Monte Carlo for Jet Quenching

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New ideas in hadronization, Durham 15. – 17. 04. 2009

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Jet Quenching in Ultra-Relativistic Heavy-Ion Collisions

Definition of jet quenching

at RHIC: suppression of high-$p_\perp$ particles

at LHC: modification of the jet fragmentation pattern

in the presence of a dense medium

Reasons for studying sub-leading fragments

- will be accessible at LHC
- likely to discriminate between different microscopic mechanisms cojectured to underly jet quenching $\longrightarrow$ essential for characterisation of medium properties
- allows to characterise jet-induced modifications of medium and to disentangle jets from background

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Why a Monte Carlo Parton Shower?

- model medium-modified jets on basis of multi-particle final states
- accounts dynamically for interactions between jet and medium
- reproduces known (vacuum) evolution in absence of medium
- exact energy-momentum conservation
- offers possibility to test different microscopic mechanisms
- interface with experiments

State of the Art

Analytic Calculations

- BDMPS, ASW, GLV, AMY, higher twist, collisional (Bjorken, Thoma & Gyulassy, Braaten & Thoma, Djordjevic, Zakharov, ...), ...
- energy loss dominated by radiative energy loss (QCD bremsstrahlung)
- work in high energy limit
  $\rightarrow$ no exact energy-momentum conservation
- focus on interference effects
- well suited for single-inclusive observables, but treatment of subleading particles difficult
- not all of them have a natural transition to vacuum physics when medium is switched off

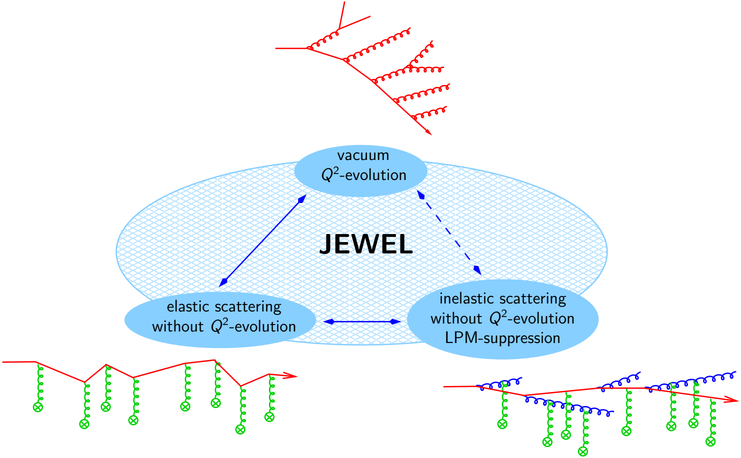
State of the Art

Monte Carlo Implementations

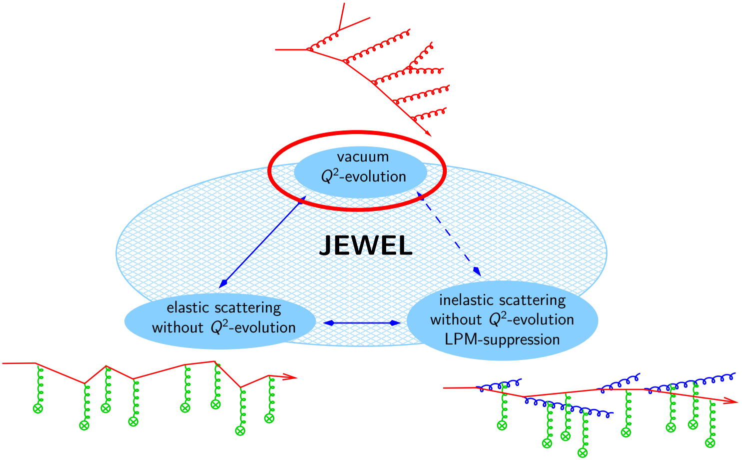
- Q-PYTHIA (Armesto, Cunqueiro, Salgado, Xiang): include BDMPS-like radiation in modified splitting function
- YaJEM (Renk): medium increases virtuality of partons during evolution
- PYQUEN (Lokhtin, Snigirev): PYTHIA afterburner, reduces energy of final state partons and adds radiated gluons according to BDMPS expectations
- PQM (Dainese, Loizides, Paic): Monte Carlo implementation of BDMPS quenching weights
- HIJING (Wang, Gyulassy): jet and minijet production with induced splitting

⇒ No implementation of a parton shower with microscopic model for interactions with medium.

Jet Evolution With Energy Loss



We work towards a dynamically consistent MC for jet quenching that is consistent with all analytically known limiting cases.



Zapp, Ingelman, Rathsman, Stachel, Wiedemann, 0804:3568 [hep-ph]

The Shower in Vacuum

Heart of the parton shower simulation

no-splitting probability (Sudakov form factor)

$$\mathcal{S}_\mathrm{a}(Q_\mathrm{i}^2, Q_\mathrm{f}^2) = \exp\left[-\int\limits_{Q_\mathrm{f}^2}^{Q_\mathrm{i}^2} \frac{\mathrm{d}Q'^2}{Q'^2} \int\limits_{z_-(Q'^2,E)}^{z_+(Q'^2,E)} \mathrm{d}z \, \frac{\alpha_\mathrm{s}}{2\pi} \sum_{\mathrm{b},c} \hat{P}_{\mathrm{a}\to\mathrm{bc}}(z)\right]$$

Procedure

- choose virtuality of initiating parton from $\frac{\partial \mathcal{S}_\mathrm{a}(Q_\mathrm{i}^2, Q^2)}{\partial Q^2}$
- choose kind of splitting $a \to b + c$
- choose energy sharing z from $P_{\mathrm{a}\to\mathrm{bc}}(z)$
- repeat for daughters until no partons with $Q^2 > Q_0^2$ left

angular ordering required

The Hadronisation Model

The Problem

- jets in nuclear environment no well-defined colour neutral system
- no well-defined colour topolgy
- other problems (later)

$\longrightarrow$ need a sufficiently simple and flexible prescription

The Solution

- idea: use Lund string fragmentation but replace knowledge about colour flow by assumption that colour neutralisation occurs locally (*Torbjörn Sjöstrand*)
- can handle any jet-system if strings are allowed to end at (artificial) endpoints at high rapidity
- works quite well even in e^+e^- collisions

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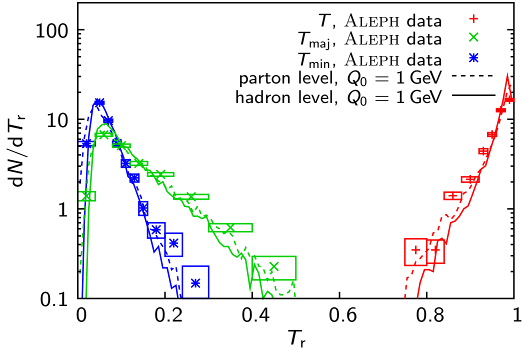
Comparison to Data: Thrust

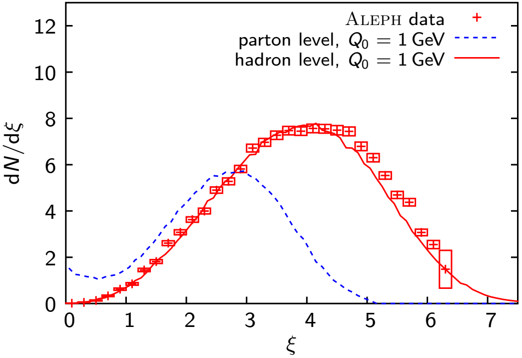


$$T \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_i \cdot \vec{n}_T|}{\sum_i |\vec{p}_i|} \qquad T_{maj} \equiv \max_{\vec{n}_T \cdot \vec{n}=0} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|} \qquad T_{min} \equiv \frac{\sum_i |\vec{p}_{ix}|}{\sum_i |\vec{p}_i|}$$

- not very sensitive to hadronisation

A. Heister *et al.* [ALEPH Coll.] Eur. Phys. J. C **35** (2004) 457

Comparison to Data: $\mathrm{d}N/\mathrm{d}\xi$



$$\xi = \ln(p_{\max}/p)$$

- sensitive to details of hadronisation

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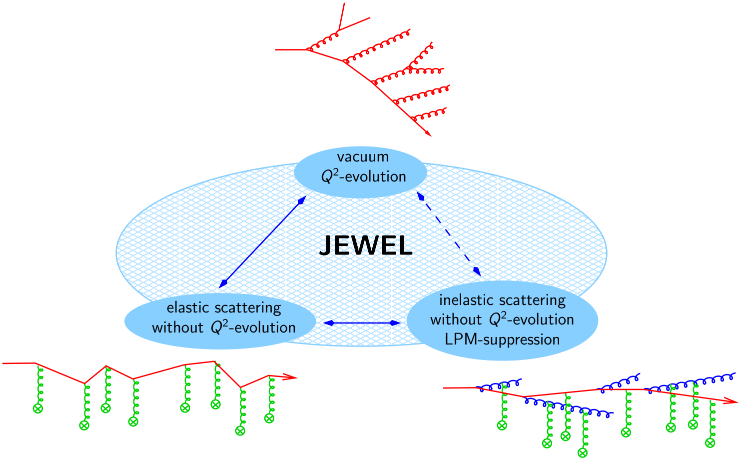
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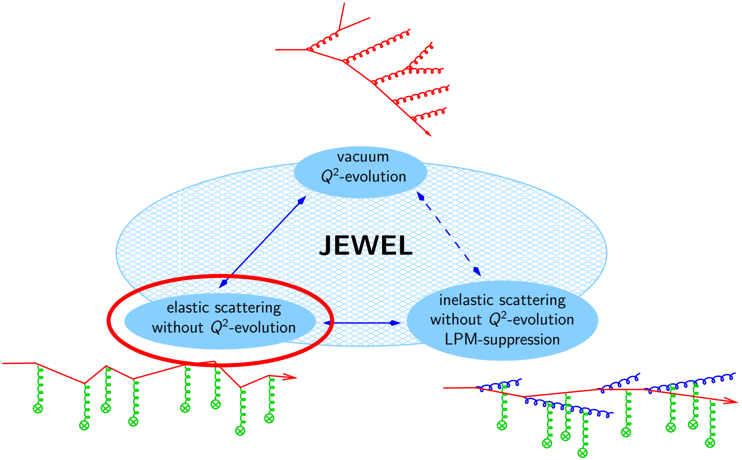

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Collisional Energy Loss

- scattering cross section:

$$\sigma^{\mathrm{I}}_{\mathrm{elas}} = \int\limits_0^{|t_{\mathrm{max}}|} \mathrm{d}|t| \, \frac{\pi\,\alpha_s^2(|t| + \mu_D^2)}{s^2} \, C_R \, \frac{s^2 + u^2}{(|t| + \mu_D^2)^2}$$

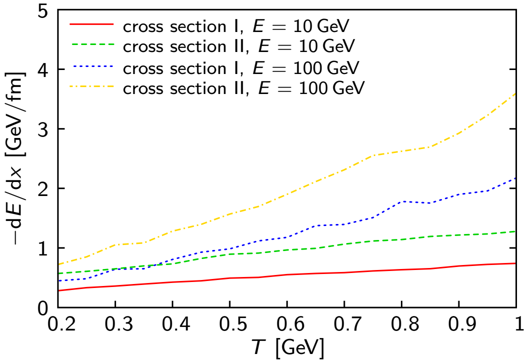
or

$$\sigma^{\mathrm{II}}_{\mathrm{elas}} = \int\limits_{\mu_D^2}^{|t_{\mathrm{max}}|} \mathrm{d}|t| \, \frac{\pi\,\alpha_s^2(|t|)}{s^2} \, C_R \, \frac{s^2 + u^2}{|t|^2}$$

- no-scattering probability: $\exp(-n\sigma_{\mathrm{elas}}\tau)$
- possibility to let the recoil scatter (not explored here)
- medium: collection of scattering centres (here: constant temperature, ideal quark-gluon gas EOS)

Elastic Energy Loss Baseline

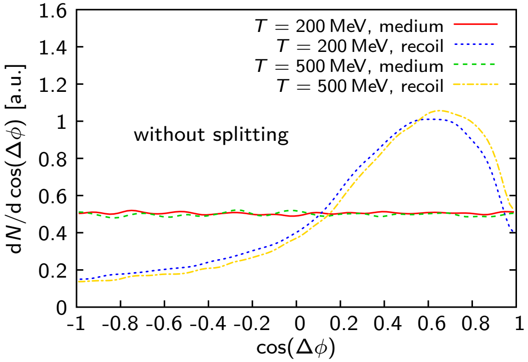
collisional energy loss without Q^2-evolution



- reproduces analytical calculations (with their dependence on regularisation schemes)

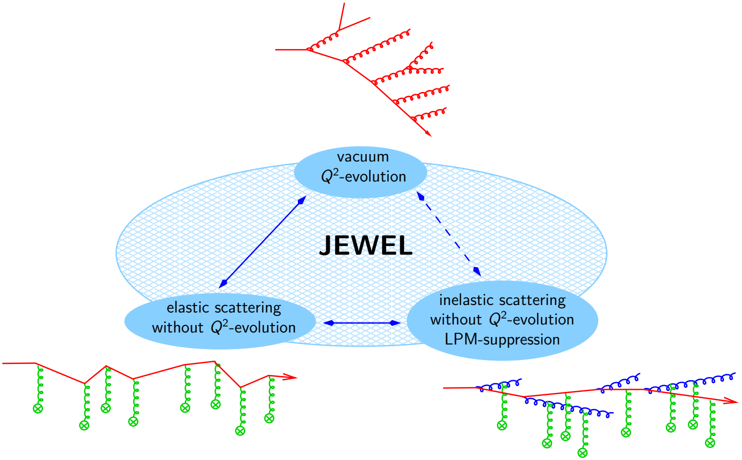
Recoil

angle between jet and recoiling scattering centre



$E = 100\,\text{GeV}$

- preferred angle nearly independent of temperature



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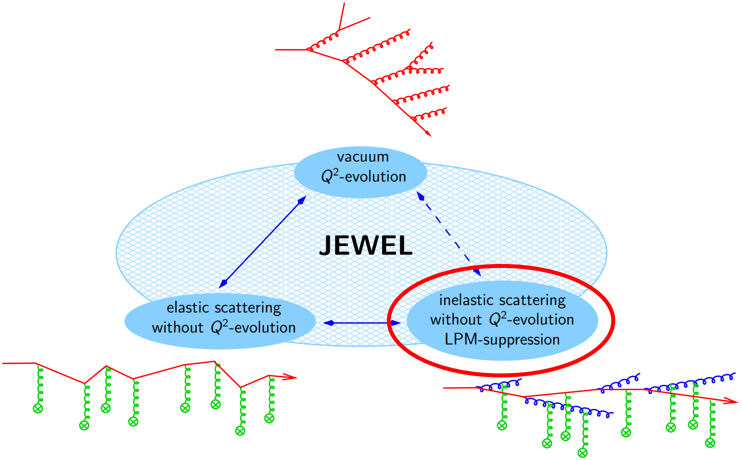

Zapp, Stachel, Wiedemann, 0812:3888 [hep-ph]

LPM in MC

BDMPS ASW opacity expansion:

$$\omega \frac{d^3 I(N=1)}{d\omega\, d\mathbf{k}_\perp\, d\mathbf{q}_\perp} =$$
$$\frac{\alpha_s}{\pi^2} \frac{C_R}{2\omega^2} \frac{1}{(2\pi)^2} |A(\mathbf{q}_\perp)|^2 (\mathbf{k}_\perp \cdot \mathbf{q}_\perp) n_0 \tau \tau_1^2 \left[\frac{L}{\tau_1} - \sin\left(\frac{L}{\tau_1}\right) \right]$$

explicit field theoretic manifestation of the formation time

$$\tau_1 = \frac{2\omega}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2}$$

interpolates between limiting cases

- $\tau_1 \gg L$: totally coherent
- $\tau_1 \ll L$: totally incoherent

MC procedure:

1. create gluon in inelastic process
2. check if scattering during t_f

no: gluon is formed, back to 1

yes: scattering after time $\Delta t < t_f$, re-evaluate formation time, back to 2

Radiative Energy Loss Baseline

BDMPS ASW results:

$$\frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \omega^{-3/2} \quad \text{for} \quad \omega < \omega_\mathrm{c}$$
$$\frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \omega^{-3} \quad \text{for} \quad \omega > \omega_\mathrm{c}$$
$$\Delta E \propto L^2 \quad \text{for} \quad L < L_\mathrm{c}$$
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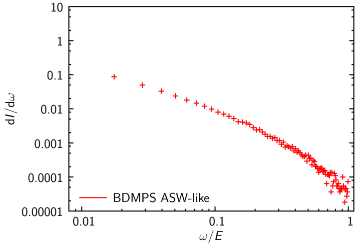
Radiative Energy Loss Baseline



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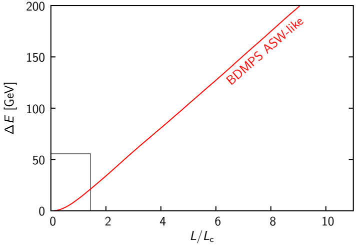

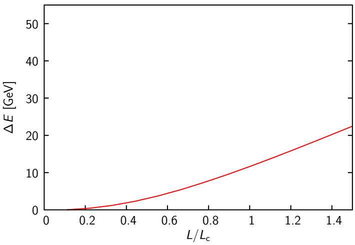

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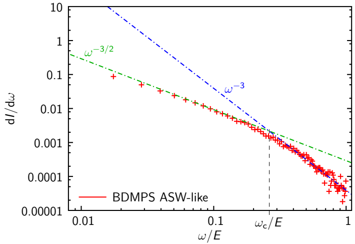

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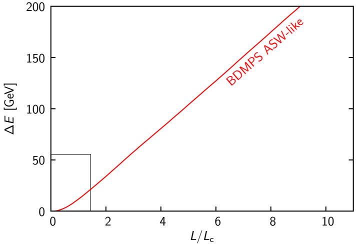
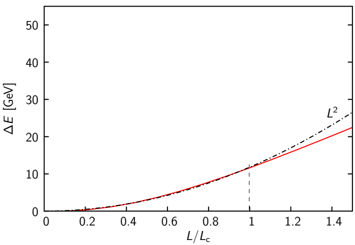


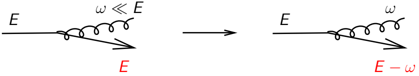


Going Beyond BDMPS ASW

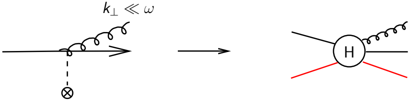
1. relaxing soft scattering approximation of BDMPS ASW

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_\perp^2} \propto \frac{1}{(q_\perp^2+\mu^2)^2}\,\theta(q_\perp^2-4\mu^2) \to \frac{1}{(q_\perp^2+\mu^2)^2}$$

2. going beyond BDMPS soft gluon approximation



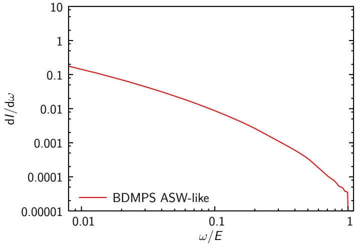
3. exploring realistic kinematics of inelastic process

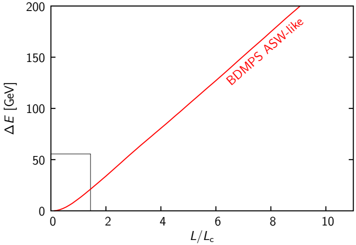


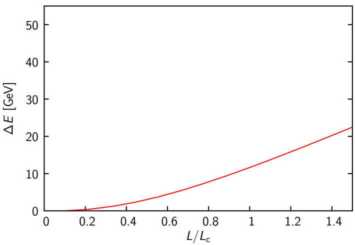
here: extreme limit $\frac{\mathrm{d}^2\sigma^{\mathrm{qQ}\to\mathrm{qQg}}}{\mathrm{d}\omega\,\mathrm{d}k_\perp^2} = \sigma^{\mathrm{qQ}\to\mathrm{qQ}}\frac{C_\mathrm{F}4\alpha_\mathrm{s}}{\pi}\frac{1}{\omega}\frac{1}{k_\perp^2}$

4. this includes recoil effects in elastic and inelastic processes

Going Beyond BDMPS ASW







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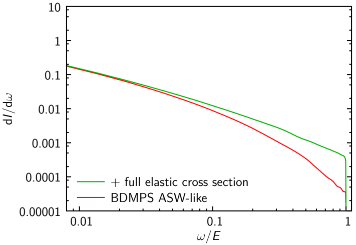

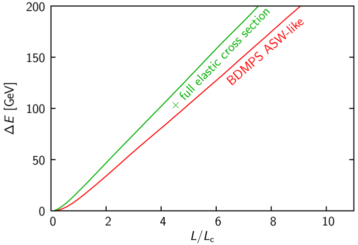

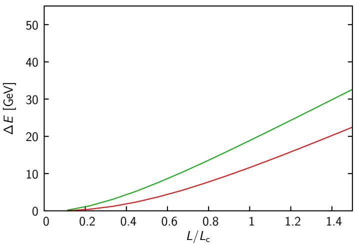

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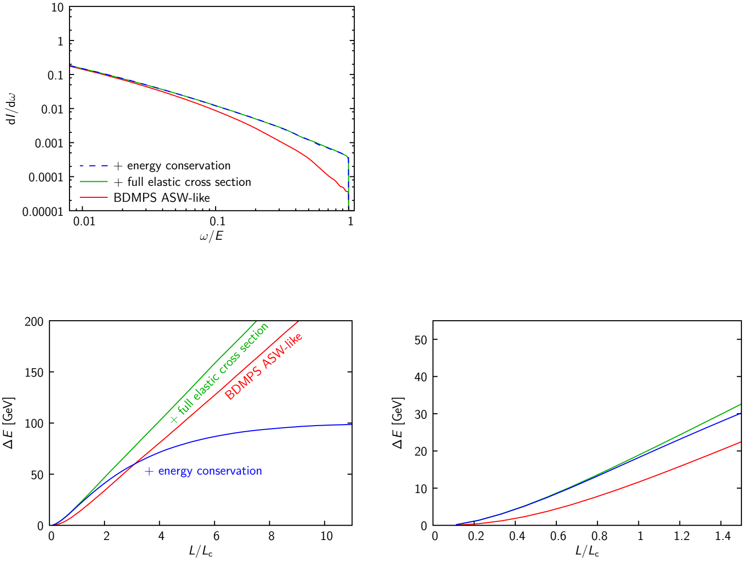

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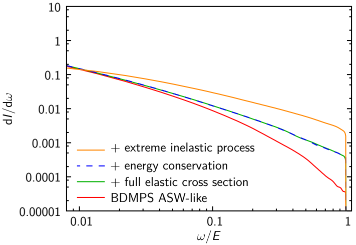

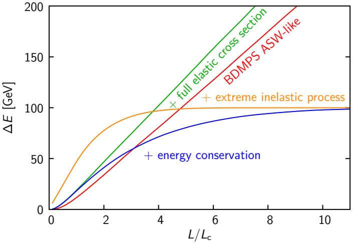

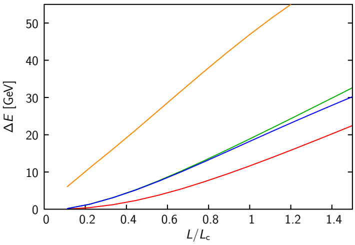

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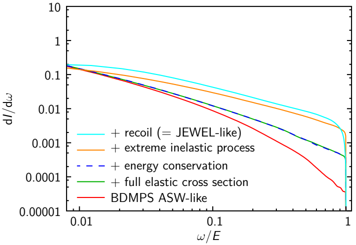

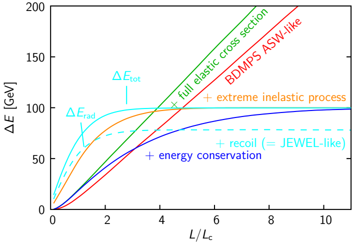

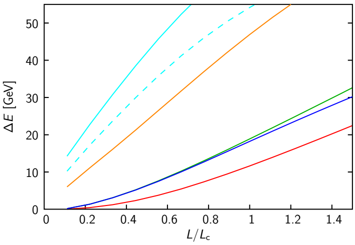

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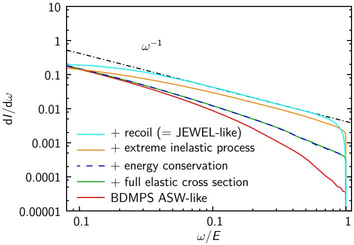
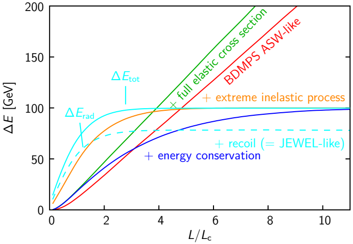
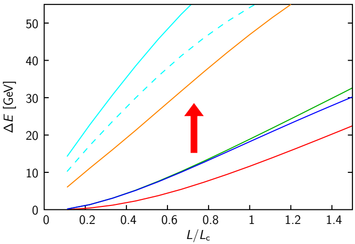
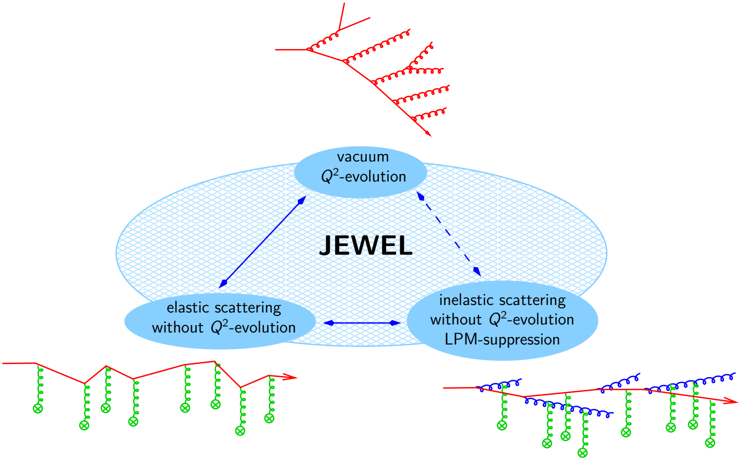


All improvements lead to

- loss of coherence
- enhanced energy loss



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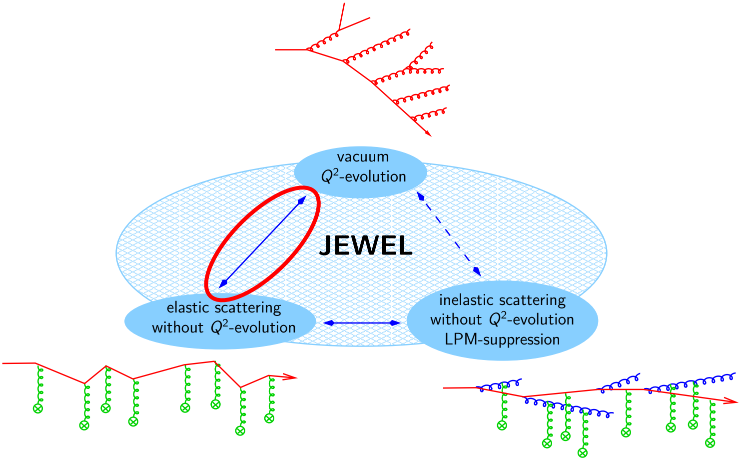

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Medium Modifications to the Shower

Spatio-temporal structure of shower

- lifetime of parton in shower (estimate from uncertainty principle):

$$\tau = \frac{E}{Q_\mathrm{f}^2} - \frac{E}{Q_\mathrm{i}^2}$$

Parton shower + elastic scattering

- assume that elastic scattering does not affect Q^2-evolution (no significant transverse phase space opened)

$\rightarrow$ parton shower and elastic scattering decoupled

To compare with: simple model for induced radiation

- increase probability for perturbative splitting by factor $1 + f_\mathrm{med}$ inside the medium

Hadronisation Issues

A few observations

- no well-defined colour flow due to interactions with medium
- parton shower is accompanied by associated partons
- high level of soft background
- soft component of jet system has momenta of order of thermal momenta
- hadronisation of bulk medium not understood

Hadronisation Issues

and a few related questions

- Is the colour topology relevant for hadronisation?
- Are recoiling scattering centres part of the ‘jet’?
- What happens to the soft component?
- Is the hadronisation mechanism itself modified by the presence of a dense medium? Is hadron formation inside the medium possible and, if yes, how?

What to do?

pragmatic ansatz:

- assume hadronisation outside the medium
- recoiling scattering centres: can be hadronised together with parton shower or don’t show up in hadronic final state
- identify observables that are insensitive to hadronisation

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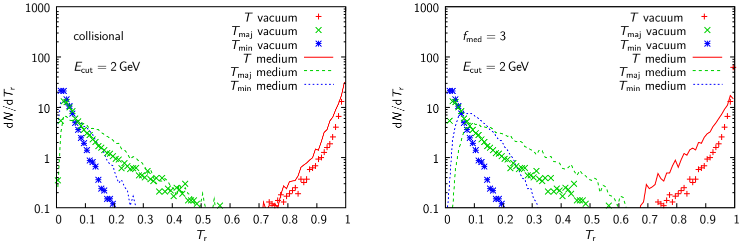
Medium Modifications: Thrust

100 GeV quark jet, only hadrons with $E_h > 2\,\text{GeV}$ included

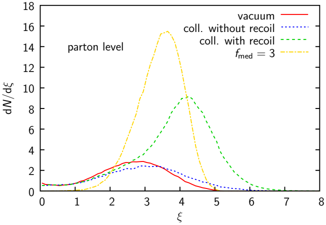


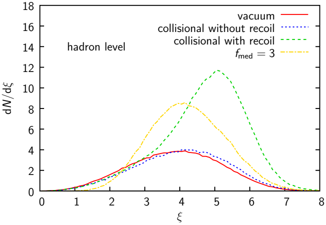
$T = 500\,\text{MeV},\ L = 5\,\text{fm}$

- might allow to distinguish between elastic and radiative energy loss

Intra-Jet Distribution $dN/d\xi$

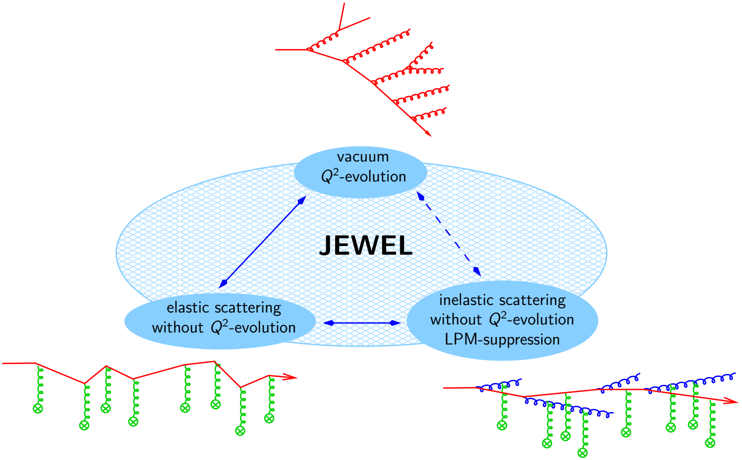
$\xi = \ln(p_{max}/p)$-distribution in a single 100 GeV quark jet





$T = 500\,\text{MeV},\ L = 5\,\text{fm},\ f_{med} = 3$

- clear increase of multiplicity due to radiative energy loss
- collisional energy loss only increases multiplicity when recoils are counted towards jet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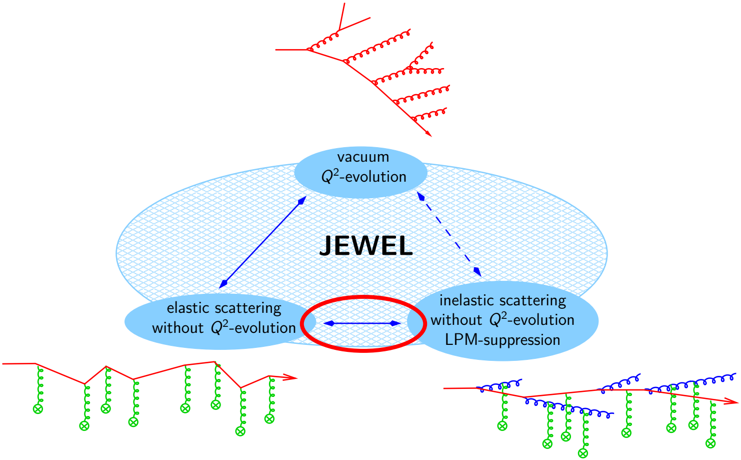
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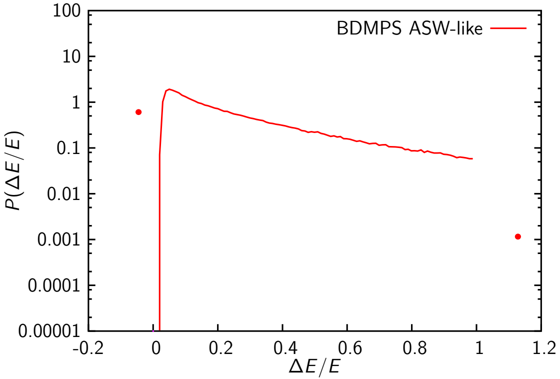
The Brick-Problem

- standard problem created by TECHQM initiative to compare different energy loss calculations

  https://wiki.bnl.gov/TECHQM/index.php/Main_Page
- task:
  - consider static medium with constant temperature and length L
  - let a quark with energy E_q propagate in medium
  - adjust medium properties to reach a given value of $\langle \Delta E/E_\mathrm{q} \rangle$
  - calculate probability distribution $P(\Delta E/E_\mathrm{q})$ for losing a fraction $\epsilon = \Delta E/E_\mathrm{q}$ of projectile's energy through elastic scattering and/or medium induced gluon radiation

JEWEL-Answer to Brick Problem



$L = 2\,\text{fm}$

$E_q = 10\,\text{GeV}$

$\langle \frac{\Delta E}{E_q} \rangle = 0.1$

JEWEL radiative: energy carried by radiated gluons

JEWEL recoil: energy carried away by recoil in elastic or inelastic scattering

$\Rightarrow$ characteristic differences between BDMPS ASW and JEWEL scenario

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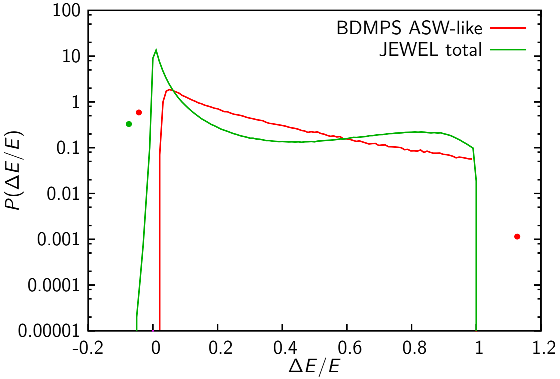

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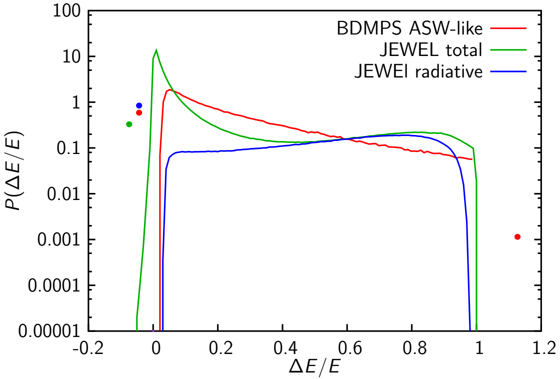

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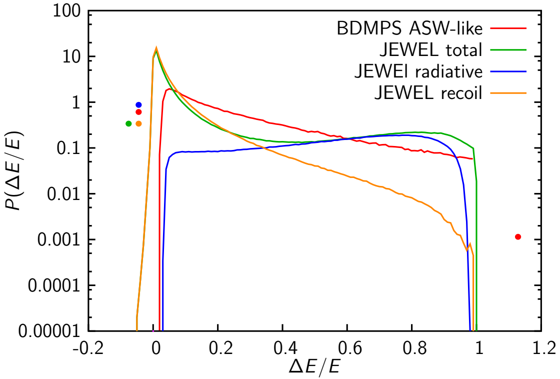

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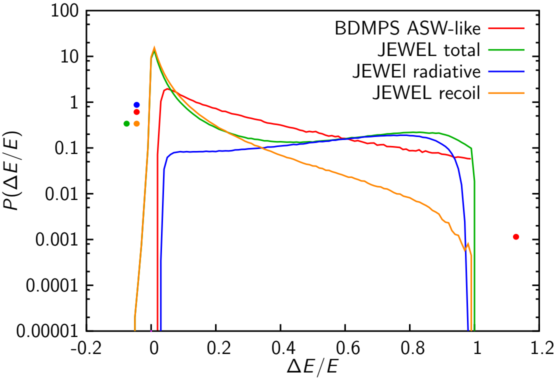

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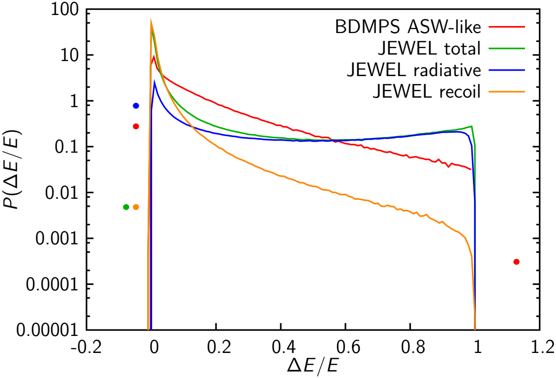

$L = 2\,\text{fm}$

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Summary & Outlook

What we have achieved

- vacuum parton shower seems to work reasonably well
- elastic energy loss without Q^2-evolution agrees with analytic calculations
- we have a way to include LPM-suppression in probabilistic MCs
- radiative energy loss has BDMPS ASW limiting case
- we can relax assumptions in analytic calculation
- one way of combining parton shower and elastic scattering is implemented and explored

Summary & Outlook

(Some) open questions

- embedding of parton shower in medium involves model-dependent assumptions
- spatiotemporal structure based on assumptions that are difficult to constrain
- pertubative treatment of interactions of jet with medium problematic
- description of inelastic scattering still incomplete
- hadronisation in nuclear environment poorly understood

More interesting questions that we hope to contribute to

- energy loss of heavy quarks
- separation of weakly coupled from strongly coupled regimes
- hadronisation

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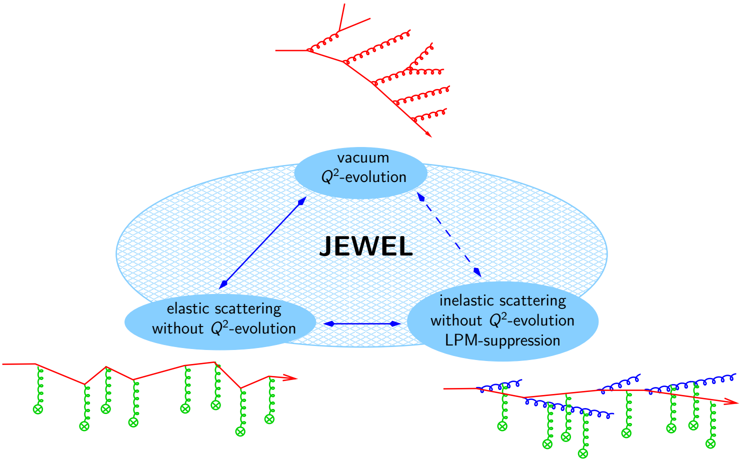

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