Simulations of jet quenching and elliptic flow in a pQCD-based partonic transport model

Oliver Fochler

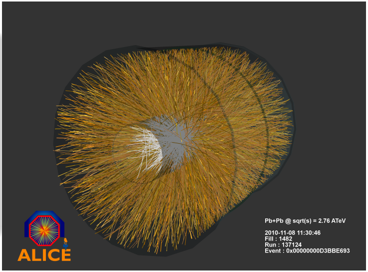
Institut für Theoretische Physik
Goethe-Universität Frankfurt

High-p_T physics at LHC
26 March 2012

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

HIC for FAIR
Helmholtz International Center

Heavy Ion Collisions are Complicated!



Models are needed for:

- Initial state
- Evolution of the medium
- High-p_T physics (“jet physics”)
- Phase transition

Some tools:

- Parameterizations (e.g. Bjorken)
- Hydrodynamics
- Transport models
- Lattice QCD
- AdS / CFT
- pQCD (BDMPS, ASW, AMY, ...)

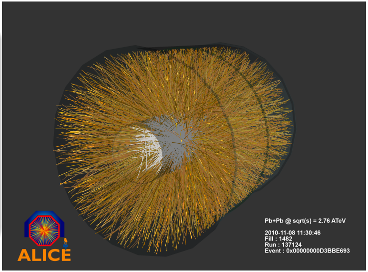
The problem

No model can describe all (most) aspects of the medium evolution.

Heavy Ion Collisions are Complicated!

Models are needed for:

- Initial state
- Evolution of the medium
- High-p_T physics ("jet physics")
- Phase transition



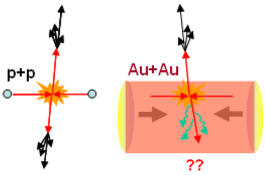
Some tools:

- Parameterizations (e.g. Bjorken)
- Hydrodynamics
- Transport models
- Lattice QCD
- AdS / CFT
- pQCD (BDMPS, ASW, AMY, ...)

The problem

No model can describe all (most) aspects of the medium evolution.

Elliptic Flow and Suppression of Jets



Jet suppression

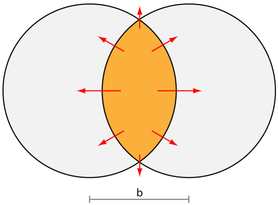
$$R_{AA} = \frac{d^2 N_{AA}/dy\, dp_T}{T_{AA}\, d^2\sigma_{NN}/dy\, dp_T}$$

- Strong suppression of jets compared to p + p reference

Collective behavior of the medium

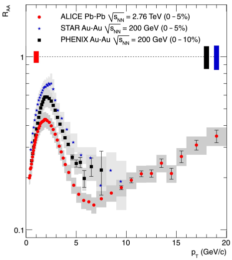
$$E\frac{d^3N}{d^3p} \sim \frac{d^2N}{dy\, dp_T}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\phi - \Psi_R)\right]\right)$$

- Elliptic flow: Fourier coefficient v_2
- Hydrodynamic behavior



Common description of R_{AA} and v_2 is difficult

Elliptic Flow and Suppression of Jets



Jet suppression

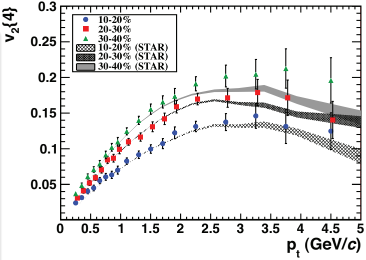
$$R_{AA} = \frac{d^2 N_{AA}/dy\ dp_T}{T_{AA}\ d^2\sigma_{NN}/dy\ dp_T}$$

- Strong suppression of jets compared to p + p reference

Collective behavior of the medium

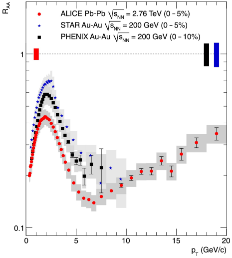
$$E\frac{d^3N}{d^3p} \sim \frac{d^2N}{dy\ dp_T}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\phi - \Psi_R)\right]\right)$$

- Elliptic flow: Fourier coefficient v_2
- Hydrodynamic behavior



Common description of R_{AA} and v_2 is difficult

Elliptic Flow and Suppression of Jets



Jet suppression

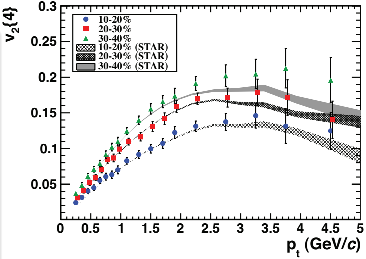
$$R_{AA} = \frac{d^2 N_{AA}/dy\, dp_T}{T_{AA}\, d^2\sigma_{NN}/dy\, dp_T}$$

- Strong suppression of jets compared to $p+p$ reference

Collective behavior of the medium

$$E\frac{d^3N}{d^3p} \sim \frac{d^2N}{dy\, dp_T}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\phi - \Psi_R)\right]\right)$$

- Elliptic flow: Fourier coefficient v_2
- Hydrodynamic behavior



Common description of R_{AA} and v_2 is difficult

Outline

Partonic Transport Model - BAMPS

BAMPS = Boltzmann Approach to Multiple Particle Scattering [1]

Microscopic transport simulations with full dynamics

Attack various problems within *one* model.
(elliptic flow, R_{AA}, thermalization, ...)

Solve Boltzmann equation for $2 \rightarrow 2$ *and* $2 \leftrightarrow 3$ processes based on LO pQCD matrix elements.

$$p^{\mu}\partial_{\mu} f(x,p) = \mathcal{C}_{2\rightarrow 2}(x,p) + \mathcal{C}_{2\leftrightarrow 3}(x,p)$$

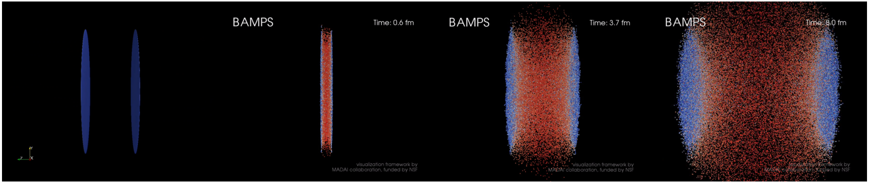
[1] Z. Xu, C. Greiner, Phys. Rev. C71 (2005)

Partonic Transport Model - BAMPS

BAMPS = Boltzmann Approach to Multiple Particle Scattering [1]

Microscopic transport simulations with full dynamics

Attack various problems within *one* model.
(elliptic flow, R_{AA}, thermalization, ...)



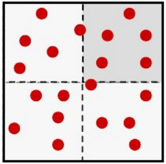
Visualization by Jan Uphoff
Visualization framework courtesy MADAI collaboration
funded by the NSF under grant NSF-PHY-09-41373

[1] Z. Xu, C. Greiner, Phys. Rev. C71 (2005)

Partonic Transport Model - BAMPS

Monte Carlo sampling of interactions

- Massless Boltzmann particles (gluons, quarks)
- Discretize:
  - Spatial cells ΔV
  - Time steps Δt
- Sampling of interaction probabilities from LO pQCD
  - $2 \rightarrow 2$ Small angle cross sections
  - $2 \leftrightarrow 3$ Gunion Bertsch matrix element
- Fixed coupling ($\alpha_s = 0.3$)



$gg \rightarrow gg$ cross section

$$\frac{d\sigma_{gg\rightarrow gg}}{dq_\perp^2} \simeq \frac{9\pi\alpha_s^2}{2(\mathbf{q}_\perp^2 + m_D^2)^2}$$

Gunion Bertsch matrix element

$$|\mathcal{M}_{gg\rightarrow ggg}|^2 = \frac{72\pi^2\alpha_s^2 s^2}{(\mathbf{q}_\perp^2 + m_D^2)^2} \frac{48\pi\alpha_s \mathbf{q}_\perp^2}{\mathbf{k}_\perp^2 [(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + m_D^2]}$$

Debye screening (dynamic): $m_D^2 = d_G \pi \alpha_s \int \frac{d^3p}{(2\pi)^3} \frac{1}{p} (N_c f_g + N_f f_q)$

Implemented Processes (gluons and light quarks)

$2 \rightarrow 2$ processes

Original BAMPS version ($N_f = 0$):

$$g\,g \rightarrow g\,g$$

Including light quarks ($N_f = 3$):

$$g\,g \rightarrow q\,\bar{q}$$

$$q\,\bar{q} \rightarrow g\,g \quad \text{and} \quad q\,\bar{q} \rightarrow q'\,\bar{q}'$$

$$q\,g \rightarrow q\,g \quad \text{and} \quad \bar{q}\,g \rightarrow \bar{q}\,g$$

$$q\,\bar{q} \rightarrow q\,\bar{q}$$

$$q\,q \rightarrow q\,q \quad \text{and} \quad \bar{q}\,\bar{q} \rightarrow \bar{q}\,\bar{q}$$

$$q\,q' \rightarrow q\,q' \quad \text{and} \quad q\,\bar{q}' \rightarrow q\,\bar{q}'$$

$2 \leftrightarrow 3$ processes

Original BAMPS version ($N_f = 0$):

$$g\,g \leftrightarrow g\,g\,g$$

Including light quarks ($N_f = 3$):

$$q\,g \leftrightarrow q\,g\,g \quad \text{and} \quad \bar{q}\,g \leftrightarrow \bar{q}\,g\,g$$

$$q\,\bar{q} \leftrightarrow q\,\bar{q}\,g$$

$$q\,q \leftrightarrow q\,q\,g \quad \text{and} \quad \bar{q}\,\bar{q} \leftrightarrow \bar{q}\,\bar{q}\,g$$

$$q\,q' \leftrightarrow q\,q'\,g \quad \text{and} \quad q\,\bar{q}' \leftrightarrow q\,\bar{q}'\,g$$

- Emission of gluon factorizes: $|\mathcal{M}_{\text{GB}}|^2 = |\mathcal{M}_{\text{coll}}|^2 \; P^g$
- Re-use $\mathcal{M}_{gg\rightarrow ggg}$: $|\mathcal{M}_{X\rightarrow Xg}|^2 = |\mathcal{M}_{X\rightarrow X}|^2 \left[|\mathcal{M}_{gg\rightarrow ggg}|^2 / |\mathcal{M}_{gg\rightarrow gg}|^2 \right]$
- Use small angle cross sections for scaling $\rightarrow$ simple prefactors
- Modell LPM effect by rate-dependent cutoff in $2 \leftrightarrow 3$ processes

Implemented Processes (gluons and light quarks)

$2 \to 2$ processes

Original BAMPS version ($N_f = 0$):

$$g\,g \to g\,g$$

Including light quarks ($N_f = 3$):

$$g\,g \to q\,\bar{q}$$

$q\,\bar{q} \to g\,g$	and	$q\,\bar{q} \to q'\,\bar{q}'$
$q\,g \to q\,g$	and	$\bar{q}\,g \to \bar{q}\,g$
$q\,\bar{q} \to q\,\bar{q}$		
$q\,q \to q\,q$	and	$\bar{q}\,\bar{q} \to \bar{q}\,\bar{q}$
$q\,q' \to q\,q'$	and	$q\,\bar{q}' \to q\,\bar{q}'$

$2 \leftrightarrow 3$ processes

Original BAMPS version ($N_f = 0$):

$$g\,g \leftrightarrow g\,g\,g$$

Including light quarks ($N_f = 3$):

$q\,g \leftrightarrow q\,g\,g$	and	$\bar{q}\,g \leftrightarrow \bar{q}\,g\,g$
$q\,\bar{q} \leftrightarrow q\,\bar{q}\,g$		
$q\,q \leftrightarrow q\,q\,g$	and	$\bar{q}\,\bar{q} \leftrightarrow \bar{q}\,\bar{q}\,g$
$q\,q' \leftrightarrow q\,q'\,g$	and	$q\,\bar{q}' \leftrightarrow q\,\bar{q}'\,g$

- Emission of gluon factorizes: $|\mathcal{M}_{\mathrm{GB}}|^2 = |\mathcal{M}_{\mathrm{coll}}|^2\; P^g$
- Re-use $\mathcal{M}_{gg\to ggg}$: $|\mathcal{M}_{X\to Xg}|^2 = |\mathcal{M}_{X\to X}|^2 \left[|\mathcal{M}_{gg\to ggg}|^2 \,/\, |\mathcal{M}_{gg\to gg}|^2 \right]$
- Use small angle cross sections for scaling $\to$ simple prefactors
- Modell LPM effect by rate-dependent cutoff in $2 \leftrightarrow 3$ processes

Implemented Processes (gluons and light quarks)

$2 \rightarrow 2$ processes

Original BAMPS version ($N_f = 0$):

$$g\,g \rightarrow g\,g$$

Including light quarks ($N_f = 3$):

$$g\,g \rightarrow q\,\bar{q}$$

$$q\,\bar{q} \rightarrow g\,g \quad \text{and} \quad q\,\bar{q} \rightarrow q'\,\bar{q}'$$

$$q\,g \rightarrow q\,g \quad \text{and} \quad \bar{q}\,g \rightarrow \bar{q}\,g$$

$$q\,\bar{q} \rightarrow q\,\bar{q}$$

$$q\,q \rightarrow q\,q \quad \text{and} \quad \bar{q}\,\bar{q} \rightarrow \bar{q}\,\bar{q}$$

$$q\,q' \rightarrow q\,q' \quad \text{and} \quad q\,\bar{q}' \rightarrow q\,\bar{q}'$$

$2 \leftrightarrow 3$ processes

Original BAMPS version ($N_f = 0$):

$$g\,g \leftrightarrow g\,g\,g$$

Including light quarks ($N_f = 3$):

$$q\,g \leftrightarrow q\,g\,g \quad \text{and} \quad \bar{q}\,g \leftrightarrow \bar{q}\,g\,g$$

$$q\,\bar{q} \leftrightarrow q\,\bar{q}\,g$$

$$q\,q \leftrightarrow q\,q\,g \quad \text{and} \quad \bar{q}\,\bar{q} \leftrightarrow \bar{q}\,\bar{q}\,g$$

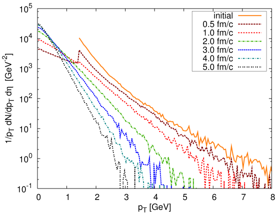
$$q\,q' \leftrightarrow q\,q'\,g \quad \text{and} \quad q\,\bar{q}' \leftrightarrow q\,\bar{q}'\,g$$

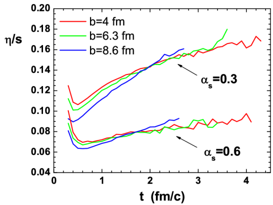
- Emission of gluon factorizes: $|\mathcal{M}_{\mathrm{GB}}|^2 = |\mathcal{M}_{\mathrm{coll}}|^2 \; P^g$
- Re-use $\mathcal{M}_{gg\rightarrow ggg}$: $|\mathcal{M}_{X\rightarrow Xg}|^2 = |\mathcal{M}_{X\rightarrow X}|^2 \left[|\mathcal{M}_{gg\rightarrow ggg}|^2 \,/\, |\mathcal{M}_{gg\rightarrow gg}|^2 \right]$
- Use small angle cross sections for scaling $\rightarrow$ simple prefactors
- Modell LPM effect by rate-dependent cutoff in $2 \leftrightarrow 3$ processes

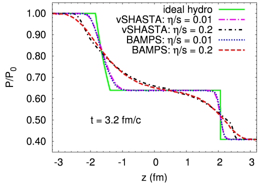
Some Results from BAMPS

- Fast thermalization, $\lesssim$ 1 fm/c Z. Xu, C. Greiner, PRC 71 (2005)
- Small viscosity, $\eta/s \simeq 0.1 - 0.2$
  Z. Xu, C. Greiner, H. Stoecker PRL 101 (2008) / Z. Xu, C. Greiner PRL 100 (2008)
- Investigate heavy quark production and dynamics
  J. Uphoff, OF et al., PRC 82 (2010)

- Can serve as reference for viscous hydro I. Bouras et al. PRL 103 (2009)
- Investigate hydrodynamic shocks / Mach cones
  I. Bouras et al. PRL 103 (2009) / I. Bouras et al. J.Phys.Conf.Ser. 270



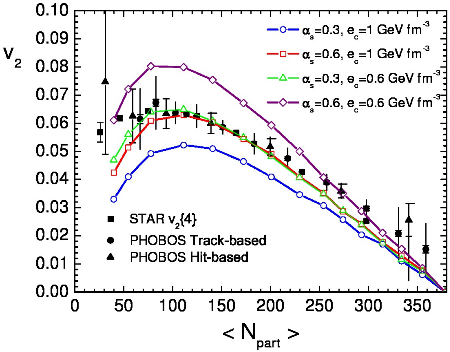




Outline

Elliptic Flow at RHIC

v_2 at RHIC from BAMPS



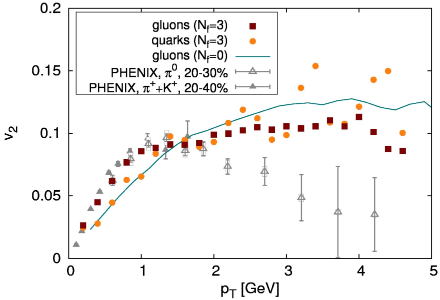
Parameters:

- Coupling $\alpha_s = 0.3$ to $\alpha_s = 0.6$
- Freeze-out energy density $\varepsilon_c = 0.6\,\mathrm{GeV\,fm^{-3}}$ to $\varepsilon_c = 1.0\,\mathrm{GeV\,fm^{-3}}$
- $N_f = 0$ (purely gluons)
- Mini jet initial conditions ($p_0 = 1.4\,\mathrm{GeV}$)

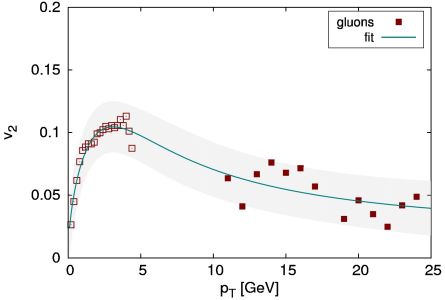
- Medium develops strong collectivity using pQCD-based interactions Xu, Greiner, PRC 79 (2009)
- $\langle v_2 \rangle$ can be described over a large range of centrality

Elliptic flow at RHIC

Differential $v_2(p_T)$ at RHIC from BAMPS



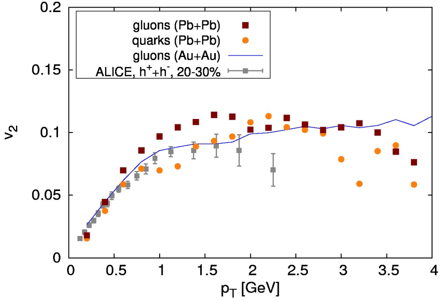
High-p_T v_2 from BAMPS



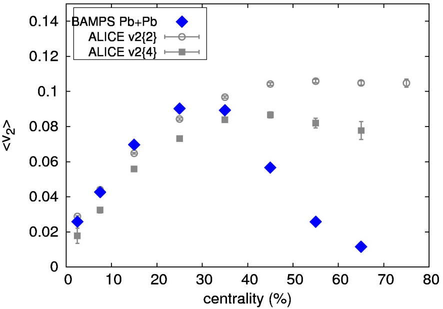
- Differential elliptic flow of gluons and quarks is (almost) the same
- NCQ scaling the experimental data, the magnitude of quark $v_2(p_T)$ is ok, but peak shifts $\Rightarrow$ hadronization mechanisms?
- Qualitative features of high-p_T v_2 agree with PHENIX π^0 data
  - fitted using $v_2(p_T) = \left(a + \frac{1}{p_T^n}\right) \frac{(p_T/\lambda)^m}{1+(p_T/\lambda)^m}$

Elliptic flow at LHC

Differential $v_2(p_T)$ at LHC from BAMPS



Integrated v_2 as a function of centrality

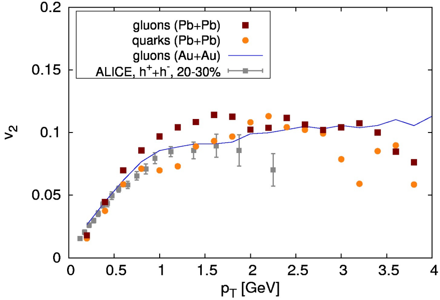


- Differential $v_2(p_T)$ in LHC and RHIC simulations (almost) the same
- Integrated v_2 is increased due to shift in $\langle p_T \rangle$
- Integrated v_2 drops too fast below $N_{\text{part}} \approx 150$

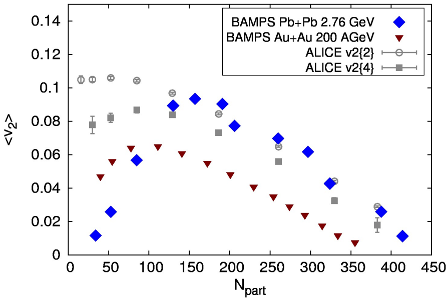
  Artefact of meanwhile fixed problem

Elliptic flow at LHC

Differential $v_2(p_T)$ at LHC from BAMPS



Integrated v_2 as a function N_{part}



- Differential $v_2(p_T)$ in LHC and RHIC simulations (almost) the same
- Integrated v_2 is increased due to shift in $\langle p_T \rangle$
- Integrated v_2 drops too fast below $N_{part} \approx 150$

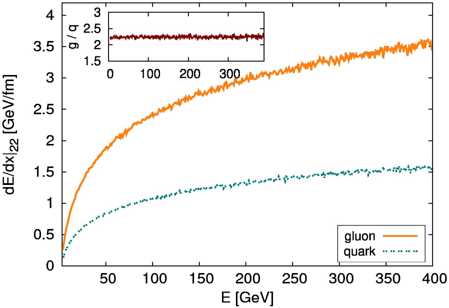
  Artefact of meanwhile fixed problem

Outline

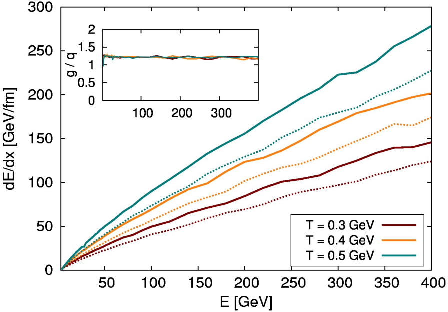
Energy Loss in a Static Medium

Static Medium (brick): $T = \text{const}$, no expansion

Energy loss from elastic processes



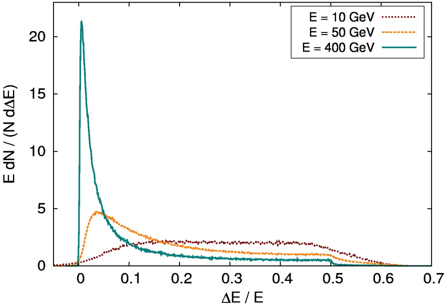
Energy loss including $2 \leftrightarrow 3$ processes



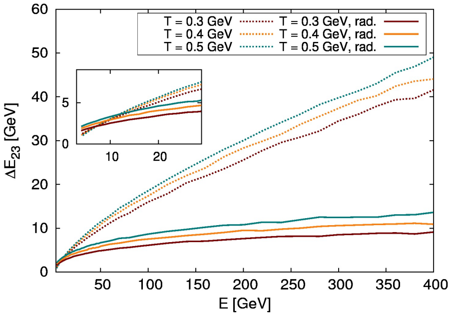
- Strong energy loss from $2 \to 3$ processes
  - Complex interplay of GB matrix element and LPM cutoff
  - Prefered gluon radiation into $y < 0$ (backward) direction
- Only small difference between quarks and gluons
  - Iterative computation of rates due to LPM restriction

Energy Loss in a Static Medium

Distribution of ΔE



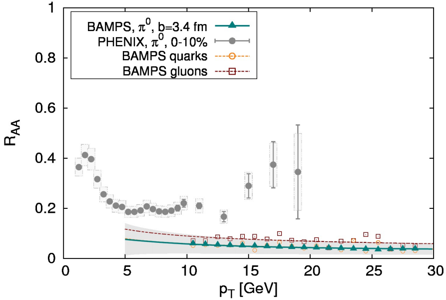
ΔE versus radiated energy ω



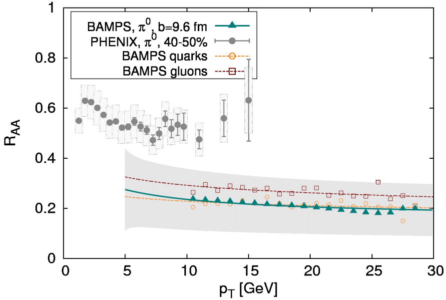
- Broad distribution of energy loss ΔE per collision
- ΔE is larger than the energy of the radiated gluon
  - $\Delta E = E_{in} - max(E^{i}_{out}) \quad \geq \omega$

Jet Suppression in RHIC Simulations

R_{AA}, Au + Au at 200 A GeV, 0 %–10 %



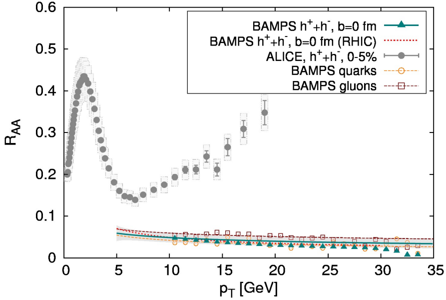
R_{AA}, Au + Au at 200 A GeV, 40 %–50 %



- Hadronization via AKK fragmentation functions
- Suppression in BAMPS is too strong
  - Strong mean energy loss in $2 \to 3$ processes
  - Sizeable conversion of quark jets into gluon jets
  - Small difference in the energy loss of quarks and gluons

Jet Suppression in LHC Simulations

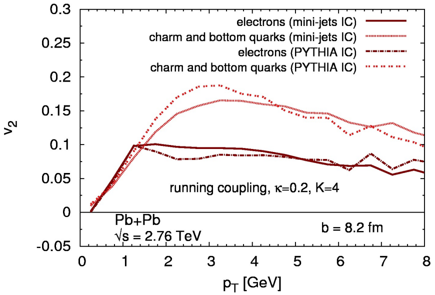
R_{AA}, Pb + Pb at 2.76 A TeV, $b = 0$ fm, (data: 0 %–5 %)



- PYTHIA initial conditions (Uphoff, OF et al. PRC 82 (2010))
  $\alpha_s = 0.3$, $\varepsilon_c = 0.6\,\mathrm{GeV\,fm^{-3}}$
- R_{AA} almost identical to RHIC, does not reproduce rise towards large p_T

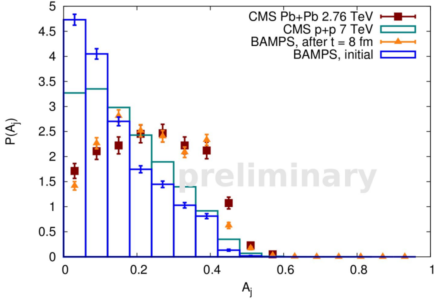
Advertisement - Other projects

Heavy flavor in BAMPS



Talk by Jan Uphoff

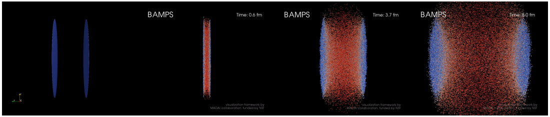
Reconstructed jets in BAMPS



Talk by Florian Senzel

Summary

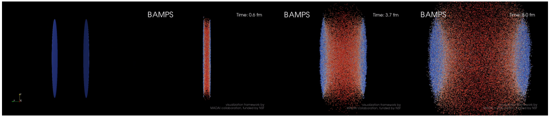
- Partonic transport provides means of:
  - exploring the dynamics of the medium evolution based on pQCD processes
  - exploring different observables within a common framework
- Strong collective flow of the medium is reproduced
- Suppression of jets is too strong using the same parameters



There is a lot of ongoing work aimed at improvements and future extensions. . .

Summary

- Partonic transport provides means of:
  - exploring the dynamics of the medium evolution based on pQCD processes
  - exploring different observables within a common framework
- Strong collective flow of the medium is reproduced
- Suppression of jets is too strong using the same parameters



There is a lot of ongoing work aimed at improvements and future extensions. . .

Outlook

Some more of our current and planned projects:

Running coupling for interactions of light quarks and gluons

- A lot of work already done for heavy quark interactions (by Jan Uphoff)
- Numerically challenging

Explore sensitivity of results on model parameters

- Especially: LPM cutoff and the freeze out criterion
- Also investigate fluctuations? (numerically challenging)

Explore local Monte Carlo implementation of the LPM effect

- Zapp, Wiedemann, et al. / Coleman-Smith, Bass, et al.
- 1st step: apply only to $2 \rightarrow 3$ involving high energy particles

Outlook

Some more of our current and planned projects:

Running coupling for interactions of light quarks and gluons

- A lot of work already done for heavy quark interactions (by Jan Uphoff)
- Numerically challenging

Explore sensitivity of results on model parameters

- Especially: LPM cutoff and the freeze out criterion
- Also investigate fluctuations? (numerically challenging)

Explore local Monte Carlo implementation of the LPM effect

- Zapp, Wiedemann, et al. / Coleman-Smith, Bass, et al.
- 1st step: apply only to $2 \rightarrow 3$ involving high energy particles

Outlook

Some more of our current and planned projects:

Running coupling for interactions of light quarks and gluons

- A lot of work already done for heavy quark interactions (by Jan Uphoff)
- Numerically challenging

Explore sensitivity of results on model parameters

- Especially: LPM cutoff and the freeze out criterion
- Also investigate fluctuations? (numerically challenging)

Explore local Monte Carlo implementation of the LPM effect

- Zapp, Wiedemann, et al. / Coleman-Smith, Bass, et al.
- 1st step: apply only to $2 \rightarrow 3$ involving high energy particles

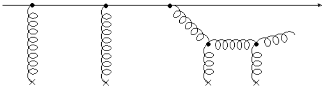
Additional material

Outline

4 Sensitivity on the LPM Cutoff

5 Rates and Spectra

Modelling of the LPM Effect



LPM effect

Multiple gluon emission $\Rightarrow$ interference

- Difficult to realize in a semi-classical transport model
- Ansatz: Discard possible interference processes (Bethe-Heitler)

Parent must not scatter during formation time of emitted gluon

$$\left|M_{gg\to ggg}\right|^2 \longrightarrow \left|M_{gg\to ggg}\right|^2 \Theta\left(\lambda - \tau\right)$$

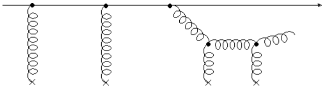
Comparison of λ und τ requires consideration of different Lorentz frames

$$\Theta\left(\lambda - \tau\right) = \Theta\left(k_\perp \lambda - \frac{\cosh y}{\sqrt{1-\beta'^2}}\left(1 + \beta' \tanh y \cos\theta\right)\right)$$

Modelling of the LPM Effect

LPM effect

Multiple gluon emission $\Rightarrow$ interference



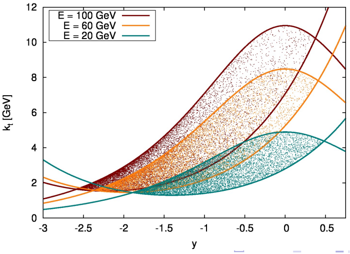
- Difficult to realize in a semi-classical transport model
- Ansatz: Discard possible interference processes (Bethe-Heitler)

Parent must not scatter during formation time of emitted gluon

$$\left|M_{gg\to ggg}\right|^2 \longrightarrow \left|M_{gg\to ggg}\right|^2 \Theta\left(\lambda - \tau\right)$$

Comparison of λ und τ requires consideration of different Lorentz frames

$$\Theta\left(\lambda - \tau\right) = \Theta\left(k_\perp \lambda - \frac{\cosh y}{\sqrt{1-\beta'^2}}\left(1 + \beta' \tanh y \cos\theta\right)\right)$$



Sensitivity on the LPM Cut-Off

Parameters in BAMPS

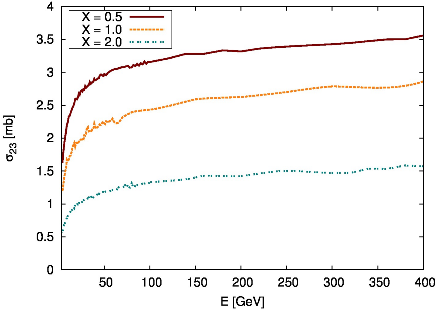
- Coupling strength α_s
- Critical freeze-out energy density ε_c
- LPM cut-off

The effective implementation of the LPM cut-off requires $\Lambda_g > \tau$.
Only qualitative argument, introduce factor X to test sensitivity.

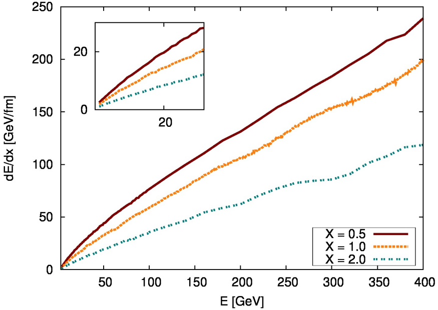
$$\Theta\left(k_\perp - \frac{\gamma}{\Lambda_g}\right) \to \Theta\left(k_\perp - X\frac{\gamma}{\Lambda_g}\right)$$

Sensitivity on the LPM Cut-Off

$\sigma_{gg\to ggg}$ for different X (T = 400 MeV)



dE/dx for different X (T = 400 MeV)

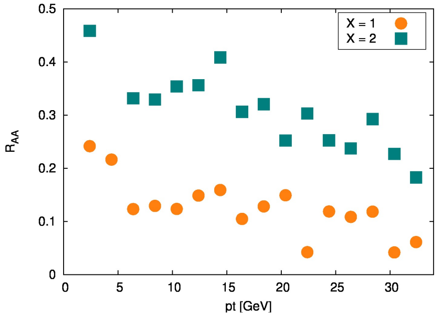


$$\sigma_{gg\to ggg} \sim \int dq_\perp^2 \int dk_\perp^2 \int y \cdots \Theta\left(k_\perp - X\frac{\gamma}{\Lambda_g}\right)$$

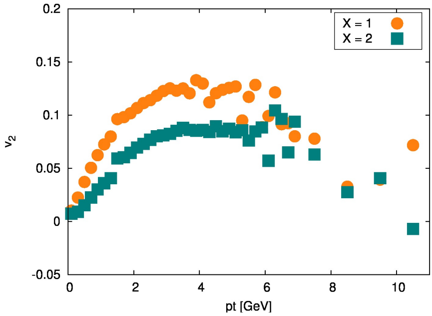
- Large X reduces total cross section
- Sampling of outgoing particles affected in non-trivial way
- Energy loss per collision only slightly affected, main contribution to the change in energy loss from change in σ.

Sensitivity on the LPM Cut-Off

R_{AA} for different X ($b = 7\,\text{fm}$)



v_2 for different X ($b = 7\,\text{fm}$)



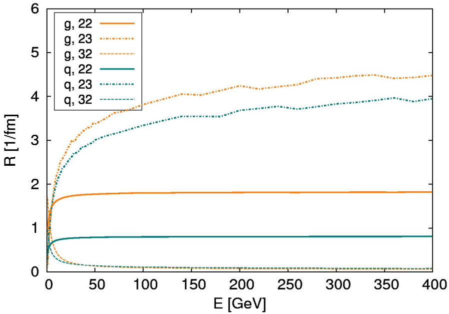
Outline

4 Sensitivity on the LPM Cutoff

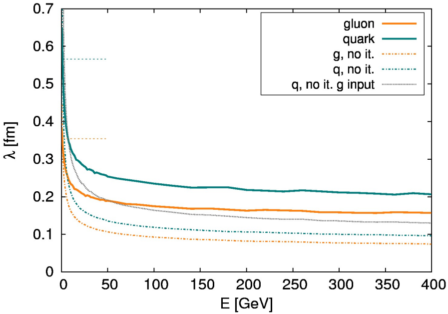
5 Rates and Spectra

Rates and Mean Free Paths

Interaction rates ($T = 0.4$ GeV)

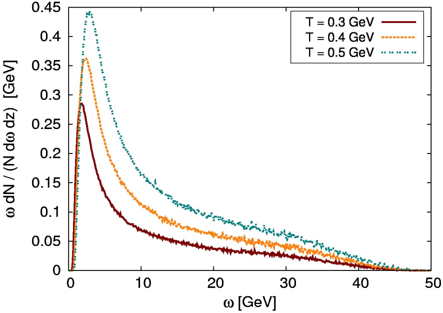


Mean free path ($T = 0.4$ GeV)



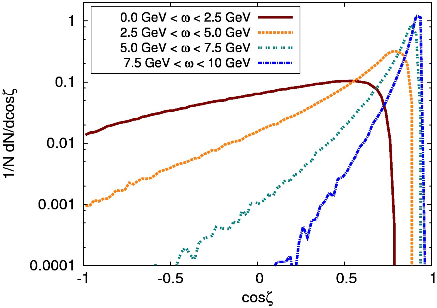
Radiation Spectra

Radiation spectrum ($E = 50\,\text{GeV}$)

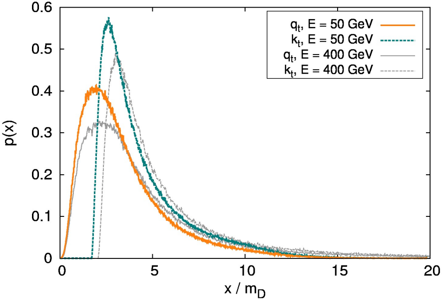


Radiation Distributions

Angular distribution ($E = 50\,\mathrm{GeV}$)



Distribution of momentum transfers



$m_D \approx 0.6\,\mathrm{GeV}$