Monte Carlo Tools for Jet Quenching

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Motivation for investigating jets

Theoretical considerations

- **single-inclusive quantities do not fully constrain models**

![Graph showing R_AA vs. p_T for PHENIX 0-5%, AMY, HT, and ASW models]  

PHENIX 0-5%, AMY, b = 2.4 fm, \( \alpha_s = 0.33 \)  
HT, b = 2.4 fm, \( \hat{q}_0 = 1.9 \text{ GeV}^2/\text{fm}, c_{\text{HG}} = 0.2 \)  
ASW, b = 2.4 fm, K = 3.6

PHENIX 20-30%, AMY, b = 7.5 fm, \( \alpha_s = 0.33 \)  
HT, b = 7.5 fm, \( \hat{q}_0 = 1.9 \text{ GeV}^2/\text{fm}, c_{\text{HG}} = 0.2 \)  
ASW, b = 7.5 fm, K = 3.6


- **sub-leading fragments more discriminating**  
**not well modelled by analytic calculations**
Motivation for investigating jets

Experimental needs

- need reliable tools to **disentangle jets** from background

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**ATLAS**

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Motivation for investigating jets

Experimental needs

➢ need reliable tools to disentangle jets from background
➢ in particular, need to understand

➢ response of jet finders to quenched jets (→ jet shapes)
➢ jet area, background, fluctuations
➢ jet induced medium modifications

➢ requires running jet finders on theory prediction
Baseline: QCD Parton Shower in Vacuum

- **collinear divergences** in real emission matrix elements
- **in collinear region factorisation** to all orders

\[ d\sigma_{n+1} \approx d\sigma_n \frac{dt \, d\phi}{t} \frac{dz}{2\pi} \frac{\alpha_s}{2\pi} \mathcal{P}(z) \]

\[ t : k_\perp^2 \approx Q^2 \approx \vartheta^2 \rightarrow \text{hardness of splitting} \]

→ **large logarithms** → need to be **resummed** to all orders

- **evolution equation** (**DGLAP**) with **ordering variable** \( t \)
- **define** **Sudakov form factor** as

\[ S(t_1, t_2) = \exp \left\{ -\int_{t_1}^{t_2} \frac{dt}{t} \int dz \frac{\alpha_s}{2\pi} \mathcal{P}(z) \right\} \]
Baseline: QCD Parton Shower in Vacuum

- evolution equation can be integrated

\[ f(x, t) = S(t_0, t)f(x, t_0) + \int_{t_0}^{t} \frac{dt'}{t'} S(t', t) \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z)f(x/z, t') \]

- \( S(t_0, t) \) probability for no emission between \( t \) and \( t_0 \)
- suitable for MC implementation → parton shower
- resums real emissions to all orders to leading logarithmic accuracy
- includes virtual corrections via unitarity
- comment: regularised soft and collinear divergences
  → observables better be infra-red and collinear safe
State of the art MC’s in p+p

(matrix-purpose event generators: Herwig, Pythia, Sherpa)

matrix elements: fixed order perturbation theory (LO or NLO)
final state parton shower: resummation of collinear/soft logarithms (LL)
initial state parton shower: like final state parton shower
hadronisation: non-perturbative QCD: modelling
Situation in A+A

matrix elements: unmodified due to high scale
final state parton shower: no general theory, only calculations for special cases
e.g. single gluon radiation spectrum in eikonal limit
initial state parton shower: found to be unmodified at RHIC except for pdf’s
hadronisation: probably modified, no theoretical guidance
Embedding the parton shower in a medium

- in quantum mechanics no instantaneous processes
- in particular: timescale for gluon radiation

\[ \tau_{\text{vac}} \approx \frac{\omega}{k_\perp^2} \approx \frac{1}{\sqrt{t}} \cdot \frac{E}{\sqrt{t}} \]

- time dilation delays decoherence of energetic fragments
- in medium: transverse momentum through interactions

\[ \tau_{\text{med}} \approx \frac{\omega}{k_\perp^2} \approx \frac{\omega}{\hat{q} \tau_{\text{med}}} \quad \Rightarrow \quad \tau_{\text{med}} \approx \sqrt{\frac{\omega}{\hat{q}}} \]

- soft emissions decohere first and at large angles
- hard core as in vacuum + soft large angle radiation?

qualitative agreement with ATLAS & CMS results

clarify by measurements of intra-jet distributions (FF’s)
Established MC models

- HIJING:
  - medium induced parton splitting process
  - complete HI events


  Deng, Wang, Xu, arXiv:1008.1841

- HYDJET++/PYQUEN:
  - gluon radiation sampled from BDMPS spectrum
  - elastic scattering
  - complete HI events


- JEWEL:
  - unified ME+PS description for all emissions


  Zapp, Stachel, Wiedemann, Phys. Rev. Lett. 103 (2009) 152302
Established MC models

- **Q-PYTHIA/Q-HERWIG:**
  - modified splitting function derived from BDMPS
  - simulates only jets
  
  Armesto, Corcella, Cunqueiro, Salgado, JHEP 0911 (2009) 122

- **YaJEM:**
  - medium interactions transfer virtuality to partons
    \( \rightarrow \) radiative energy loss
  - and degrade their energy
  - simulates only jets


- **MARTINI:**
  - based on AMY transition rates
  - + elastic scattering transition rate
  - simulates only jets

Non-eikonal kinematics

Problems with eikonal kinematics

- analytical calculations require: \(E \gg \omega \gg k_\perp \gg \Lambda_{\text{QCD}}\)
- RHIC and LHC kinematics: \(E \geq \omega \geq k_\perp \geq \Lambda_{\text{QCD}}\)
- large uncertainties due to kinematic ambiguities

Consequences of non-eikonal kinematics

- phase space restrictions due to \(E/p\)-conservation
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Consequences of non-eikonal kinematics
- phase space restrictions due to $E/p$-conservation
- dynamical scattering centres
  - $\rightarrow$ collisional energy loss
  - $\rightarrow$ radiation off scattering centres
- no clear distinction between elastic & inelastic scattering
- no clear separation of vacuum & medium radiation
Non-eikonal kinematics

From a MC perspective

- energy-momentum conservation: no problem
- elastic vs. inelastic scattering: needs unified description
- dynamical scatterings centres: difficult for models based on effective descriptions
  - collisional energy loss: typically neglected or added as separate process
  - radiation off scattering centres: model dependent
- vacuum vs. medium radiation: models use either unified description or assume complete factorisation
Multiple gluon emission & LPM-effect

Problems with analytic calculations

- single gluon radiation only + probabilistic iteration
- affected by E/p non-conservation in eikonal limit
- unclear how multiple gluon emissions interplay

  first theoretical progress: radiation off colour dipole

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Consequences of multiple gluon emission

- radiated gluons radiate → democratic treatment

$$L = 2.5 \, \text{fm}, \quad E_{\text{proj}} = 100 \, \text{GeV}, \quad \mu = 0.7 \, \text{GeV}, \quad \lambda_{\text{elas}} = 0.1 \, \text{fm}, \quad \lambda_{\text{inel}} = 0.1 \, \text{fm}, \quad \omega_{\text{min}} = 50 \, \text{MeV}$$

\[ \frac{1}{\sigma \omega^2} \frac{d^2 \sigma}{d^2 \omega} \]

1 GeV $< \omega <$ 2 GeV

$\kappa^2 = k_T^2/\hat{q}L$
Multiple gluon emission & LPM-effect

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*first theoretical progress: radiation off colour dipole*


Consequences of multiple gluon emission

- radiated gluons radiate → **democratic treatment**
- energy loss not meaningful quantity
  
  need to observe entire fragmentation pattern

- **E/p conservation** crucial for multi-parton final states
- theory without democratic treatment not suitable for jet-phenomenology
Multiple gluon emission & LPM-effect

From a MC perspective: LPM-effect

- **LPM-effect**: typically effective description of single gluon radiation
- **probabilistic and local** formulation of LPM-interference


Multiple gluon emission

- **probabilistic iteration** sometimes involving **formation time** arguments
- iteration involves **model dependent** assumptions
- **democratic treatment** normally easy to achieve except for scattering centre
- **common assumption**: partons radiate **independently** supported by Casalderrey-Solana’s & Iancu’s results
$k_\perp$-broadening

Challenges

- affects response of jet algorithms to quenched jets
- analytic calculations: Brownian motion
- sensitive to
  - energy-momentum conservation
  - democratic radiation

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- contamination by energetic recoils
$k_{\perp}$-broadening

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  - energy-momentum conservation
  - democratic radiation
  - contamination by energetic recoils

From a MC perspective

- assumptions about transverse dynamics vary from collinear emission to parton shower kinematics
- room for improvements of microscopic dynamics
Recoils, medium modelling, background

Challenges

- jets modify the background in their vicinity
- important for experimental background subtraction
- and interesting in its own right
  interplay weakly & strongly coupled regimes
- goal: unified description of jets and medium evolution
- first approaches:
  - track recoiling scattering centres
  - hydrodynamics with source terms


  and many more
Recoils, medium modelling, background

From a MC perspective

- most MC’s use hydro calculations as medium model → effect of jet in medium difficult to quantify
  
  good potential for HIJING

- some convert it into population of scattering centres → model dependence

- jet quenching MC’s not designed to describe background modifications
  
  description relies on ordering of scales

- parton cascades not (yet) designed for detailed treatment of jet evolution
  
  largely based on scattering integrals
Hadronisation

Challenges

- conceptually **interesting** but **difficult** question
  - inherently non-perturbative
- common assumption: **hadronisation in vacuum**
- but medium does change **colour structure**
- not clear how **jet** and **medium** hadronisation **interplay**
- potentially large **uncertainties**
- even within **factorised approach**

![Graph showing hadron level with different interactions: vacuum, radiative, collisional: cascade, collisional: all.](image)
Hadronisation

From a MC perspective

- all models assume hadronisation in vacuum
- some models allow modifications of the colour topology
- nearly all rely on Lund string fragmentation model except for Q-HERWIG
- desirable: investigation of systematics
  - e.g. study different assumptions about colour topology
- not all implemented prescriptions are infra-red and collinear safe
- little effort to implement alternative ideas
  - e.g. pre-hadron formation should be suitable for MC’s
Conclusions

- theoretical and experimental arguments for going from single-inclusive observables to jets
- raises important conceptual (and technical) issues
- theory tool: Monte Carlo generators
  - describe jets on basis of multi-particle final states
  - account dynamically for jet – medium interactions
  - versatile to explore conceptual issues
  - jet finders and entire analyses can run on MC events
  - have to rely on phenomenological modelling
- ultimately: unified description of jet & medium evolution
- expect major progress in next years
- and fruitful interaction between experimentalists and theorists