy
  \[ \frac{dQ^2}{Q^2} = \frac{dk^2}{k^2} = \frac{d\theta^2}{\theta^2} \]
Aside: $p_\perp$ balance in boson-jet processes

- $x_{j\gamma} \neq 1$ in $p+p$ mainly due to initial state radiation
- final state recoils against initial state emissions
- rest comes from jet $\neq$ parton

CMS, arXiv:1711.09738
Resumming collinear logarithms

Quasi-collinear limit

- gluon radiation off massive quark
- for $k_\perp$, $m_q \ll E_q$:

$$P_{gQ}(z, \theta) \approx \frac{C_F}{1 - z} \left(1 + z^2 - \frac{2z}{1 + z^2(\theta E_q/m_q)^2}\right)$$

- emission suppressed for $\theta \lesssim m_q/E_q$

$\rightarrow$ "dead cone"

Soft limit

- soft limit also universal
- soft gluons come from everywhere in the event
⇒ quantum interference – independent evolution picture still valid?
Angular ordering

- outside cone soft gluons sum coherently
- don’t resolve two partons, but see only combined charge
- angular ordering
  
  automatically incorporated when using $\theta$ as evolution variable

- analogue of Chudakov effect in QED
  
  suppression of soft bremsstrahlung from $e^+e^-$ pairs

- “colour coherence”
Interference between initial and final state

- Initial conditions for showers set by colour structure of hard process
- ISR+FSR add coherently in regions of colour flow and destructively else
- Emission from each parton confined to cone extending to its colour partner
Experimental observation of colour coherence

rapidity of third hardest jet in jet events

HERWIG: full colour coherence
ISAJET: no CC
PYTHIA: no CC
PYTHIA+: partial CC
modern generators: full CC
Jet sub-structure observables

- observables built from jet constituents
  - particles, partons, calorimeter cells, ...

- characterise distribution of momentum & find structures inside jet

- various grooming techniques studied in p+p to separate hard structure from soft contaminations
  - filtering, trimming, pruning, ...

- interesting for heavy ions, but requires careful studies

Image from David Krohn
Grooming

- aim: remove contamination from background
- exploit knowledge about perturbative QCD radiation
  - small angle
  - symmetric
  - hard
- background is typically soft & large angle
- filtering: re-cluster jet with smaller radius $R_{\text{filt}}$ and keep $n_{\text{filt}}$ hardest (sub-)jets
- trimming: re-cluster jet with smaller radius $R_{\text{trim}}$ and keep (sub-)jets with $p_{\perp} > \epsilon_{\text{trim}} p_{\perp}^{(\text{jet})}$
  - Krohn, Thaler, Wang, JHEP 1002 (2010) 084
- pruning: re-cluster jet with $k_{\perp}$ or C/A algorithm, in each clustering step discard softer sub-jet if $\Delta R > R_{\text{prun}}$ and $\frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} < z_{\text{prun}}$
An example: SoftDrop

Soft Drop/modified Mass Drop Tagger algorithm:

1. cluster jet with anti-\(k_{\perp}\)
2. re-cluster with Cambridge/Aachen
3. undo last clustering step, compute \(z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}\) and \(\Delta R_{12}\)
4. if \(z_g > z_{\text{cut}}(\Delta R_{12}/R)^\beta\) stop
   else reject softer prong and go back to 3

- identifies hardest 2-prong structure in jet
- calculation:
  \[
p(z_g) = \frac{P(z_g) + P(1 - z_g)}{\int_{z_{\text{cut}}}^{1/2} dz \, P(z) + P(1 - z)} \Theta(z_g - z_{\text{cut}})
  \]
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Suppression of single-inclusive jets

- **ATLAS** Preliminary
  - anti-$k_T$, $R = 0.4$ jets, $\sqrt{s_{NN}} = 5.02$ TeV

2015 Pb+Pb data, 0.49 nb$^{-1}$
2015 $pp$ data, 25 pb$^{-1}$

- **suppression** of jets by factor 2 relative to expectation from $p+p$

need to scale $p+p$ reference by number of hard $N+N$ collisions

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Modeling jet quenching

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Di-jet momentum asymmetry

\[ A_J = \frac{p_{T_1} - p_{T_2}}{p_{T_1} + p_{T_2}} \]

- enhancement of asymmetric configurations

Intra-jet energy distribution: Jet profile

- suppression of activity at intermediate $r$
- increase near the edge of the jet

Intra-jet energy distribution: fragmentation function

\[ z = \frac{p_{\perp,h}}{p_{\perp,J}} \cos(\Delta R_{hJ}) \]

- distribution of hadrons inside jets
- suppression at intermediate & enhancement of soft momenta

Groomed shared momentum fraction

\[ z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \rightarrow p_{\perp} \text{ sharing between two hardest prongs} \]

- suppression of symmetric configurations
- and/or enhancement of very asymmetric ones

CMS-HIN-16-006

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Summary of experimental results

- jet production suppressed by factor $\sim 2$ up to $p_{\perp}$'s of 1 TeV
- hard structures inside jets survive largely unmodified
- enhancement of soft activity at edges of jet
- and far away from jet

![Diagram showing jet substructure and quenching effects](image-url)
Jet quenching warm-up
Jet quenching warm-up

- jets produced in earliest phase of heavy ion collision
- “calibrated” probe: well understood in p+p
- jet production in heavy ion collisions unmodified (short distance process) except for nuclear effects in pdf’s
- jet quenching allows to observe process of equilibration
  soft observables see result of equilibration
- jets give access to scale dependence of medium properties

Modeling jet quenching

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What happens to jets in medium?

**Scenario I: hard partons don’t resolve quasi-particles**
- interactions between jet & medium at large coupling
- AdS/CFT techniques

**Scenario II: hard partons do resolve quasi-particles**
- jet – medium interactions at weak(ish) coupling
- perturbative techniques
- thermalisation through elastic re-scattering (slow)
- parton energy loss through QCD bremsstrahlung
- destructive interference in multiple scattering

**LPM effect**

**relevant scale:** momentum transfer $q$ between hard parton and medium
How long does it take to radiate a gluon?

\[ k^\mu = (\omega, \vec{k}_\perp, k_\parallel) \]
\[ p^\mu = (E, 0, 0, p_\parallel) \]
\[ = (k^\mu + p'^\mu) \]
\[ p'^\mu = (E', \vec{p}'_\perp, p'_\parallel) \]

- virtual state: \( p^2 = E^2 - p^2 \neq 0 \rightarrow m^2_{\text{virt}} = p^2 \)
- uncertainty principle: \( 1 = \Delta t \Delta E = \Delta t \ m_{\text{virt}} \)
- gluon formation time: \( t_{\text{form}} = \Delta t \times (\text{boost factor}) \)
\[
  t_{\text{form}} = \frac{1}{m_{\text{virt}}} \frac{E}{m_{\text{virt}}} = \frac{E}{2p_\mu k^\mu} \simeq \frac{E}{\omega E \theta^2} \simeq \frac{\omega}{k^2_\perp}
\]
- time for entire jet evolution: \( \mathcal{O}((1 - 10) \text{ fm}) \)
- (transverse) size of medium: \( \mathcal{O}((1 - 10) \text{ fm}) \)

Modeling jet quenching

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Bremsstrahlung in medium: heuristic discussion


Brownian motion of the gluon: $\langle k^2 \rangle = \hat{q}L$
formation time of the radiated gluon:

$$t_f \sim \frac{\omega}{k^2} \sim \frac{\omega}{\hat{q} t_f} \quad \Rightarrow \quad t_f = \sqrt{\frac{\omega}{\hat{q}}}$$
and
$$N_{coh} = \frac{t_f}{\lambda}$$

 gluon energy spectrum:

$$\frac{d^2 I^{coh}}{d\omega dy} \sim \frac{1}{N_{coh}} \frac{d^2 I^{incoh}}{d\omega dy} \propto \frac{\alpha_s}{\omega \lambda} \sqrt{\hat{q}} \omega^{-3/2}$$

radiative energy loss:

$$\Delta E = \int_0^L dy \int_0^{\omega_c} d\omega \omega \frac{d^2 I}{d\omega dy} \propto \alpha_s \hat{q} L^2$$
Colour coherence and re-scattering

- consider colour singlet dipole in medium
- in vacuum colour coherence leads to angular ordering of radiation
- re-scattering in medium introduces new scale: $q_{\perp}$
- medium modifications depend on whether dipole is resolved

- in particular: unresolved structures remain unperturbed

Medium response

- medium response: medium’s reaction to energy & momentum deposited by jet
- gives rise to additional soft activity
- momentum conservation → additional particles follow jet direction
- correlated background

- correlated background cannot and should not be subtracted
- should be regarded as part of jet
- have to understand what background subtraction procedures do
- fluctuations matter
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Particle distribution outside jets

- **CMS** Particle yield vs. $\Delta r$
  - $pp$ 27.4 pb$^{-1}$ (5.02 TeV)
  - PbPb 404 μb$^{-1}$ (5.02 TeV)
  - $p_T>120$ GeV, $|\eta_{jet}|<1.6$

- **Enhancement of soft particles far away from jet**

- Modeling jet quenching

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Theoretical ideas

- treat medium response in hydro: energy and momentum deposited by jet constitute source term

\[ \partial_\mu T^{\mu\nu}_{\text{bulk}} = J^\nu \quad \text{with} \quad J^\nu = -\partial_\mu T^{\mu\nu}_{\text{hard}} \]

- solve hydro exactly with source term

Tachibana, Chang, Qin, Phys. Rev. C 95 (2017) no.4, 044909

- assume source term to be small perturbation and do linear response

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, JHEP 1703 (2017) 135

- trace recoiling thermal partons in transport code

Gao, Ma, Qin, Zhang, Phys. Rev. C 97 (2018) no.4, 044903

- free streaming of recoiling thermal partons

Kunnawalkam Elayavalli, Zapp, JHEP 1707 (2017) 141