Studies of the difference between light and heavy flavor energy loss by reconstructed jets

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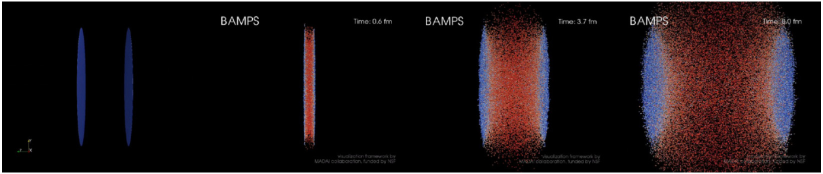
with **F. Senzel**, J. Uphoff and C. Greiner

based on arXiv:1602.05086



清華大學 Tsinghua University

Hard Probes 2016

Wuhan, 24.09.2016

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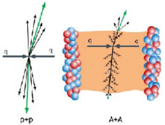
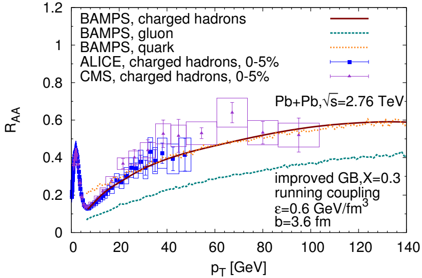
Heavy flavor puzzle: no mass hierarchy?

Nuclear modification factor

$$R_{AA} = \frac{d^2 N_{AA}/dp_t dy}{N_{bin}\, d^2 N_{pp}/dp_t dy}$$

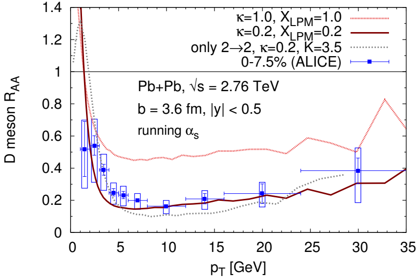


light flavor



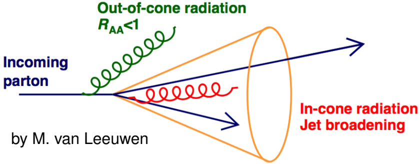
Uphoff, FS, Fochler, Wesp, Xu, Greiner
Phys. Rev. Lett. 114 (2015) 112301

heavy flavor



Uphoff, Fochler, Xu, Greiner
J.Phys. G42 (2015) 11, 115106

Nowadays: Jet reconstruction in heavy-ion collisions!



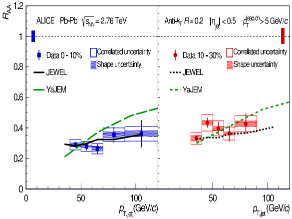
by M. van Leeuwen

clustering particles with

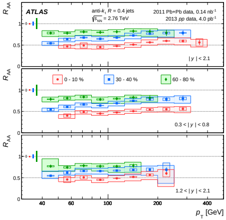
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta y^2} < R$$

inclusive jets

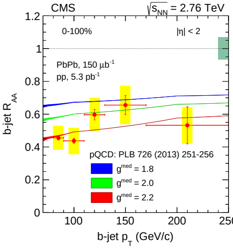
beauty-tagged jets



ALICE collaboration
Phys.Lett. B746 (2015) 1-14



ATLAS collaboration
Phys. Rev. Lett. 114 (2015) 072302



CMS collaboration
Phys. Rev. Lett. 113 (2014) 132301

Our question:

What can we learn about the different energy loss mechanisms of

light flavor and heavy flavor partons

by studying reconstructed jets in heavy-ion collisions?

The partonic transport model BAMPS

BAMPS $\widehat{=}$ Boltzmann Approach to Multi-Parton Scattering

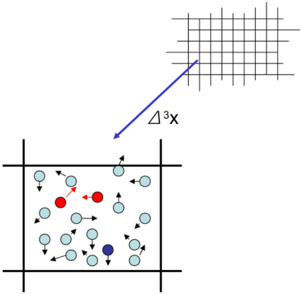
Numerically solving the (3+1)D Boltzmann transport equation for partons on the mass-shell:

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{E}\frac{\partial f}{\partial \mathbf{r}} = C_{2\to 2} + C_{2\leftrightarrow 3}$$

- Massless particles (gluons & quarks)
- Discretized space ΔV and time Δt:

$$P_{2\to 2} = v_{rel}\sigma_{2\to 2}\frac{\Delta t}{\Delta V} \qquad P_{2\to 3} = v_{rel}\sigma_{2\to 3}\frac{\Delta t}{\Delta V}$$

- Test-particles ansatz N_{test}

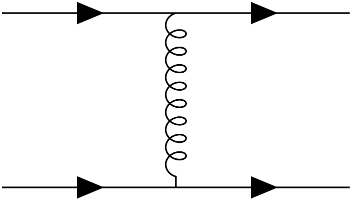


Xu and Greiner, Phys. Rev. C71 (2005); Xu and Greiner, Phys. Rev. C76 (2007)

BAMPS in a nutshell - elastic and radiative processes

Screened leading-order pQCD

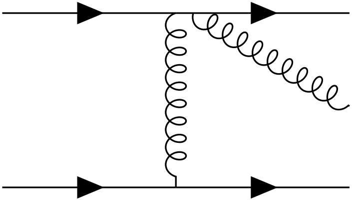
$$\left|\overline{\mathcal{M}}_{X\to Y}\right|^2 \sim \frac{\alpha_s^2(t)}{[t-\kappa m_D^2(\alpha_s(t))]^2}$$



Uphoff, Fochler, Xu, Greiner: Phys. Rev. C84 (2011)

Improved Gunion-Bertsch approx.

$$\left|\overline{\mathcal{M}}_{X\to Y+g}\right|^2 \sim \left|\overline{\mathcal{M}}_{X\to Y}\right|^2 \times \alpha_s(q_t^2, k_t^2) P_g\,(q_t, k_t, y, \phi, M)$$



Gunion, Bertsch: Phys. Rev. D25 (1982)
Fochler, Uphoff, Xu, Greiner: Phys. Rev. D88 (2013)

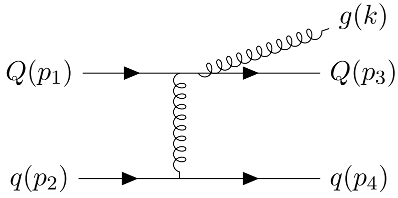
BAMPS in a nutshell - improved GB approximation

Improved Gunion-Bertsch matrix element

$$\left|\overline{\mathcal{M}}_{X\to Y+g}\right|^2 = \left|\overline{\mathcal{M}}_{X\to Y}\right|^2 48\pi\alpha_s (1-\bar{x})^2 \times \left[\frac{\mathbf{k}_\perp}{k_\perp^2 + x^2M^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + m_D^2(\alpha_s) + x^2M^2}\right]^2 *$$

$2 \to 3$ processes

$$\begin{array}{lllllll} g\,g & \to & g\,g\,g & & & & \\ q\,g & \to & q\,g\,g & \text{and} & \bar{q}\,g & \to & \bar{q}\,g\,g \\ q\,\bar{q} & \to & q\,\bar{q}\,g & & & & \\ q\,q & \to & q\,q\,g & \text{and} & \bar{q}\,\bar{q} & \to & \bar{q}\,\bar{q}\,g \\ q\,q' & \to & q\,q'\,g & \text{and} & \bar{q}\,\bar{q}' & \to & \bar{q}\,\bar{q}'\,g \end{array}$$



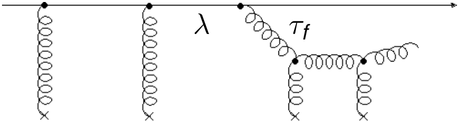
Gunion, Bertsch: Phys. Rev. D25 (1982)
Fochler, Uphoff, Xu, Greiner: Phys. Rev. D88 (2013)

*with $\bar{x} = k_\perp e^{|y|}/\sqrt{s}$

BAMPS in a nutshell - LPM effect

Issue

Coherence effects within a semi-classical approach are not trivial.



Effective implementation

Parent parton is not allowed to scatter before emitted gluon is formed:

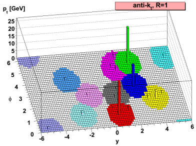
$$|\mathcal{M}_{2\to3}|^2 \to |\mathcal{M}_{2\to3}|^2 \,\Theta\left(\lambda - X_{\text{LPM}}\,\tau_f\right)$$

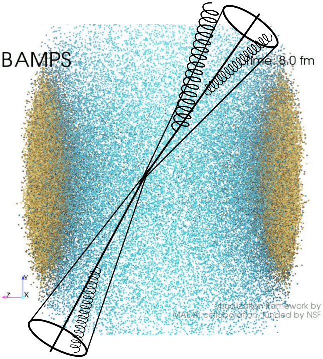
$X_{\text{LPM}} = 0$	No LPM suppression
$X_{\text{LPM}} = 1$	Only independent radiations (forbids too many emissions)
$X_{\text{LPM}} \in (0;1)$	Allows effectively some collinear gluon radiations

Modeling jets within BAMPS collisions

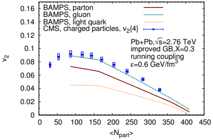
PYTHIA 6.4

FastJet: anti-k_t

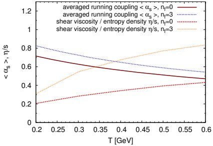




Elliptic flow v_2

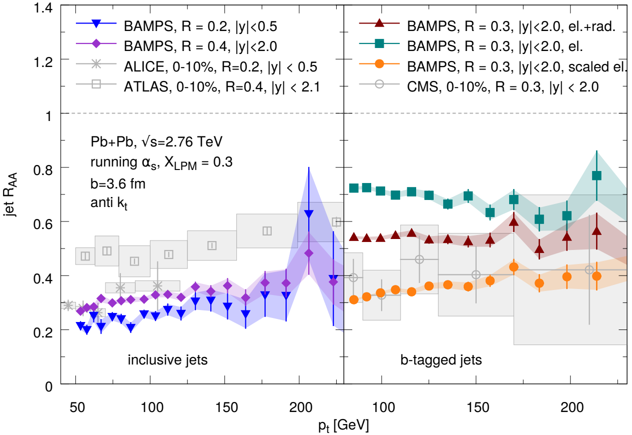


Shear viscosity η/s



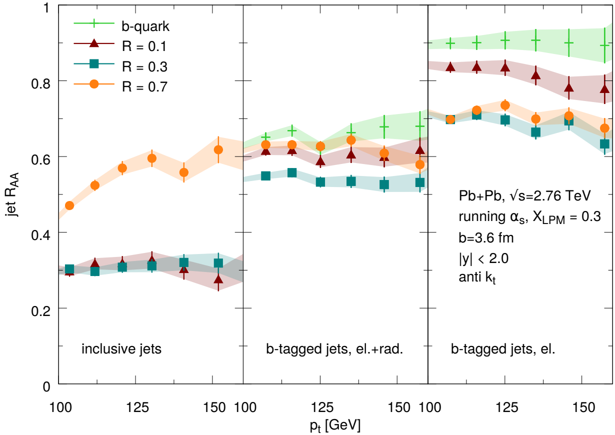
Uphoff, FS, Fochler, Wesp, Xu, Greiner: Phys. Rev. Lett. 114 (2015) 112301

Suppression of reconstructed jets within BAMPS



- Comparable suppression of inclusive and b-tagged jets.
- Pure pQCD elastic collisions are too weak for b-tagged jets.

Jet size *R* dependence of jet suppression



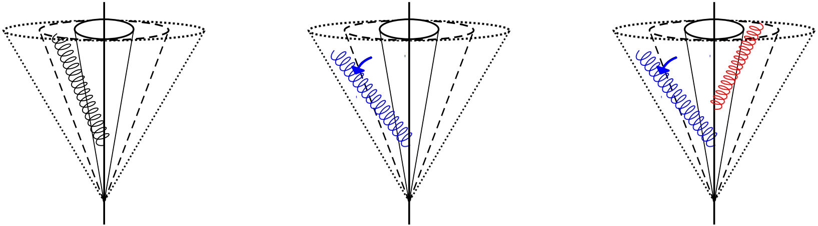
- Inclusive and b-tagged jet R_{AA} show different R dependence.
- Decreasing R shows less b-tagged jet suppression.

Picture behind the *R* dependence of jet suppression

PYTHIA

PYTHIA
+ medium transport

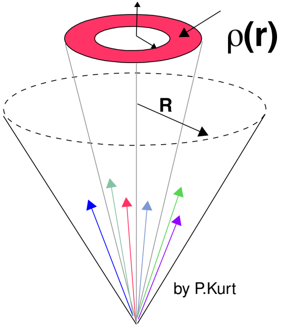
PYTHIA
+ medium transport
+ med.ind.radiation



Jet shapes - How is the intra-jet structure modified?

Differential jet shape

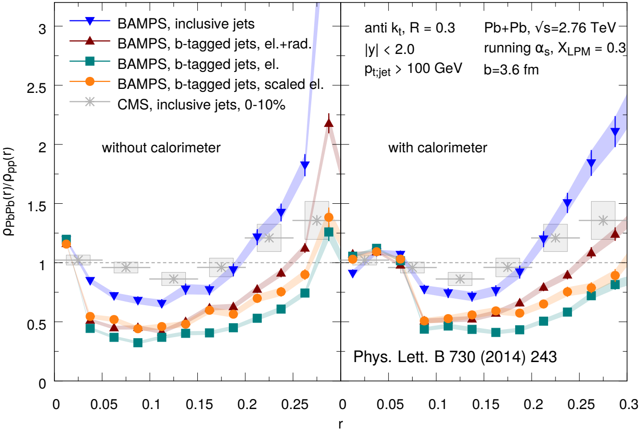
$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}} \frac{\sum_{\text{particles} \in [r_a,\, r_b)} p_T^{\text{track}}}{p_T^{\text{jet}}}$$



jet shape $\rho(r)$:

"fraction of reconstructed jet momentum between $r - \delta r/2$ and $r + \delta r/2$ around the jet axis."

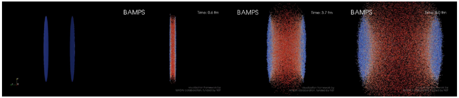
Jet shapes in a heavy-ion collision



- Effects are indeed visible in the different jet shapes.
- b-tagged jet shapes will provide information about HQ processes.

Conclusions

- Reconstructing jets provide means for studying the energy loss of hard probes in heavy-ion collisions.
- Suppression of light and heavy flavor jets is comparable.
- Transport of PYTHIA gluons out of jet cones dominates the suppression of b-tagged jets.
- Jet shapes may be able to discriminate between different underlying energy loss mechanisms.

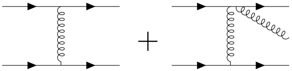
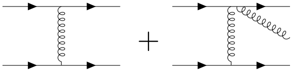
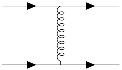
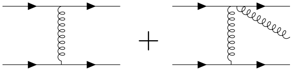
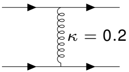
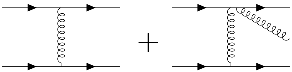


Future plans:

- How does a revisited modeling of the LPM effect change the energy loss and its path-length dependence?
- More systematic comparisons with data . . .

Backup slides

Investigated scenarios for the E-loss of b-tagged jets

scenario	heavy quarks	parton shower	HQ R_{AA}	HQ v_2
el.+rad.			✓	✗
el.			✗	✗
scaled el.	$K = 3.5 \times$ 		✓	✓

cf. Uphoff, Fochler, Xu, Greiner: J.Phys. G42 (2015) 11, 115106

BAMPS in a nutshell - dead cone effect

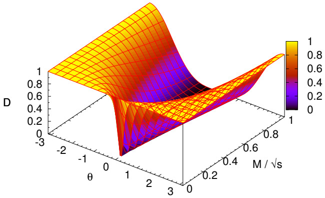
Heavy quark suppression factor

$$\mathcal{D} = \frac{1}{(1 + \frac{M^2}{\theta^2 E^2})^2} = \frac{1}{(1 + \frac{\theta_D^2}{\theta^2})^2}$$

Dokshitzer, Kharzeev: Phys.Lett. B519 (2001

Dead cone effect in BAMPS

While original dead cone effect is limited to a kinematical region, dead cone effect in BAMPS is valid in total phase space.

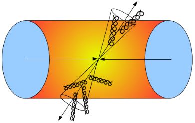


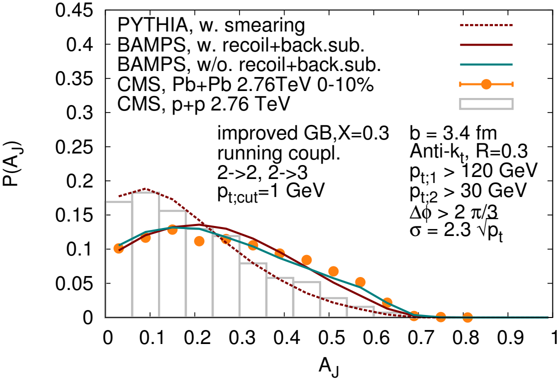
Abir, Greiner, Martinez, Mustafa, Uphoff: Phys. Rev. D85 (2012)

Momentum imbalance A_J of reconstructed di-jets ✓

Definition

$$A_J = \frac{p_{t;Leading\ Jet} - p_{t;Subleading\ Jet}}{p_{t;Leading\ Jet} + p_{t;Subleading\ Jet}}$$





$A_J \to 0$

balanced
leading jet momenta

$A_J \to 1$

unbalanced
leading jet momenta

FS, Fochler, Uphoff, Xu, Greiner: J.Phys. G42 (2015) 11, 115104

Implemented processes - elastic collisions

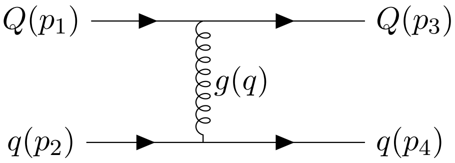
Screened matrix elements

$$\text{e.g. } |\overline{\mathcal{M}}_{qQ\to qQ}|^2 = \frac{64}{9}\pi^2\alpha_s^2 \frac{(M^2-u)^2+(s-M^2)^2+2M^2t}{[t-\kappa m_D^2(\alpha_s)]^2}$$

$$\text{with} \quad m_D^2(\alpha_s) = d_G\pi\alpha_s \int \frac{d^3p}{(2\pi)^3}\frac{1}{p}\left(N_c f_g + N_f f_q\right)$$

LO pQCD cross-sections

$$
\begin{array}{lllllll}
g\,g & \to & g\,g & & & & \\
g\,g & \to & q\,\bar{q} & & & & \\
q\,\bar{q} & \to & g\,g & \text{and} & q\,\bar{q} & \to & q'\,\bar{q}' \\
q\,g & \to & q\,g & \text{and} & \bar{q}\,g & \to & \bar{q}\,g \\
q\,\bar{q} & \to & q\,\bar{q} & & & & \\
q\,q & \to & q\,q & \text{and} & \bar{q}\,\bar{q} & \to & \bar{q}\,\bar{q} \\
q\,q' & \to & q\,q' & \text{and} & q\,\bar{q}' & \to & q\,\bar{q}'
\end{array}
$$



Uphoff, Fochler, Xu, Greiner: Phys. Rev. C84 (2011)

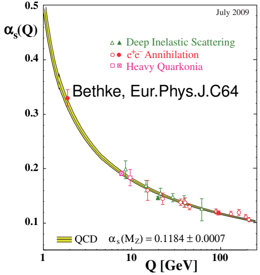
Running coupling evaluated at the microscopic scale

$2 \to 2$ processes

$$\alpha_s \to \alpha_s(Q^2),\ Q^2 \in \{s, t, u\}$$

$2 \to 3$ processes

$$\alpha_s \to \alpha_s(Q^2),\ Q^2 \in \{k_t^2, q_t^2\}$$



Remark

Due to universality arguments [1], the running coupling can be limited by $\alpha_{s;\max} = 1.0$.

[1] Y. Dokshitzer, Nucl.Phys. A711 (2002)

Jet momentum loss underlying the suppression in HIC