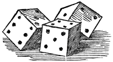
Monte Carlo Tools for Jet Quenching

Korinna Zapp

Institute for Particle Physics Phenomenology, Durham University

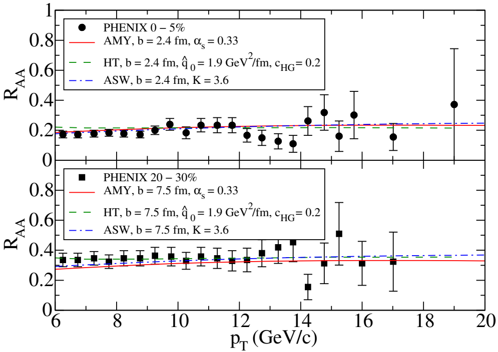
Quark Matter, Annecy 25. 05. 2011



Motivation for investigating jets

Theoretical considerations

- single-inclusive quantities do not fully constrain models



Bass *et al.*, Phys. Rev. C **79** (2009) 024901

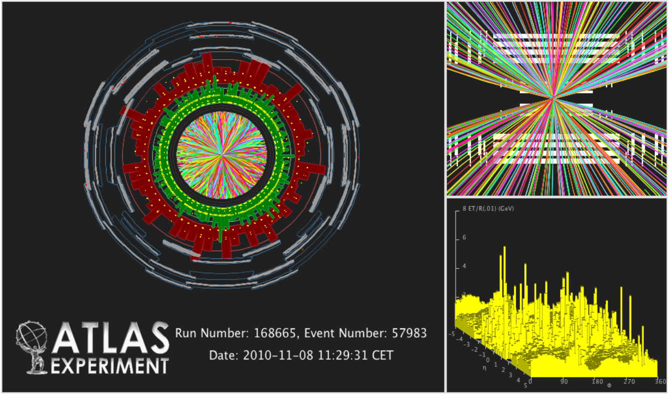
- sub-leading fragments more discriminating

not well modelled by analytic calculations

Motivation for investigating jets

Experimental needs

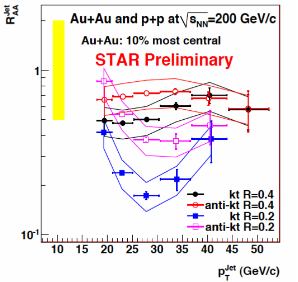
- need reliable tools to disentangle jets from background



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 ($\to$ jet shapes)
  - jet area, background, fluctuations
  - jet induced medium modifications



Bruna for the STAR Collaboration, J. Phys. Conf. Ser. **230** (2010) 012009

- 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

$$\mathrm{d}\sigma_{n+1} \approx \mathrm{d}\sigma_n \frac{\mathrm{d}t}{t} \frac{\mathrm{d}\phi}{2\pi} \mathrm{d}z \frac{\alpha_s}{2\pi} \mathcal{P}(z)$$

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

$\rightarrow$ large logarithms $\rightarrow$ need to be resummed to all orders

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

$$\mathcal{S}(t_1, t_2) = \exp\left\{ -\int_{t_1}^{t_2} \frac{\mathrm{d}t}{t} \int \mathrm{d}z \frac{\alpha_s}{2\pi} \mathcal{P}(z) \right\}$$

Baseline: QCD Parton Shower in Vacuum

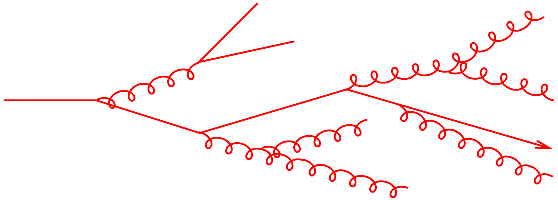
- evolution equation can be integrated

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

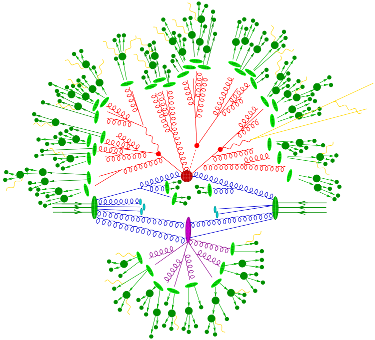
- $\mathcal{S}(t_0,t)$ probability for no emission between t and t_0
- suitable for MC implementation → parton shower
- resums real emissions to all orders

  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



(multi-purpose event generators: HERWIG, PYTHIA, SHERPA)

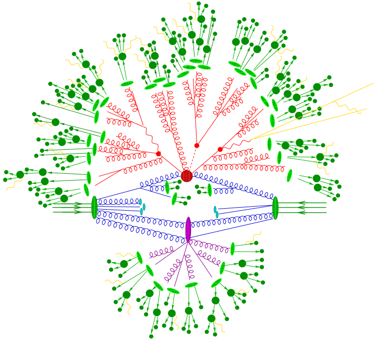
matrix elements: fixed order perturbation theory (LO or NLO)

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

$$\tau_{\mathrm{vac}} \approx \frac{\omega}{k_\perp^2} \approx \frac{1}{\sqrt{t}} \cdot \frac{E}{\sqrt{t}}$$

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

$$\tau_{\mathrm{med}} \approx \frac{\omega}{k_\perp^2} \approx \frac{\omega}{\hat{q}\tau_{\mathrm{med}}} \quad \Rightarrow \quad \tau_{\mathrm{med}} \approx \sqrt{\frac{\omega}{\hat{q}}}$$

- 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)

Casalderrey-Solana, Milhano, Wiedemann, J. Phys. G **38** (2011) 035006

Established MC models

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

Wang, Gyulassy, Phys. Rev. D **44** (1991) 3501

Deng, Wang, Xu, arXiv:1008.1841

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

Lokhtin, Snigirev, Eur. Phys. J. C **45** (2006) 211

Lokhtin *et al.*, Comput. Phys. Commun. **180** (2009) 779

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

    work in progress
  - elastic scattering
  - simulates only parton shower + hadronisation

Zapp, Ingelman, Rathsman, Stachel, Wiedemann, Eur. Phys. J. C **60** (2009) 617

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

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

Renk, Phys. Rev. C **78** (2008) 034908

Renk, Phys. Rev. C **79** (2009) 054906

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

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

Non-eikonal kinematics

Problems with eikonal kinematics

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

Consequences of non- eikonal kinematics

- phase space restrictions due to E/p-conservation

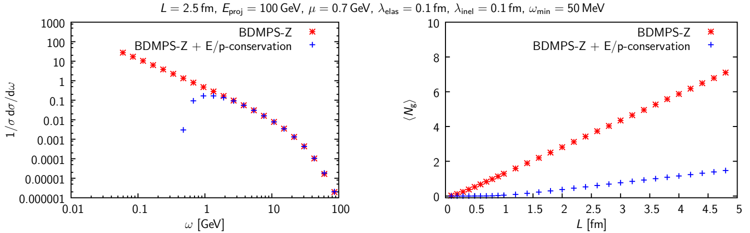
Non-eikonal kinematics

Problems with eikonal kinematics

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

Consequences of non- eikonal kinematics

- phase space restrictions due to E/p-conservation



Non-eikonal kinematics

Problems with eikonal kinematics

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

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

  in preparation

- dynamical scatterings centres: difficult for models based on effective descriptions

  e.g. modified splitting functions

  - collisional energy loss: typically neglected or added as separate process
  - radiation off scattering centres: model dependent

  first steps in preparation

- 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

Mehtar-Tani, Tywoniuk, arXiv:1105.1346 & Casalderrey-Solana, Iancu, arXiv:1105.1760

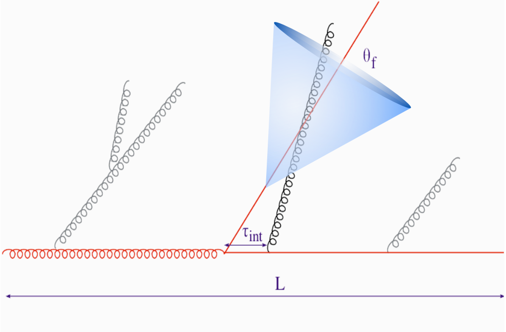
Multiple gluon emission & LPM-effect

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

Mehtar-Tani, Tywoniuk, arXiv:1105.1346 & Casalderrey-Solana, Iancu, arXiv:1105.1760



Multiple gluon emission & LPM-effect

Problems with analytic calculations

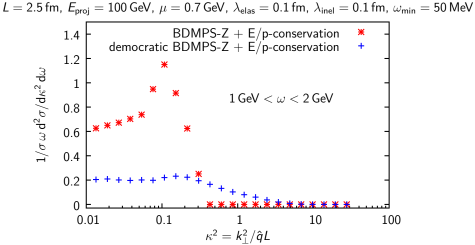
- single gluon radiation only + probabilistic iteration
- affected by E/p non-conservation in eikonal limit
- unclear how multiple gluon emissions interplay

first theoretical progress: radiation off colour dipole

Mehtar-Tani, Tywoniuk, arXiv:1105.1346 & Casalderrey-Solana, Iancu, arXiv:1105.1760

Consequences of multiple gluon emission

- radiated gluons radiate → democratic treatment



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

Mehtar-Tani, Tywoniuk, arXiv:1105.1346 & Casalderrey-Solana, Iancu, arXiv:1105.1760

Consequences of multiple gluon emission

- radiated gluons radiate $\rightarrow$ 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

Zapp, Stachel, Wiedemann, Phys. Rev. Lett. **103** (2009) 152302 & arXiv:1103.6252

Multiple gluon emission

- probabilistic iteration sometimes involving formation time arguments
- iteration involves model dependent assumptions
- democratic treatment normally easy to achieve

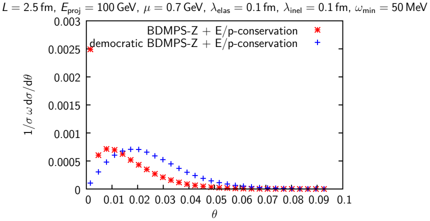
  except for scattering centre
- common assumption: partons radiate independently

  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



  - contamination by energetic recoils

$k_\perp$-broadening

Challenges

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

From a MC perspective

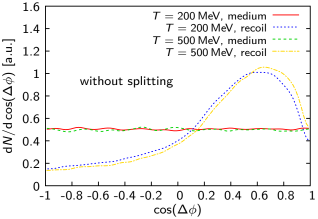
- assumptions about transverse dynamics vary from collinear emission to parton shower kinematics
- room for improvements of microscopic dynamics

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



Zapp, Ingelman, Rathsman, Stachel, Wiedemann, Eur. Phys. J. C **60** (2009) 617

  - hydrodynamics with source terms — Neufeld, Renk, arXiv:1001.5068

and many more

Recoils, medium modelling, background

From a MC perspective

- most MC's use hydro calculations as medium model
  $\rightarrow$ effect of jet in medium difficult to quantify

  good potential for HIJING

- some convert it into population of scattering centres

  $\rightarrow$ 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

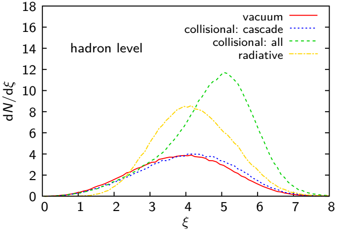
Hadronisation

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



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