Jet quenching in perturbative QCD with JEWEL

Korinna Zapp

CERN

Ab initio approaches in many-body QCD confront heavy-ion experiments, Heidelberg 15. – 17. 12. 2014

Construction principle

- in vacuum: description of jets in collinear factorisation pQCD extremely successful

  fixed order matrix elements

  resummation of collinear logs (parton shower)

  matching & merging

  . . .

- Can we use this language for medium-modified jets?
- single hard re-scattering same as jet production in p+p

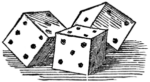
  except for pdf's

  - hard re-scattering resolves medium's partonic structure
  - describe interactions using standard pQCD techniques
- use this as starting point for construction of jet quenching model
- make sure to recover known analytical results in appropriate limits

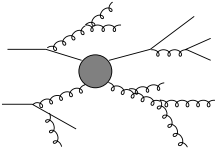
Assumptions

- 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

KCZ, Krauss & Wiedemann, JHEP **1303** (2013) 080
KCZ, Eur.Phys.J. **C74** (2014) 2762
KCZ, Phys.Lett. **B735** (2014) 157
`jewel.hepforge.org`

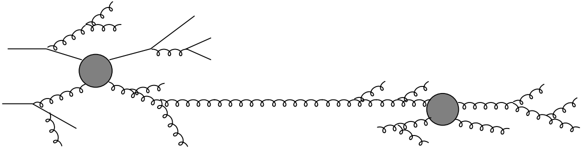


JEWEL in a nutshell



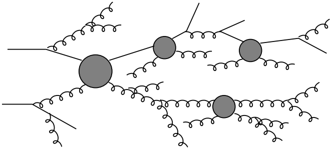
- jet production in initial N+N collisions: ME+PS

JEWEL in a nutshell



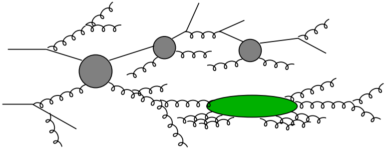
- jet production in initial N+N collisions: ME+PS
- re-scattering: ME+PS
  - generates elastic & inelastic processes
  - with leading log correct relative rates
  - general kinematics

JEWEL in a nutshell



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

JEWEL in a nutshell



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

KCZ, Stachel, Wiedemann, JHEP **1107** (2011) 118

  - also governed by formation times
  - without kinematic restrictions

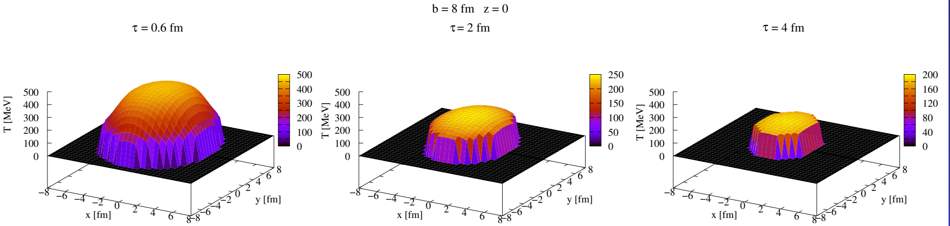
Event generation

- 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 $\Rightarrow n \propto T^3$ & $\epsilon \propto T^4$
  - boost-invariant longitudinal expansion Bjorken, PRD **27** (1983)

  $\Rightarrow T(\tau) \propto \tau^{-1/3} \quad \Rightarrow \quad n(\tau) \propto \tau^{-1}$ & $\epsilon(\tau) \propto \tau^{-4/3}$
  - 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



The background

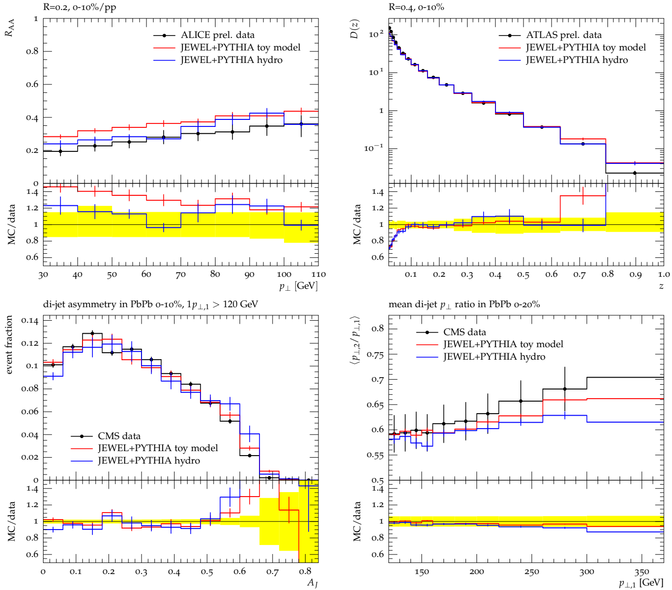
Hydro: 1+1 viscous hydro

Floerchinger & Wiedemann, Phys. Lett. B **728** (2014) 407

- azimuthally symmetric ($b = 0$)
- boost-invariant long. expansion + transv. expansion
- viscosity: $\eta/s = 0.08$
- EOS: parametrisation of lattice + hadron resonance gas Huovinen & Petreczky, Nucl. Phys. A **837** (2010) 26
- initial conditions: $T_\mathrm{i} = 485\,\mathrm{MeV}$ and $\tau_\mathrm{i} = 0.6\,\mathrm{fm}$
  transverse profile from Glauber model

Shen & Heinz, Phys. Rev. C **85** (2012) 054902

JEWEL+hydro: some results



CMS, Eur. Phys. J. C **72** (2012) 1945; ALICE, arXiv:1208.6169
ALTAS-CONF-2012-115; CMS, Phys. Lett. B **712** (2012) 176

The source term

Definitions

- interface: 4-momentum transfer in scattering processes
- source term: $J^\mu(x) = \sum_i \Delta p_i^\mu \delta^{(4)}(x - x_i)$
- hydro equations: $\partial_\mu T^{\mu\nu} = J^\nu$
- projections w.r.t. fluid velocity:
  $J_S = u_\nu J^\nu \quad \& \quad J_V^\mu = \Delta^\mu{}_\nu J^\nu$
- characterise J^μ in terms of
  - event averages: $\langle J_S(x)\rangle$, $\langle J_V^\mu(x)\rangle$
  - correlators: $\langle J_S(x) J_S(y)\rangle$, $\langle J_S(x) J_V^\mu(y)\rangle$, $\langle J_V^\mu(x) J_V^\nu(y)\rangle$

for Gaussian fluctuations this is sufficient

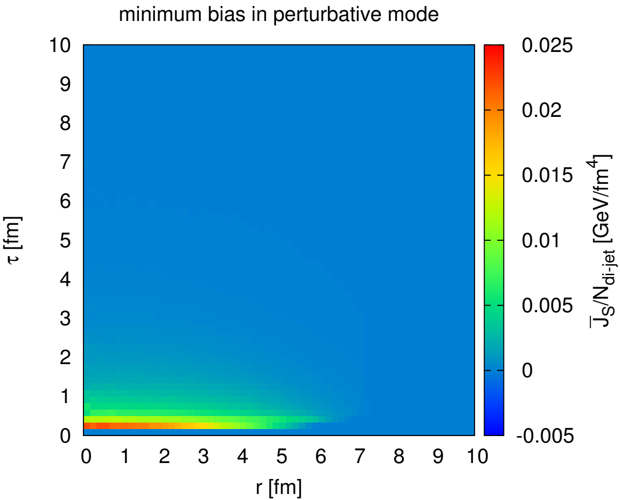
Setup for 'typical event'

- restrict first study to $b = 0$, $|\eta| < 0.5$

this is simply a matter of convenience

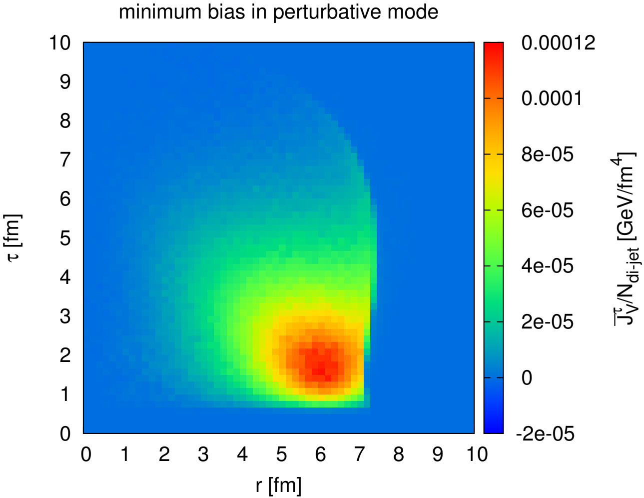
- $p_{\perp,\mathrm{cut}} = 3\,\mathrm{GeV}$ generate jets where they dominate over bulk
- $\langle N_{\text{di-jet}}\rangle = T_{AA}\sigma_{\text{di-jet}} \approx 1700$

The source term of MinBias events: averages



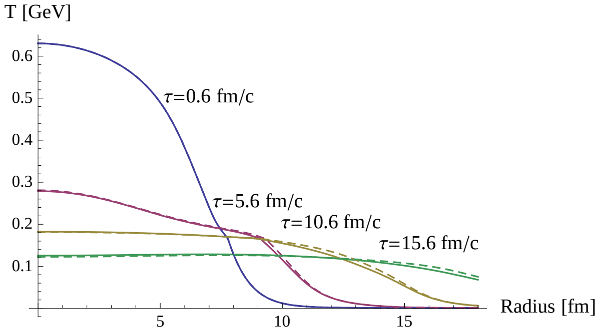
- follows temperature profile

The source term of MinBias events: averages



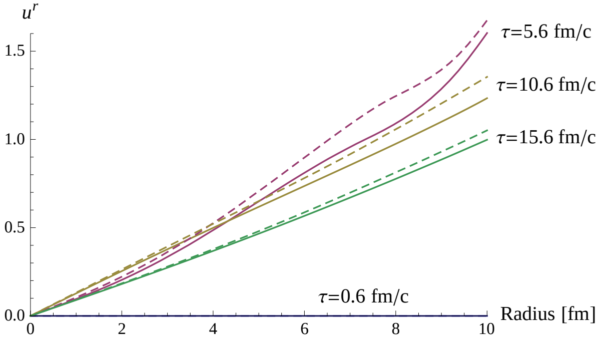
- non-trivial functional dependence

Hydro with source term of MinBias events



- effect of jets on temperature negligible

Hydro with source term of MinBias events



- small increase of transverse flow

Conclusions: Jet Quenching in JEWEL

- jet evolution interleaved with scattering off partonic medium constituents

  simultaneous evolution in scale and space-time

- consistent perturbative formulation
- minimal modelling and tuning
- possibility to quantify uncertainties
- very reasonable description of variety of data
- hard structures cannot be perturbed by medium
- misses increase of soft multiplicity

  energy transferred to background is lost

Conclusions: Hydro & jets in dialogue

Our approach

- construct realistic source term for hydro evol. from jets
- characterise it in terms of averages and correlators

no need to do event-by-event hydro

Influence of hydro on jets

- small differences between hydro and toy model

smaller than current uncertainties

Influence of jets on hydro

- effect on temperature negligible
- small increase of radial flow
- effect of additional hard jets tiny
- potentially sizeable impact on correlations

work in progress – stay tuned

Re-scattering cross section

- cross section for scattering in medium

$$\sigma_i(p,T) = \int_0^{|\hat{t}|_{\max}(p,T)} \mathrm{d}|\hat{t}| \int_{x_{\min}(|\hat{t}|)}^{x_{\max}(|\hat{t}|)} \mathrm{d}x \sum_{j\in\{\mathrm{q},\bar{\mathrm{q}},\mathrm{g}\}} f_j^i(x,|\hat{t}|) \frac{\mathrm{d}\hat{\sigma}_j}{\mathrm{d}|\hat{t}|}(x\hat{s},|\hat{t}|)$$

- neglect radiation off thermal parton
- requires a 'partonic pdf' $f_j^i(x,|\hat{t}|)$

  encodes possible radiation off hard parton
- keep only leading contribution to partonic cross section

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}|\hat{t}|}(\hat{s},|\hat{t}|) \approx C_\mathrm{R} 2\pi\alpha_\mathrm{s}^2 (|\hat{t}| + \mu_\mathrm{D}^2) \frac{1}{(|\hat{t}| + \mu_\mathrm{D}^2)^2}$$

- regulated by $\mu_\mathrm{D}^2 \approx 3T$

Partonic pdf's

- partonic pdf's defined through DGLAP equation

$$f_i^j(x,Q^2) = \mathcal{S}_j(Q^2,Q_0^2) f_i^j(x,Q_0^2)\delta_{ij} + \int\limits_{Q_0^2}^{Q^2} \frac{\mathrm{d}q^2}{q^2}\, \mathcal{S}_i(Q^2,q^2) \int\limits_x^{z_\mathrm{max}} \frac{\mathrm{d}z}{z}\, \frac{\alpha_\mathrm{s}(k_\perp^2)}{2\pi} \sum_k \hat{P}_{ik}(z) f_k^j(x/z,q^2)$$

- at the cut-off scale Q_0 one has

$$f_i^j(x,Q_0^2) = \begin{cases} \delta(1-x) & ; \quad i=j \\ 0 & ; \quad i\neq j \end{cases}$$

- considering at most one emission one gets

$$f_\mathrm{q}^\mathrm{q}(x,Q^2) = \mathcal{S}_\mathrm{q}(Q^2,Q_0^2)\delta(1-x) + \int\limits_{Q_0^2}^{Q^2} \frac{\mathrm{d}q^2}{q^2}\, \mathcal{S}_\mathrm{q}(Q^2,q^2)\, \frac{\alpha_\mathrm{s}(k_\perp^2)}{2\pi} \hat{P}_\mathrm{qq}(x)$$

etc.

Probabilistic formulation of the LPM-effect

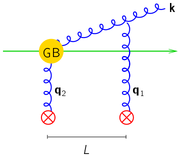
- naive MC purely incoherent
- consider gluon radiation with two momentum transfers

Wiedemann, Nucl. Phys. **B 588**(2000),303

- analytical calculation interpolates between

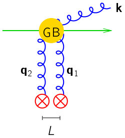
incoherent production

$$\tau_1 \ll L$$



coherent production

$$\tau_1 \gg L$$



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

→ momentum transfers during formation time act coherently

Coherent emission

Kinematics

- coherent scattering centres act as one

  one momentum transfer:

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

  two momentum transfers:

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

- consistent determination of scattering centres and formation time

Emission probability

- suppression compared to incoherent emission by factor $1/N_{\text{coh}}$

  N_{coh}: number of coherent momentum transfers

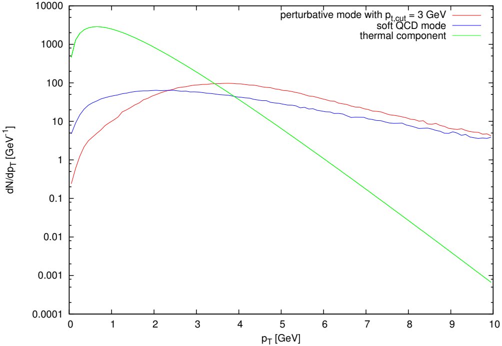
Setup

Setup for 'typical event'

- problem: jet cross section IR-divergent

  eikonalisation through MPI, but let's not go there. . .

- two possible regularisations:
  - 'perturbative mode': $p_{\perp,\mathrm{cut}} = 3\,\mathrm{GeV}$ default
  - 'soft QCD mode': PYTHIA's minimum bias mode



Setup

Setup for 'typical event'

- problem: jet cross section IR-divergent

  eikonalisation through MPI, but let's not go there. . .
- two possible regularisations:
  - 'perturbative mode': $p_{\perp,\mathrm{cut}} = 3\,\mathrm{GeV}$ default
  - 'soft QCD mode': PYTHIA's minimum bias mode
- $\langle N_{\text{di-jet}} \rangle = T_{AA} \sigma_{\text{di-jet}} \approx 1350 - 1700$
- large uncertainties (factor ~ 3)

Setup

Setup for 'typical event'

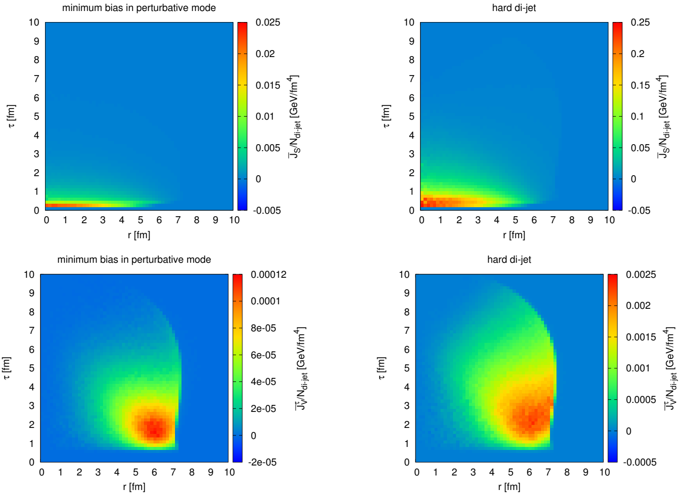
- problem: jet cross section IR-divergent

  eikonalisation through MPI, but let's not go there. . .
- two possible regularisations:
  - 'perturbative mode': $p_{\perp,\text{cut}} = 3\,\text{GeV}$ default
  - 'soft QCD mode': PYTHIA's minimum bias mode
- $\langle N_{\text{di-jet}} \rangle = T_{AA} \sigma_{\text{di-jet}} \approx 1350 - 1700$
- large uncertainties (factor ~ 3)

Triggered di-jet event

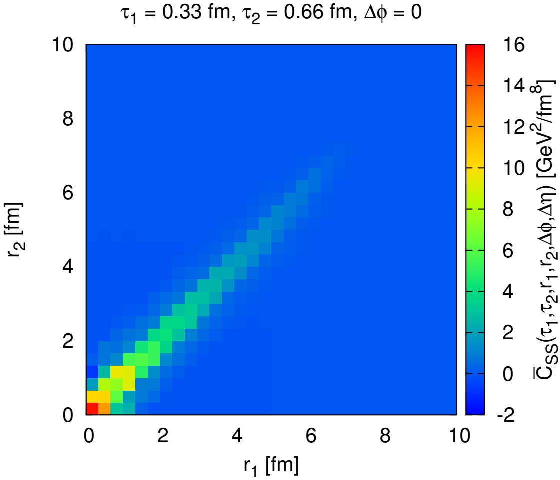
- study effect of hard di-jet $\rightarrow p_{\perp,\text{cut}} = 100\,\text{GeV}$
- need to add 'mini-jets' à la minimum bias mode

The source term of 100 GeV jets: averages



- source term of hard jets extends to later τ
- global effect of hard di-jet negligible

The source term of MinBias events: Correlators



$$\bar{C}_{SS}(x,y) = \langle J_S(x) J_S(y) \rangle - \bar{J}_S(x)\bar{J}_S(y)$$

- contributes to correlations (e.g. v_n)