Investigation of jet quenching and elliptic flow within a pQCD-based partonic transport model

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Winter Workshop on Nuclear Dynamics
2 January 2010 - 9 January 2010

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

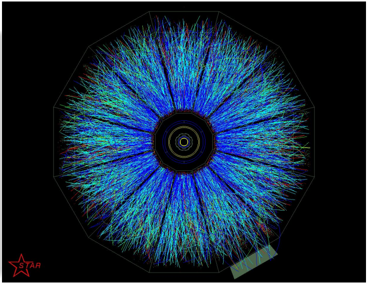
H-QM Helmholtz Research School Quark Matter Studies

Introduction

Heavy ion collisions are complicated!

Need models and theories for

- Initial state
- Medium evolution
- High-p_T physics
- Phase transition
- Freeze-out



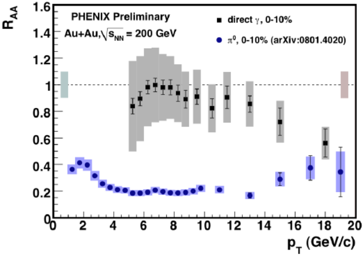
Some tools:

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

Problem

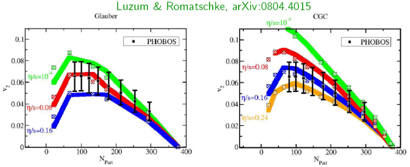
No model can describe all (most) aspects of the QGP evolution.

Introduction



[a]

[a]HP 2008, C. Vale



Key observables

- Jet quenching, R_{AA} (high-p_t physics)
- Elliptic flow, v_2 (bulk physics)

- Difficult to describe within one model
- (Partonic) Transport with only $2 \rightarrow 2$ processes:
  Need unphysical cross sections for v_2. ($\Rightarrow R_{AA}$ too small)

BAMPS results

$2 \leftrightarrow 3$ processes + pQCD cross sections $\Rightarrow$ enough elliptic flow
What about R_{AA}?

Outline

1. The Model - BAMPS
2. Static Medium - Brick Scenario
3. Central and Non-Central Au+Au Collisions
4. Sensitivity on the LPM Cut-Off

Partonic Transport Model - BAMPS

BAMPS = Boltzmann Approach to Multiple Particle Scattering [1]

Microscopic transport simulations with full dynamics.

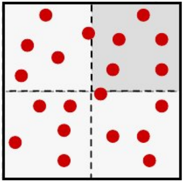
Attack various problems within *one* model.
(elliptic flow, R_{AA}, thermalization, ...)

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



Implemented processes

$gg \to gg$ and $gg \leftrightarrow ggg$

- Massless Boltzmann particles
- Sample transition probabilities for (test)particles in a given
  - Spatial cell, ΔV
  - Time step, Δt
- Use small angle cross section for $gg \to gg$ and Gunion-Bertsch matrix element for $gg \leftrightarrow ggg$

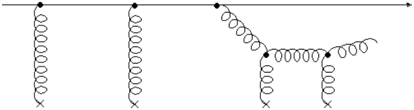
$$\frac{d\sigma_{gg\to gg}}{dq_\perp^2} \simeq \frac{9\pi\alpha_s^2}{(\mathbf{q}_\perp^2 + m_D^2)^2} \qquad |\mathcal{M}_{gg\to ggg}|^2 = \frac{72\pi^2\alpha_s^2 s^2}{(\mathbf{q}_\perp^2 + m_D^2)^2} \frac{48\pi\alpha_s \mathbf{q}_\perp^2}{\mathbf{k}_\perp^2 [(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + m_D^2]}$$

- Debye screening: $m_D^2 = d_G \pi \alpha_s \int \frac{d^3p}{(2\pi)^3} \frac{1}{p} N_c f$

Landau-Pomeranchuk-Migdal (LPM) Effect

LPM effect

Multiple emission $\Rightarrow$ Interference



- Not realizable in transport model with classical particles.
- Discard possible interference effects (Bethe-Heitler regime)

Parent must not scatter during formation time of emitted gluon.

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

Affects:

- Total cross section

$$\sigma_{gg\rightarrow ggg} \sim \int dq_\perp^2 \int dk_\perp^2 \int dy \int d\phi \cdots \left|M_{gg\rightarrow ggg}\right|^2 \Theta\left(\lambda - \tau\right)$$

- Sampling of outgoing momenta

Landau-Pomeranchuk-Migdal (LPM) Effect

LPM effect

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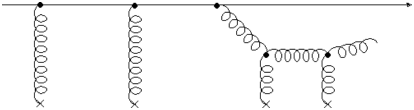

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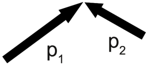
Reference Frames for the LPM Cut-Off



lab frame

$\lambda = 1/R = 1/\langle n\sigma \rangle$

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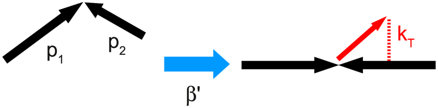

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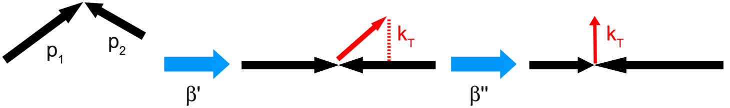

lab frame

$\lambda = 1/R = 1/\langle n\sigma \rangle$

CM frame

$\tau = 1/k_\perp$

$\beta'' = \tanh y$
$\gamma'' = \cosh y$

- Total boost: $\gamma = \gamma' \gamma'' \left(1 + \vec{\beta}' \vec{\beta}''\right) = \frac{\cosh y}{\sqrt{1-\beta'^2}} \left(1 + \beta' \tanh y \cos\theta\right)$

$$\Theta\left(\lambda - \tau\right) \rightarrow \Theta\left(k_\perp - \frac{\gamma}{\lambda}\right) \rightarrow \Theta\left(k_\perp - \frac{1}{\lambda}\right) \Theta\left(B - \left(\cosh y + A \sinh y\right)\right)$$

$A = \beta' \cos\theta,\ B = k_\perp \Lambda_g \sqrt{1 - \beta'^2}$

- Integral cuts: $\sigma_{gg\rightarrow ggg} \sim \int dq_\perp^2 \int_{1/\lambda^2}^{s/4} dk_\perp^2 \int_{y_{\min}}^{y_{\max}} dy \int d\phi$
- $\beta' \ll 1$ (thermal particles): $\Theta\left(\lambda - \tau\right) \simeq \Theta\left(k_\perp - \frac{\cosh y}{\lambda}\right)$

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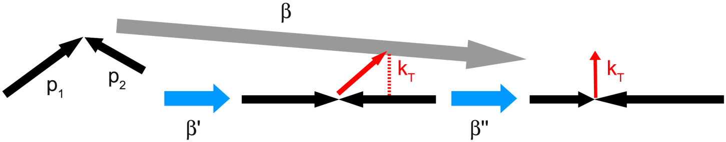

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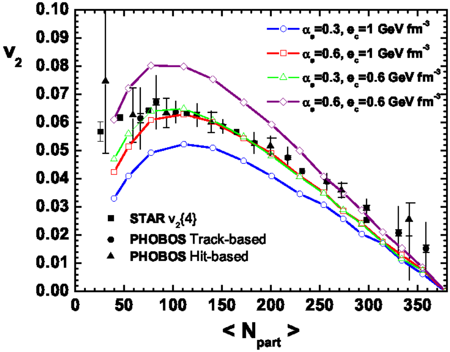
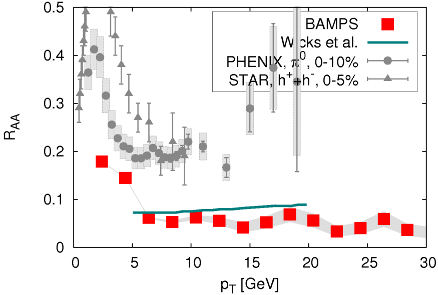
Integrated v_2 as function of N_{part}



Gluonic R_{AA} for $b = 0\,\text{fm}$



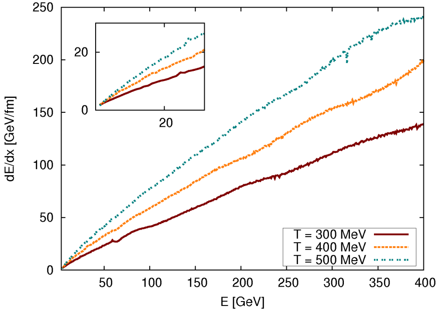
OF, Z. Xu, C. Greiner, PRL 102 (2009)

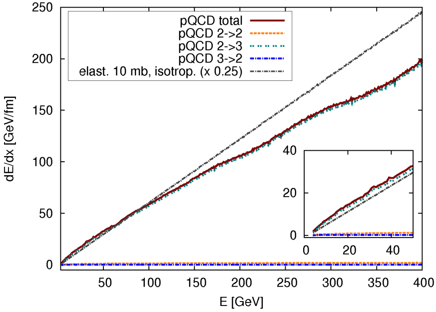
We'll come back to this later..

Energy Loss in a Static Medium

Brick

- Constant temperature T
- Only gluons, $N_f = 0$
- Static medium, no expansion
- $\alpha_s = 0.3$
- $m_D^2 = \frac{8}{\pi} N_c \alpha_s T^2$

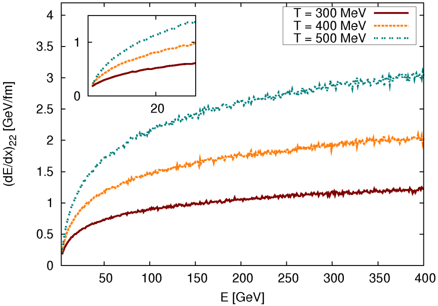




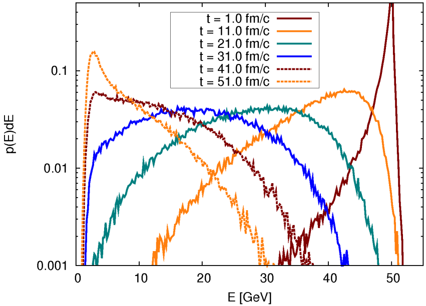
T = 400 MeV

Energy Loss in Binary Collisions

Elastic dE/dx for different T



E-spectrum ($T = 400\,\text{MeV}$, $E_0 = 50\,\text{GeV}$)

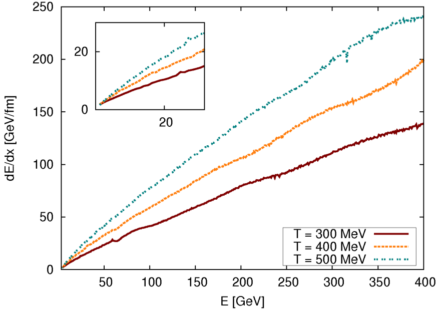


- Elastic energy loss
  $\frac{dE}{dx}\Big|_{2\to2} \propto C_R \pi \alpha_s^2 T^2 \ln\left(\frac{4ET}{m_D^2}\right)$

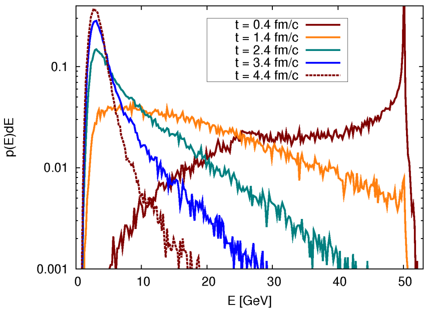
- Broad distribution
- Not: Mean energy loss + momentum diffusion (Gaussian)

Energy Loss in $gg \to ggg$ Processes

Total dE/dx for different T



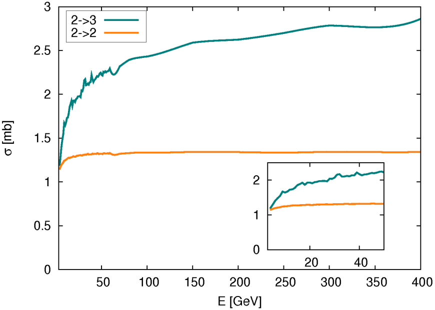
E-spectrum ($T = 400$ MeV, $E_0 = 50$ GeV)



- Large differential energy loss due to $gg \to ggg$
- Roughly $dE/dx \propto E$
- Rapid evolution of the energy spectrum

Energy Loss in $gg \rightarrow ggg$ Processes

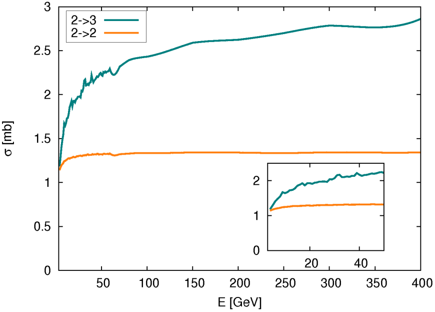
Cross sections (T = 400 MeV)



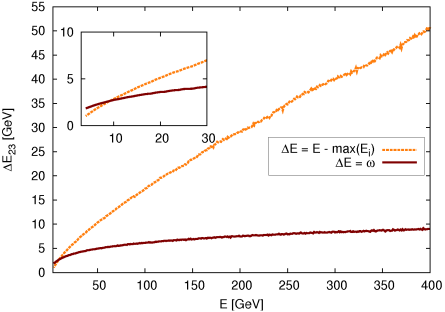
- Reasonable partonic cross sections over the whole energy range.
- Definition of the energy loss ΔE matters:
  - $\Delta E = E_{in} - max(E^i_{out})$
  - $\Delta E = \omega$

Energy Loss in $gg \to ggg$ Processes

Cross sections (T = 400 MeV)



Energy loss in single $gg \to ggg$



- Reasonable partonic cross sections over the whole energy range.
- Definition of the energy loss ΔE matters:
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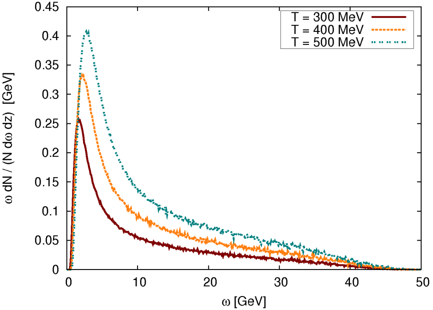
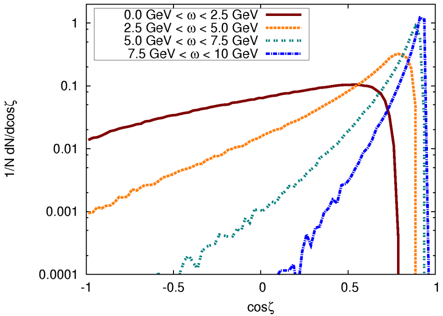
Gluon Radiation from the Gunion-Bertsch Matrix Element

Energy spectrum

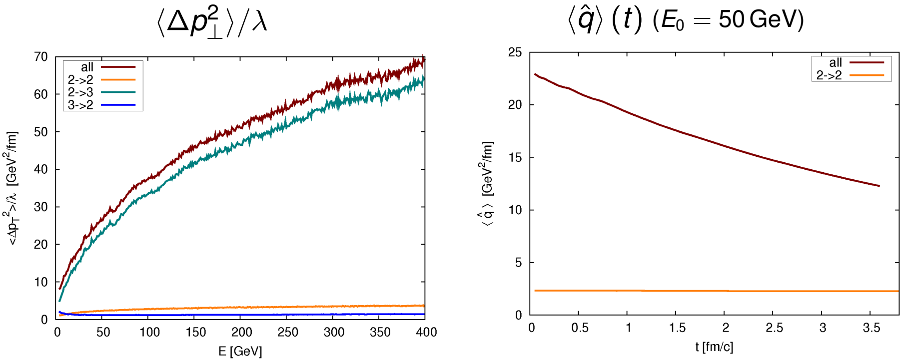


Angular distribution



- Emission at small angles not allowed due to LPM cut-off $\Theta\left(k_\perp - \frac{\gamma}{\lambda}\right)$
- Effect more pronounced for small gluon energies.

Accumulated Transverse Momenta



- $\hat{q}$: Transverse momentum accumulated over path length L.

$$\hat{q}\,(L) = \frac{1}{L} \sum_i \left(\Delta p_\perp^2 \right)_i \qquad \langle \hat{q} \rangle \, (t) = \frac{1}{t} \int_0^t \left. \frac{\langle \Delta p_\perp^2 \rangle}{\lambda} \right|_{E(\tilde{t})} d\tilde{t}$$

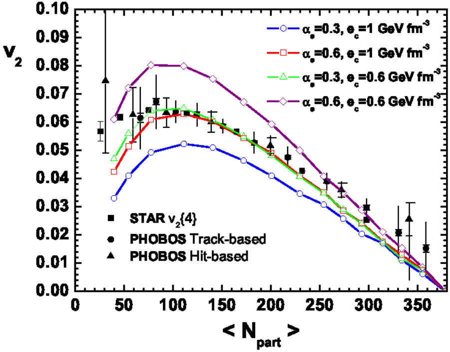
- We extend investigation to $2 \rightarrow 3$ processes.

Setup for Au+Au Collisions in BAMPS

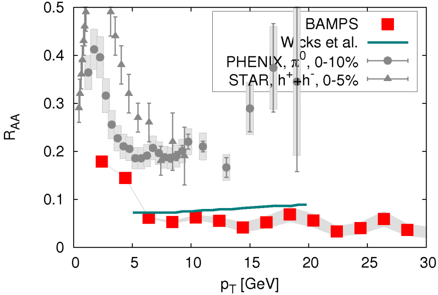
- Au+Au at RHIC energy 200 AGeV
- Currently limited to gluons
- $\alpha_s = 0.3$
- Mini-Jet initial conditions (lower cut-off $p_0 = 1.4\,\text{GeV}$)
  - Glück-Reya-Vogt PDFs
  - Wood-Saxon density profile + Glauber model
- Formation time for each parton $\Delta t_f = \cosh(y)/p_T$
- Free streaming applied to cells where $\varepsilon < \varepsilon_c$
  (choices: $\varepsilon_c = 0.6\,\text{GeV}/\text{fm}^3$ or $\varepsilon_c = 1\,\text{GeV}/\text{fm}^3$)

v_2 and R_{AA} for Central Collisions

Integrated v_2 as function of N_{part}



Gluonic R_{AA} for $b = 0\,\mathrm{fm}$

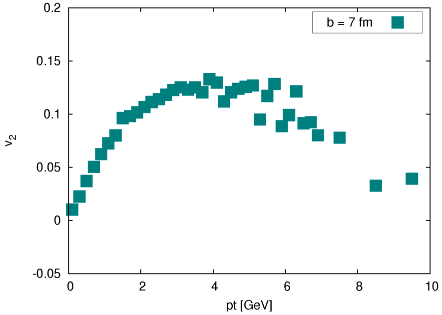


- Elliptic flow generated in BAMPS compatible with experiment.
- Suppression of gluon jets slightly stronger than found by Wicks et al. (Nucl.Phys.A784).

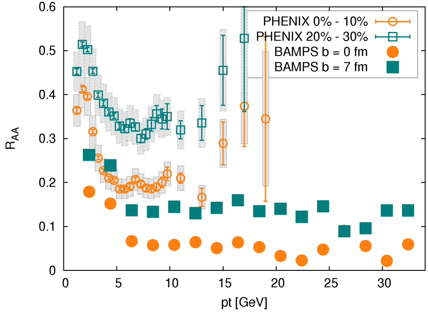
OF, Z. Xu, C. Greiner, PRL 102 (2009)

Non-Central R_{AA} and High-p_T Elliptic Flow

Differential v_2 for $b = 7$ fm

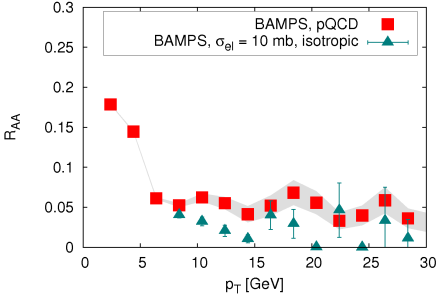


Gluon R_{AA} for $b = 0$ and $b = 7$ fm

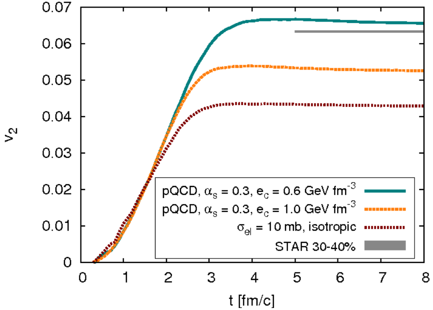


R_{AA} and v_2 from Elastic Collisions with Fixed σ

Gluon R_{AA} for fixed $\sigma = 10\,\text{mb}$



Time evolution of v_2



Elastic collisions can't get R_{AA} and v_2 right simultaneously

For binary $\sigma = 10\,\text{mb}$: R_{AA} too strong, v_2 still too weak

OF, Z. Xu, C. Greiner, PRL 102, 202301 (2009)

Sensitivity on the LPM Cut-Off

Parameters in BAMPS

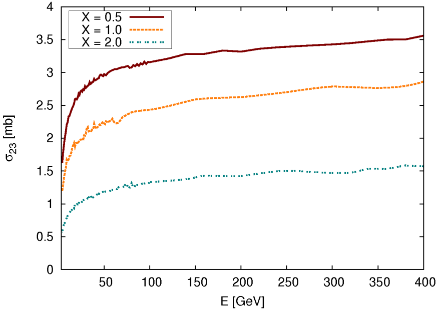
- Coupling strength α_s
- Critical freeze-out energy density ε_c
- LPM cut-off

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

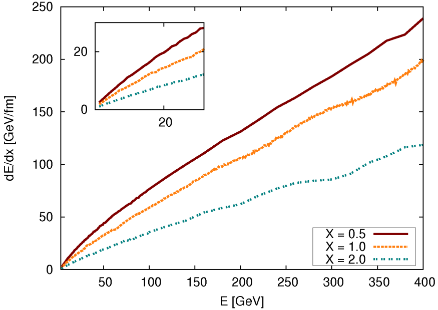
$$\Theta\left(k_\perp - \frac{\gamma}{\Lambda_g}\right) \rightarrow \Theta\left(k_\perp - X\frac{\gamma}{\Lambda_g}\right)$$

Sensitivity on the LPM Cut-Off

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



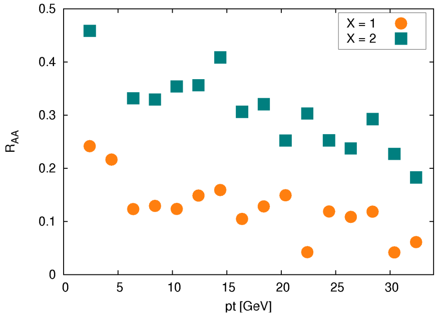
dE/dx for different X (T = 400 MeV)



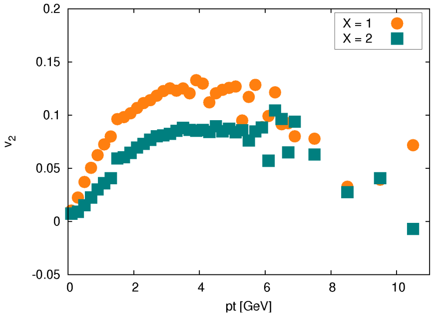
$$\sigma_{gg\to ggg} \sim \int dq_\perp^2 \int dk_\perp^2 \int y \cdots \Theta\left(k_\perp - X\frac{\gamma}{\Lambda_g}\right)$$

- 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.

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



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



Summary

- Partonic transport based on pQCD including $2 \rightarrow 3$ processes provides means of investigating medium and high-p_T physics within a common framework.
- Integrated gluon v_2 ok, gluon R_{AA} slightly below analytic reference

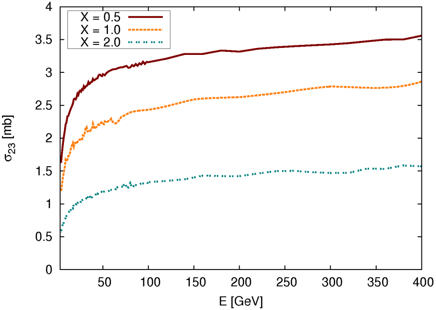
More quantitative and detailed studies needed

- More accurate idetification $\langle b \rangle \leftrightarrow$ centrality class needed
- Need to include light quarks
- Need fragmentation (hadronization) scheme
- Need to investigate more (differential) observables

Thank you!

Sensitivity on the LPM Cut-Off

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



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