Understanding jets in heavy ion collisions

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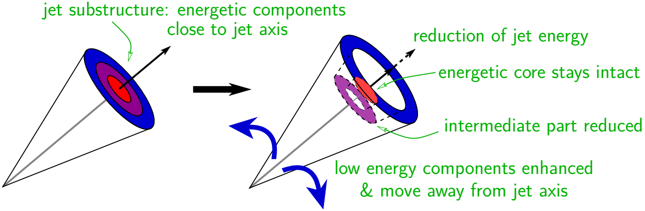
MCnet

Introduction

jets in A+A different from p+p:

- rate reduced by factor 2-4
- modifications to jet substructure

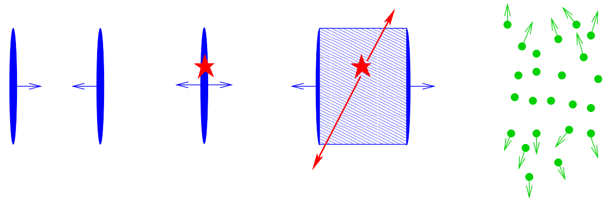


- larger asymmetry in di-jet events

$\Rightarrow$ 'jet quenching'

Introduction

- naive picture of heavy ion collision:



- jets produced in earliest phase of collision
- propagate through dense and hot QCD matter
- what is known about this medium:
  - it is deconfined
  - it shows collective behaviour
  - characteristic scales are soft

Introduction

Why jet quenching is a hard problem

- spatio-temporal structure matters
- re-scattering and jet evolution on same timescale
- hard part of fragmentation pattern unchanged
- jet and background strongly or weakly coupled?
- what exactly is the background?
- multi-scale problem
- interferences

$\Rightarrow$ very different approaches

What we might learn from it

- interplay between weakly and strongly coupled regimes
- nature of the medium
- ...

What happens to jets in medium?

Perturbative approaches

- jet – medium interactions at weak(ish) coupling
- jet resolves quasi-particles
- thermalisation through elastic re-scattering (slow)
- energy loss through QCD bremsstrahlung
- only calculable in certain approximations

  eikonal kinematics and/or single gluon emission and/or . . .
- destructive interference in multiple scattering LPM effect
- zero-temperature perturbation theory
  - re-scattering of a hard parton off a collection of scattering centres
  - can include a parton shower like "vacuum" emission
- thermal field theory
  - re-scattering of hard parton in thermal parton bath
  - difficult to accommodate parton shower evolution

What happens to jets in medium?

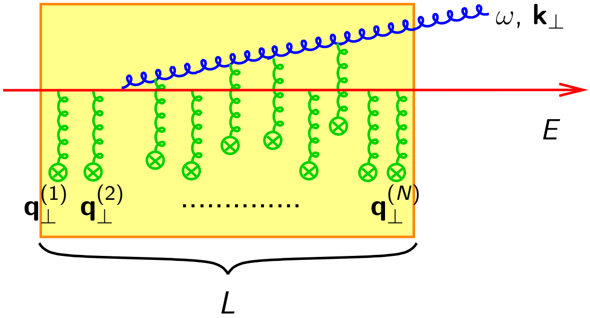
Non-perturbative approach

- interactions between jet & medium at large coupling
- AdS/CFT techniques
  - no jets
  - correspondence to QCD not exact
  - energy loss by drag

Monte Carlo models

- can go beyond analytic calculations
- in particular: full jet evolution
- build on an analytic calculation
- involve modelling

Gluon radiation in eikonal limit



- high energy approximation: $E \gg \omega \gg k_\perp, q_\perp$
- static scattering centres $\rightarrow$ no collisional energy loss
- single gluon radiation $\rightarrow$ unsuitable for jet description
- destructive interference $\rightarrow$ LPM-effect

Baier, Dokshitzer, Mueller, Peigne, Schiff, Nucl. Phys. B **484** (1997) 265

LPM-Effect: Heuristic Discussion

Baier, Schiff, Zakharov, Ann. Rev. Nucl. Part. Sci. **50** (2000) 37

gluon decoheres from projectile when relative phase $\varphi > 1$

$$\varphi = \left\langle \frac{k_\perp^2}{2\omega}\,\Delta z \right\rangle = \frac{\hat{q}L^2}{2\omega} = \frac{\omega_\mathrm{c}}{\omega}$$

coherence time of radiated gluons:

$$t_\mathrm{coh} \simeq \frac{2\omega}{k_\perp^2} \simeq \frac{2\omega}{\hat{q}\,t_\mathrm{coh}} \quad \Rightarrow \quad t_\mathrm{coh} = \sqrt{\frac{2\omega}{\hat{q}}}$$

gluon energy spectrum:

$$\omega\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}z} \simeq \frac{\lambda}{t_\mathrm{coh}}\omega\frac{\mathrm{d}^2 I^{(1)}}{\mathrm{d}\omega \mathrm{d}z} \propto \alpha_\mathrm{s}\sqrt{\frac{\hat{q}}{\omega}}$$

radiative energy loss:

$$\Delta E = \int_0^L \mathrm{d}z \int_0^{\omega_\mathrm{c}} \mathrm{d}\omega\,\omega\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}z} \propto \alpha_\mathrm{s}\hat{q}L^2$$

Can a perturbative picture make sense?

can compute coherent QCD bremsstrahlung in eikonal limit

- formation time of medium induced emissions:

$$\tau_{\text{coh}} = \sqrt{\frac{2\omega}{\hat{q}}}$$

  $\Rightarrow$ soft gluons decohere first...

- formation angle:

$$\theta_{\text{coh}} \approx \frac{k_\perp}{\omega} = \frac{\sqrt{\hat{q}\tau_{\text{coh}}}}{\omega} = \frac{(2\hat{q})^{1/4}}{\omega^{3/4}}$$

  $\Rightarrow$ ...and at large angles

- decoherence rate of colour dipole:

$$\Delta_{\text{med}} = 1 - e^{-(\theta_{\text{jet}}/\theta_{\text{med}})^2}$$

  $\Rightarrow$ hard (vacuum) structures stay coherent longer

☺ qualitatively in line with observations

Casalderrey-Solana, Milhano, Wiedemann, J. Phys. G **38** (2011) 035006
Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk, Phys. Lett. B **725** (2013) 357

Jet quenching Monte Carlos

Zero-temperature perturbation theory

- HIJING
- HYDJET++
- Q-PYTHIA/Q-HERWIG
- JEWEL
- parton cascades: VNI/BMS, AMPT, BAMPS, . . .
- MCs for single-inclusive hadrons: CUJET, MATTER++

Thermal field theory

- MARTINI

Strong coupling

- "The Hybrid"

Phenomenological models

- YaJEM

Q-PYTHIA/Q-HERWIG

Armesto, Cunqueiro, Salgado, Eur. Phys. J. C **63** (2009) 679

Armesto, Corcella, Cunqueiro, Salgado, JHEP **0911** (2009) 122

- idea: minimal, theory based model
- jet production: ME + PS from PYHTIA/HERWIG
- radiative energy loss: modified splitting function: $P_{\text{tot}} = P_{\text{vac}} + \Delta P$, ΔP from BDMPS gluon spectrum
- collisional energy loss: none
- medium: specified by user
- hadronisation: Lund string/Herwig cluster

MARTINI

Schenke, Gale, Jeon, Phys. Rev. C **80** (2009) 054913

- idea: MC based on AMY results on induced radiation
- jet production: ME + PS from PYTHIA
- radiative energy loss: from AMY transition rates
- collisional energy loss: pQCD+HTL transition rate
- medium: hydro
- hadronisation: Lund string

The Hybrid

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, JHEP **1410** (2014) 19

- idea: standard parton shower evolution with a posteriori energy loss partons
- jet production: ME + PS from PYTHIA
- radiative energy loss: none
- collisional energy loss: from AdS/CFT calculation of energy loss of light quarks and gluons
- medium: hydro
- hadronisation: Lund string

JEWEL: Basic idea and assumptions

Basic idea

- complexity of problem asks for a MC event generator
- hard re-scattering resolves medium's partonic structure
- describe interactions using standard pQCD techniques

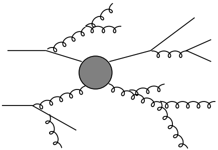
LO ME + PS

Assumptions

- medium as seen by jet: collection of quasi-free partons
- use infra-red continued perturbation theory to describe all jet-medium interactions
- formation times govern the interplay of different sources of radiation
- use results from eikonal limit to include LMP-effect

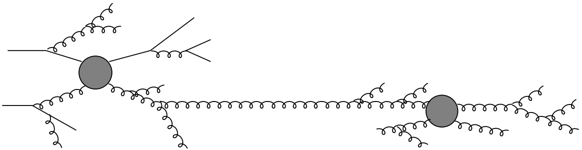
Zapp, Krauss & Wiedemann, JHEP **1303** (2013) 080

JEWEL in a nutshell



- jet production in initial N+N collisions: ME+PS

JEWEL in a nutshell



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- re-scattering: ME+PS
  - generates elastic & inelastic processes
  - with leading log correct relative rates
  - general kinematics

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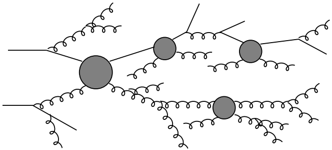

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- emission with shortest formation time is realised
  - all emission ("vacuum" & "medium induced") are equal
  - hard structures remain unperturbed

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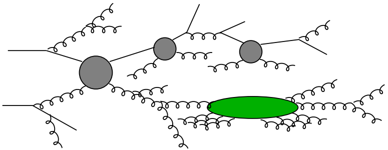

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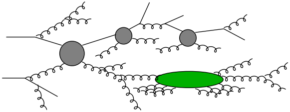
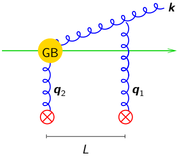
  - generates elastic & inelastic processes
  - with leading log correct relative rates
  - general kinematics
- emission with shortest formation time is realised
  - all emission ("vacuum" & "medium induced") are equal
  - hard structures remain unperturbed
- LPM interference — Zapp, Stachel, Wiedemann, JHEP **1107** (2011) 118
  - also governed by formation times
  - without kinematic restrictions

Probabilistic formulation of the LPM-effect

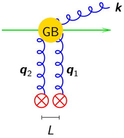


- analytical calculation interpolates between

incoherent production $\tau_1 \ll L$



coherent production $\tau_1 \gg L$



- $\tau_1 \equiv \frac{2\omega}{(\boldsymbol{k} + \boldsymbol{q}_1)^2}$ is the gluon formation time

$\rightarrow$ momentum transfers during formation time act coherently

Coherent emission

Kinematics

- coherent scattering centres act as one

  one momentum transfer:

$$\omega \frac{\mathrm{d}^3 I^{(1)}}{\mathrm{d}\omega \mathrm{d}\boldsymbol{k}} \propto \int \mathrm{d}\boldsymbol{q}\, |A(\boldsymbol{q})|^2 R(\boldsymbol{k}, \boldsymbol{q})$$

  two momentum transfers:

$$\omega \frac{\mathrm{d}^3 I^{(2)}}{\mathrm{d}\omega \mathrm{d}\boldsymbol{k}} \propto \int \mathrm{d}\boldsymbol{q}_1\, \mathrm{d}\boldsymbol{q}_2\, |A(\boldsymbol{q}_1)|^2 |A(\boldsymbol{q}_2)|^2 R(\boldsymbol{k}, \boldsymbol{q}_1 + \boldsymbol{q}_2)$$

- consistent determination of scattering centres and formation time

Emission probability

- suppression compared to incoherent emission by factor $1/N_{\mathrm{coh}}$ N_{coh}: number of coherent momentum transfers

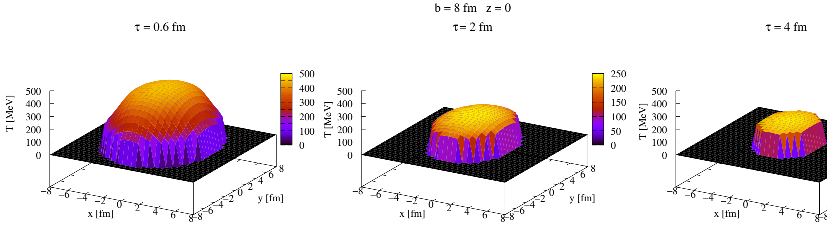
Event generation

- jet production MEs & ISR: PYTHIA Sjostrand et al., JHEP **0605** 26
- nuclear PDFs: EPS09 Eskola, Paukkunen & Salgado, JHEP **0904** (2009) 065
- jet evolution in medium: JEWEL
- medium: do whatever you like, e.g.
  - geometry: Glauber model Eskola et al., Nucl. Phys. B **323** 37

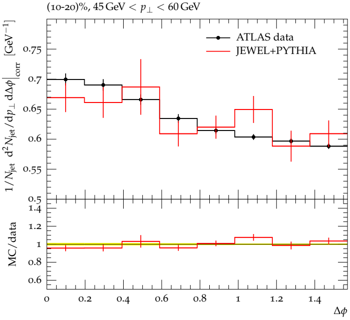
    distribution of jets and temperature profile
  - EOS: ideal quark-gluon gas $\Rightarrow n \propto T^3 \quad \& \quad \epsilon \propto T^4$
  - boost-invariant longitudinal expansion Bjorken, PRD **27** (1983)

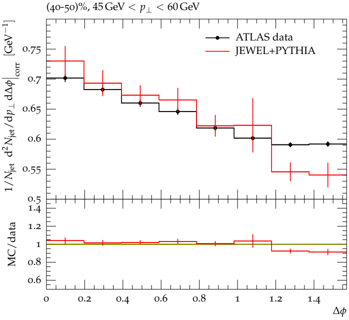
  $\Rightarrow \; T(\tau) \propto \tau^{-1/3} \quad \Rightarrow \quad n(\tau) \propto \tau^{-1} \quad \& \quad \epsilon(\tau) \propto \tau^{-4/3}$
  - initial conditions: $T_\mathrm{i} = 486\,\mathrm{MeV}$ at $\tau_\mathrm{i} = 0.6\,\mathrm{fm}$

    Shen and Heinz, Phys. Rev. C **85** (2012) 054902
- hadronisation: PYTHIA string fragmentation

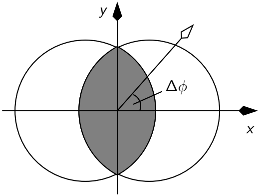


Angular variation





ATLAS, Phys. Rev. Lett. **111** (2013) 152301



- centrality dependent angular variation
- suppression depends on amount of matter seen by jet

Conclusions

Jet quenching

- jets in A+A: characteristic differences from p+p
- arise from re-interaction of jets in soft QCD medium
- severe limitations of analytical approaches

$\Rightarrow$ need MCs to describe full jet evolution

- prize: loss of analytical control

JEWEL

- consistent modelling of modified jet evolution using standard pQCD techniques
- jet evolution + elastic and inelastic re-scattering
- LPM interference
- reasonable description of LHC jet data

showed only one example, many more observables