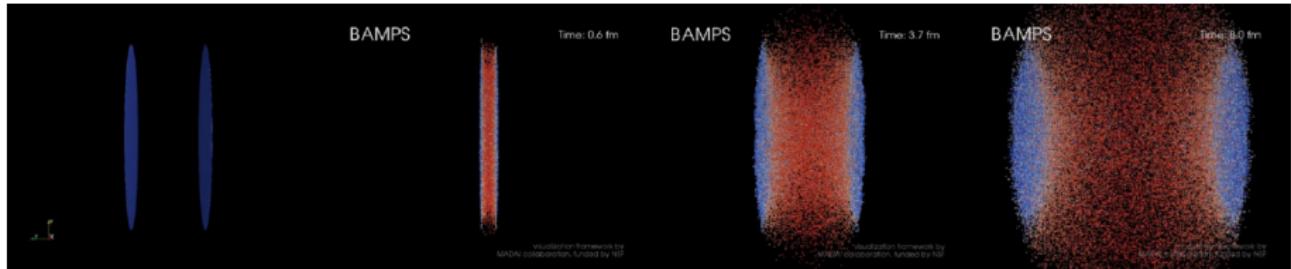


The LPM effect in a partonic transport approach

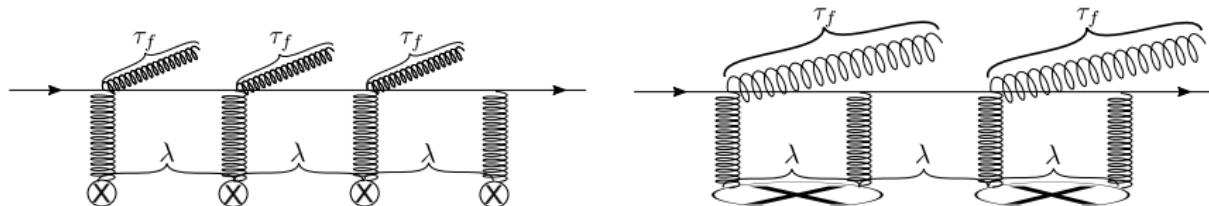
Florian Senzel
with M. Greif and C. Greiner



Hard Probes, Aix-les-Bains, 02.10.2018

Brief reminder: What is the LPM effect?

- The Landau-Pomeranchuk-Migdal effect is coherence effect caused by finite emission time.

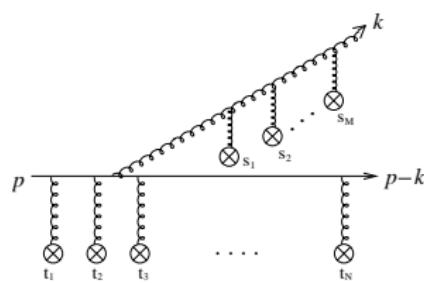


- Scattering centers act coherently during formation time τ_f when

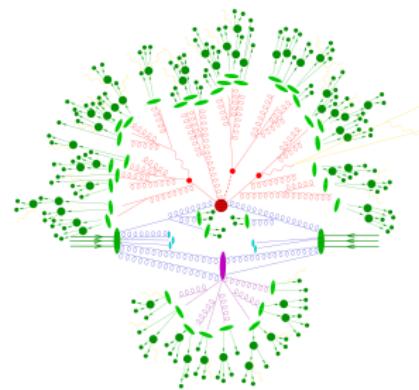
$$\tau_f = \frac{\omega}{k_t^2} > \lambda_{\text{MFP}}$$

- Coherent scatterings lead to suppression of emissions.
- In principle, resummation of infinite number of diagrams necessary.

Jet quenching: from analytics to Monte-Carlo tools



\Leftrightarrow



Limitations of analytic pQCD energy loss calculations

- Eikonal limit violates energy-momentum conservation.
- Kinematic approximations:
static scattering centers, multiple soft/one hard scattering,...
- Modern jet studies demand for single events, not event averages.

Coherence effects within **Monte-Carlo** approaches are not trivial.

The partonic transport model BAMPS

- Solving (3+1)D Boltzmann equation for massless partons:

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

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

- Simulates jets and background with **same** microscopic processes:

Elastic processes:

Screened LO pQCD

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

Bremsstrahlung processes:

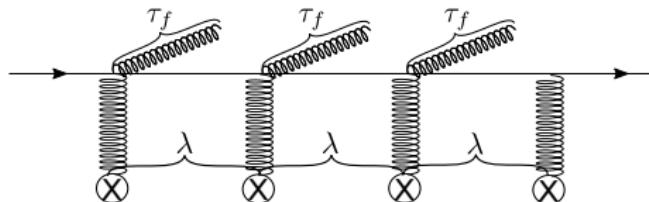
Improved Gunion-Bertsch

$$|\overline{\mathcal{M}}_{X \rightarrow Y+g}|^2 \sim |\overline{\mathcal{M}}_{X \rightarrow Y}|^2 \times \alpha_s \left[\frac{\mathbf{k}_\perp}{k_\perp^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + m_D^2(\alpha_s)} \right]^2$$

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

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

Effective LPM effect in BAMPS: “ Θ -LPM”



Ensuring incoherent gluon emissions

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

$$|\mathcal{M}_{2 \rightarrow 3}|^2 \rightarrow |\mathcal{M}_{2 \rightarrow 3}|^2 \Theta(\lambda - X_{\text{LPM}} \tau_f)$$

$X_{\text{LPM}} = 0$ No LPM suppression

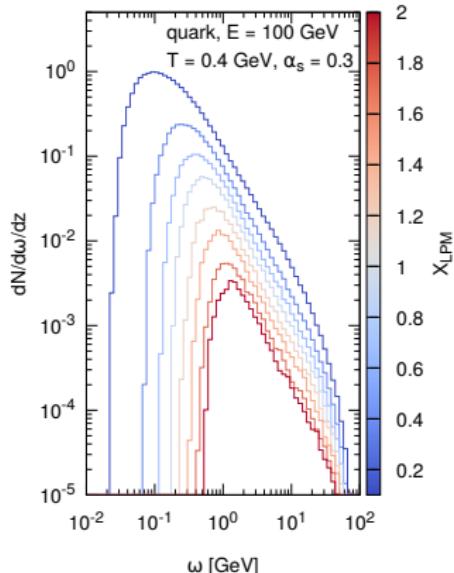
$X_{\text{LPM}} = 1$ Only independent scatterings (forbids too many emissions)

$X_{\text{LPM}} \in (0; 1)$ Allows effectively some collinear gluons.

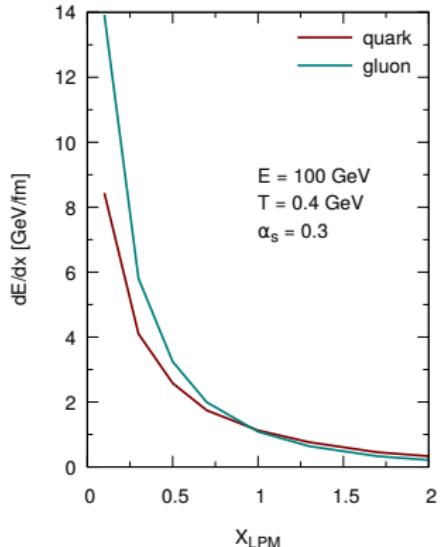
- Remark: Θ -function effectively screens soft k_t divergence.

Sensitivity of radiative energy loss on X_{LPM}

Gluon spectrum $\frac{dN}{d\omega}$



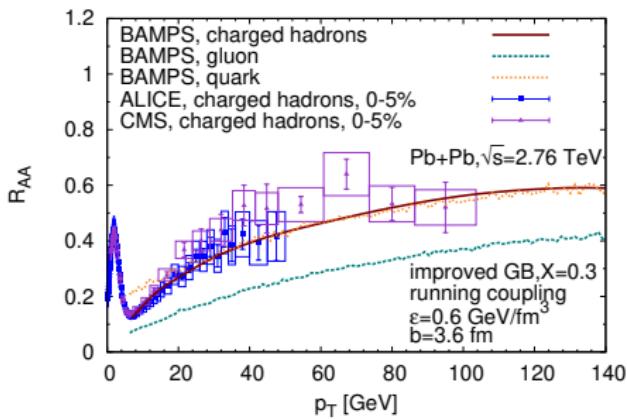
Differential energy loss $\frac{dE}{dx}$



- X_{LPM} controls both softness and number of gluon emissions.
- ↪ Resulting energy loss strongly depends on X_{LPM} .

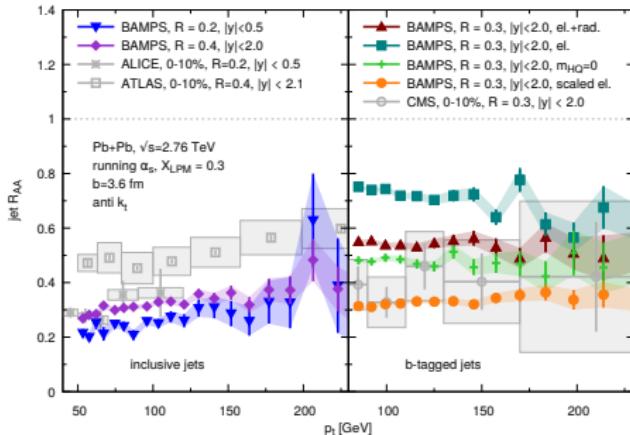
Previous jet quenching results with BAMPS

Inclusive hadrons



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

Reconstructed jets



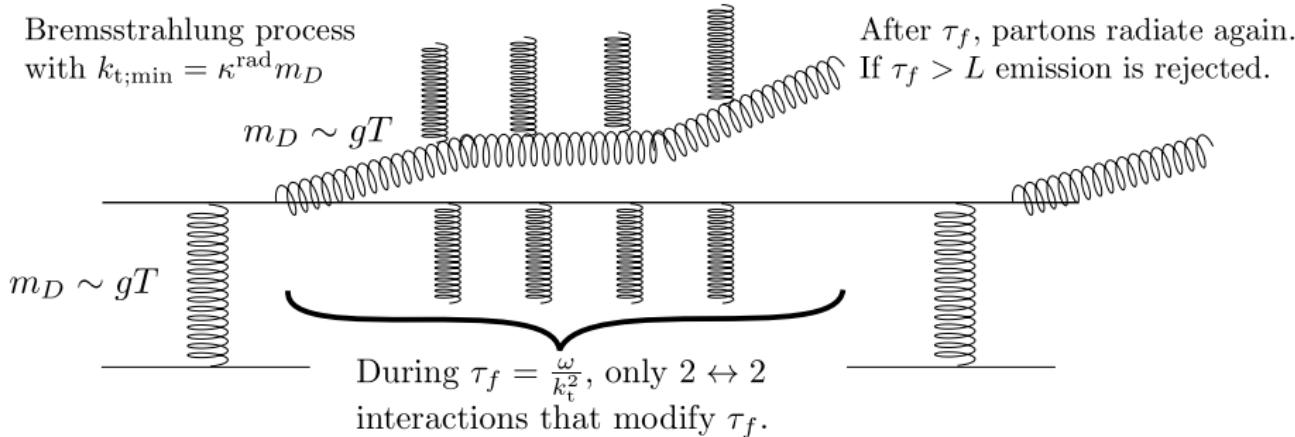
FS, Uphoff, Xu, Greiner
Phys.Lett. B773 (2017) 620-624

Open questions

- How can we determine the LPM parameter X_{LPM} theoretically?
- Why are reconstructed jets so strongly suppressed?

Stochastic LPM effect in BAMPS: “sLPM”

Bremsstrahlung process
with $k_{t,\min} = \kappa^{\text{rad}} m_D$



Other approaches:

MARTINI: LPM via AMY

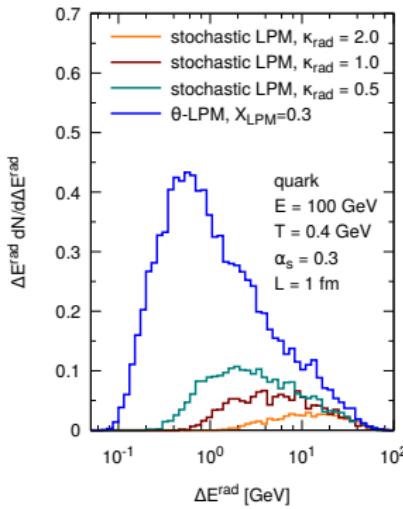
C.Park et al., Nucl.Part.Phys.Proc. 289-290 (2017)
S.Caron-Huot and C. Gale, Phys.Rev. C82 (2010)

JEWEL: LPM via BDMPS

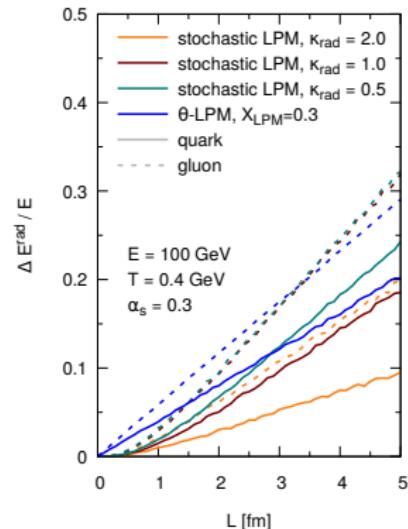
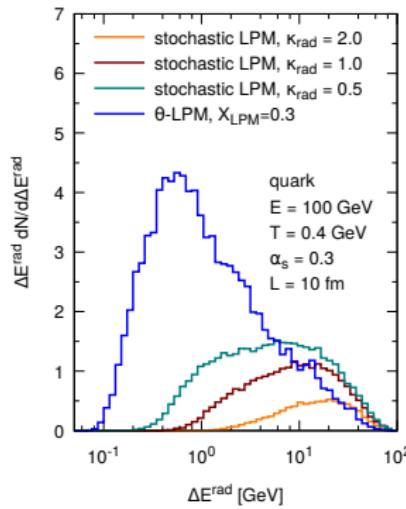
K.Zapp et al., Phys.Rev.Lett. 103 (2009)
K.Zapp et al., JHEP 1107 (2011)

Length dependence of radiative energy loss ΔE^{rad}

$L = 1 \text{ fm}$

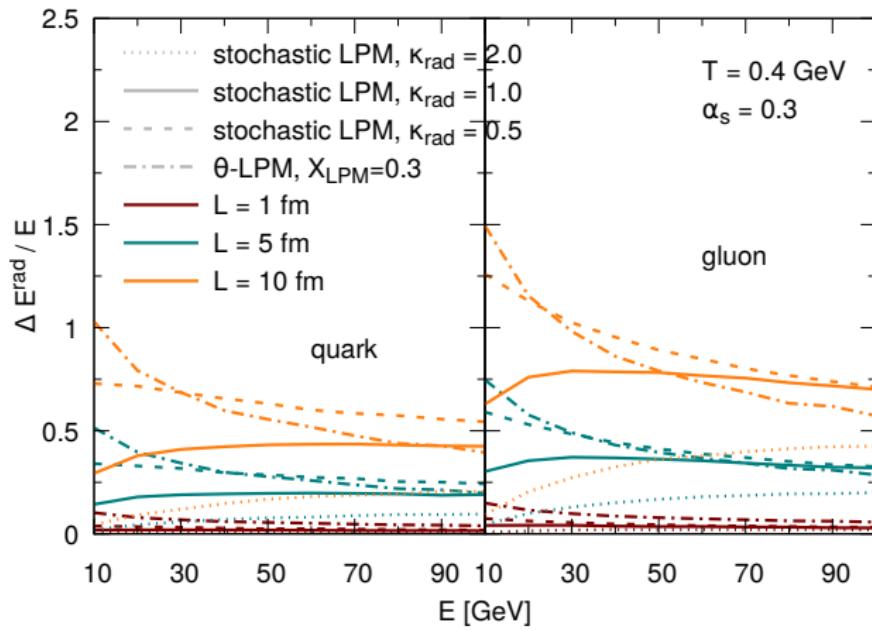


$L = 10 \text{ fm}$



- For small L , finite τ_f suppresses gluon emissions.
- At larger L , sLPM distribution becomes harder but still suppressed.
- $\Delta E(L)$ of stochastic LPM shows characteristic $\Delta E \sim L^2$.

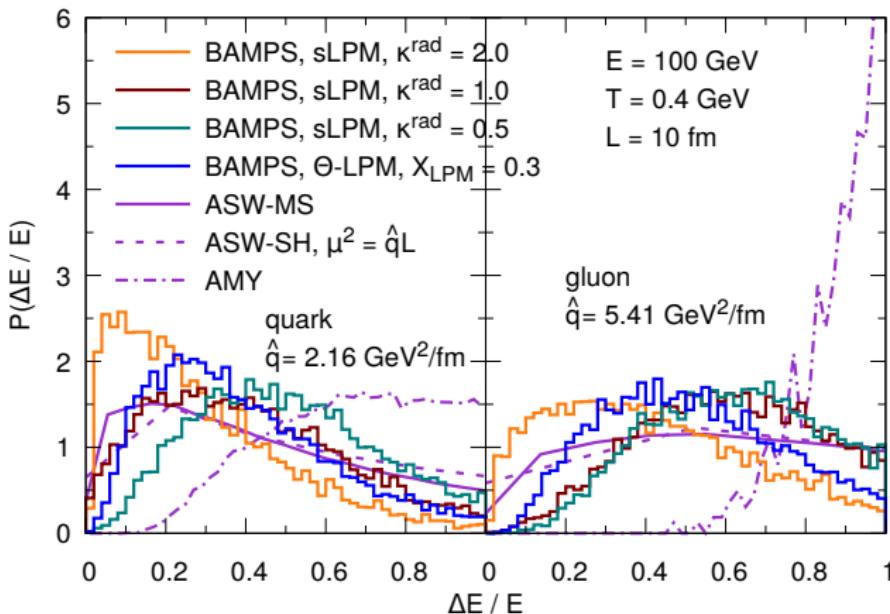
Energy dependence of radiative energy loss ΔE^{rad}



- Large differences between θ - and sLPM at smaller jet energies.
- sLPM shows flatter energy dependence of radiative energy loss.

Comparison with analytical models

“quenching weights” $P(\Delta E / E)$



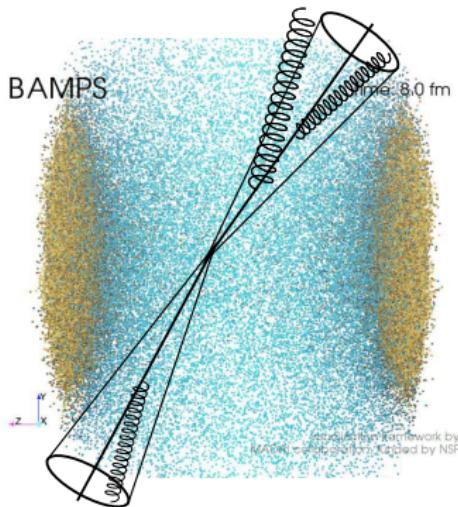
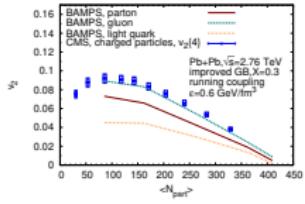
- Quarks:
sLPM with $\kappa^{\text{rad}} \leq 1.0$ comparable with ASW.
- Gluons:
ASW shows broader distribution than sLPM.
- AMY shows much stronger energy loss.

Modeling jet quenching within heavy-ion collisions

Microscopic
running coupling

$$\alpha_S(s, t, u)$$

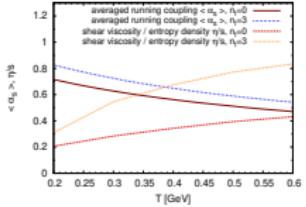
Elliptic flow v_2



Fragmentation
functions:

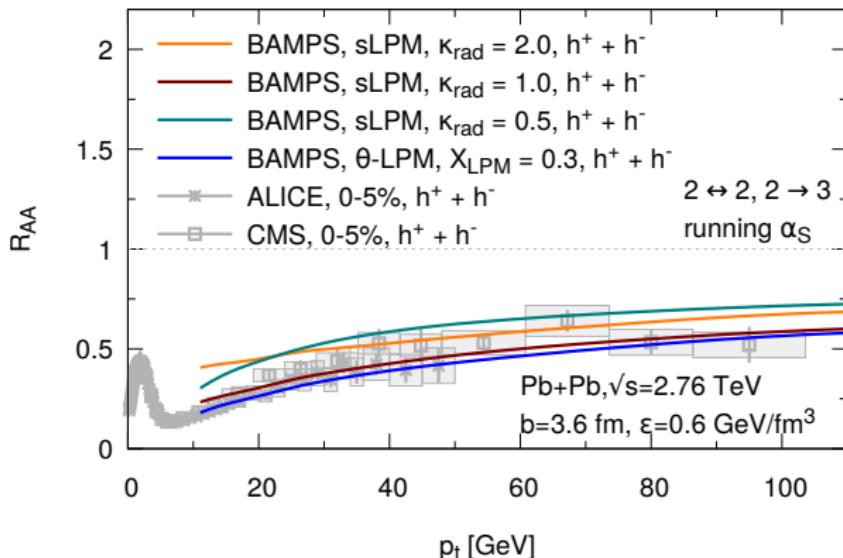
$$D_{i \rightarrow h}(z, Q^2)$$

Shear viscosity η/s



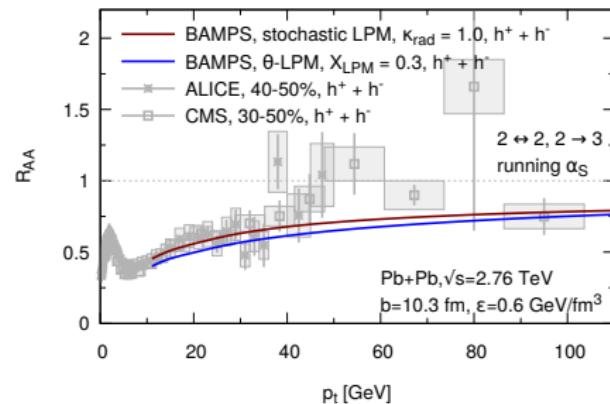
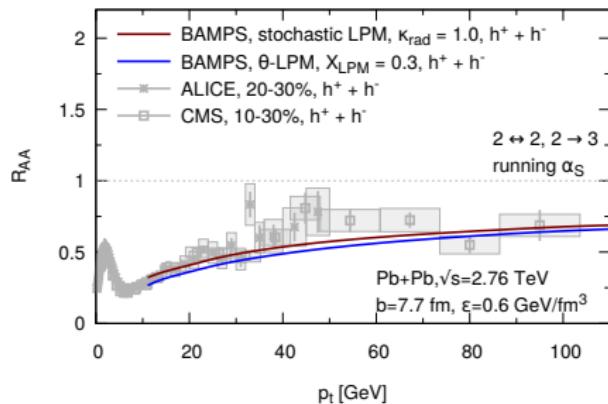
Uphoff, FS, Fochler, Wesp, Xu, Greiner: Phys. Rev. Lett. 114 (2015) 112301

Sensitivity of R_{AA} on κ_{rad}



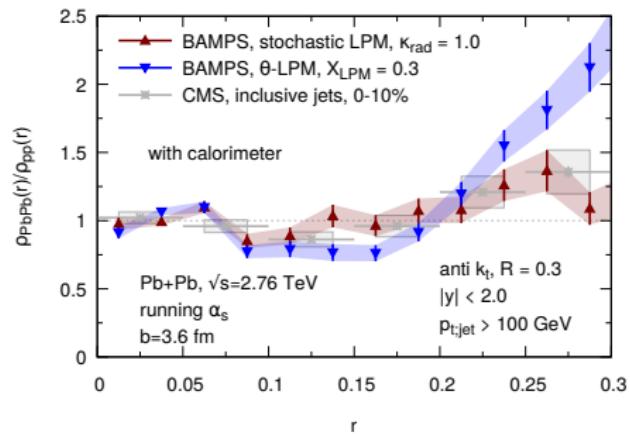
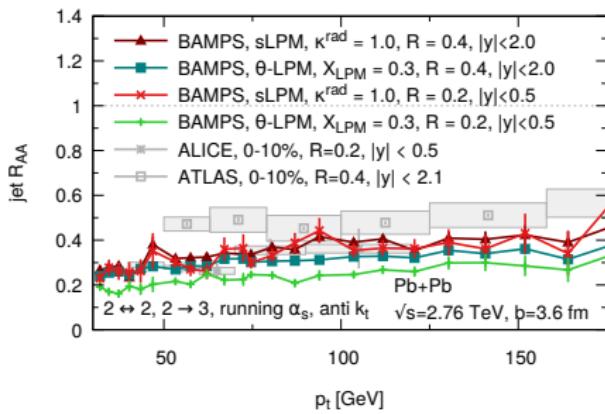
- Stochastic LPM shows realistic jet quenching via R_{AA} .
- $\kappa_{rad} = 1.0$ shows strongest suppression.
- Less sensitivity on κ^{rad} than X_{LPM} .

Centrality dependence of R_{AA} in BAMPS



- sLPM and Θ -LPM show (almost) same R_{AA} in peripheral collisions.
→ Peripheral R_{AA} not sensitive to length dependence of sLPM.

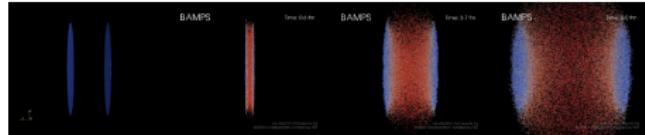
Jet R_{AA} and medium modification of jet shapes



- Jets with $R = 0.2$ can be described with stochastic LPM. Decreasing resolution ($R = 0.4$) still too strongly suppressed.
- sLPM gives less large angle emissions/transport in comparison with θ -LPM.

Conclusions

- Implementation of stochastic LPM in BAMPS leads to length-dependent energy loss.
- Comparable energy loss with previous Θ -LPM ($X_{\text{LPM}} = 0.3$).
- Realistic description of R_{AA} at different centralities.
- Jet suppression too strong, but jet shapes show more realistic large angle behavior.



Open questions:

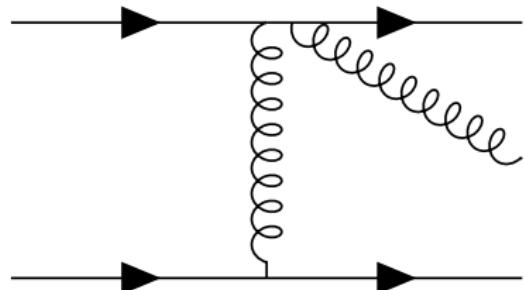
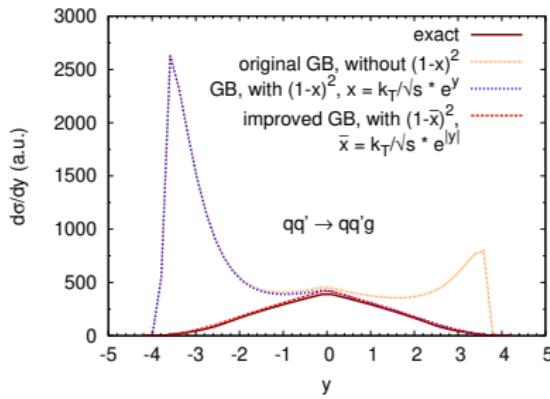
- Are other observables sensitive to difference in L -dependence?
- How will sLPM change medium interactions? Elliptic flow v_2 ?
- Can sLPM be adapted to heavy flavor studies within BAMPS?

Backup slides

Closer look on the radiative processes

Improved Gunion-Bertsch ME

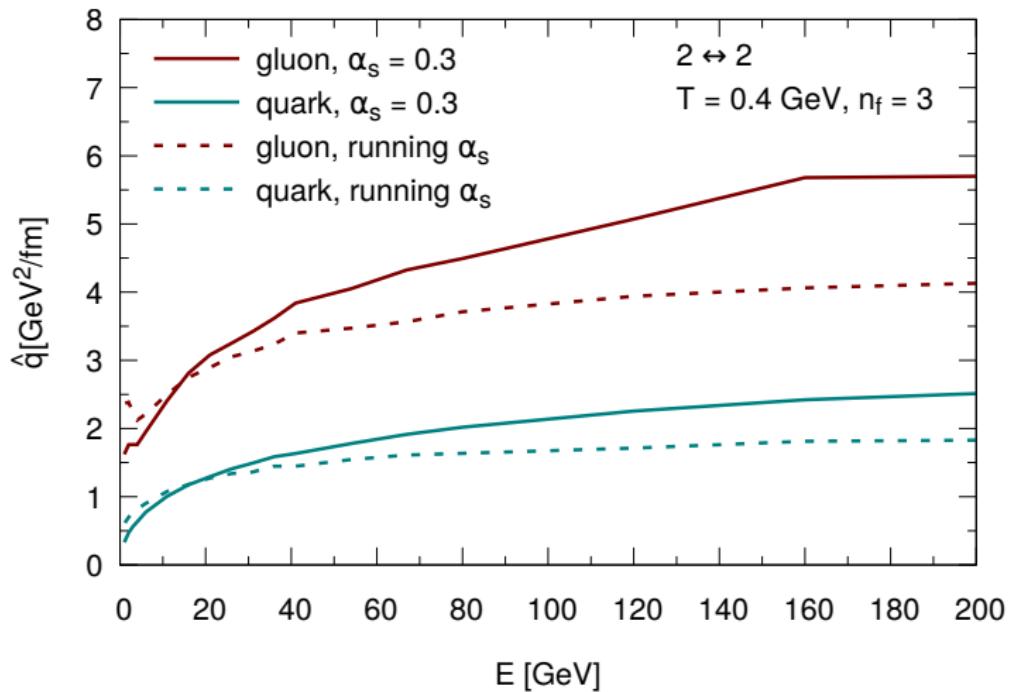
$$|\overline{\mathcal{M}}_{X \rightarrow Y+g}|^2 = 48\pi\alpha_s |\overline{\mathcal{M}}_{X \rightarrow Y}|^2 (1 - \bar{x})^2 \left[\frac{\mathbf{k}_\perp}{k_\perp^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + m_D^2(\alpha_s)} \right]^2$$



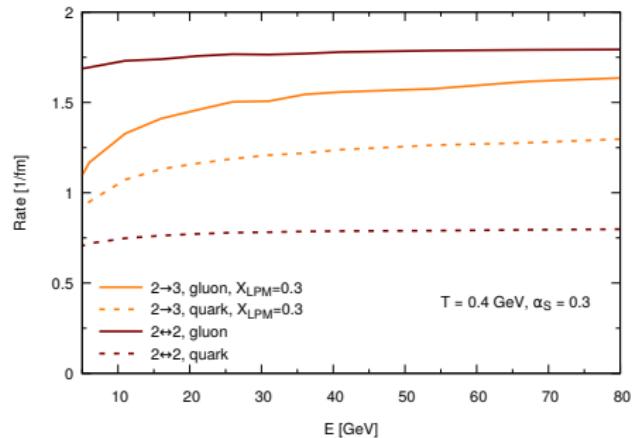
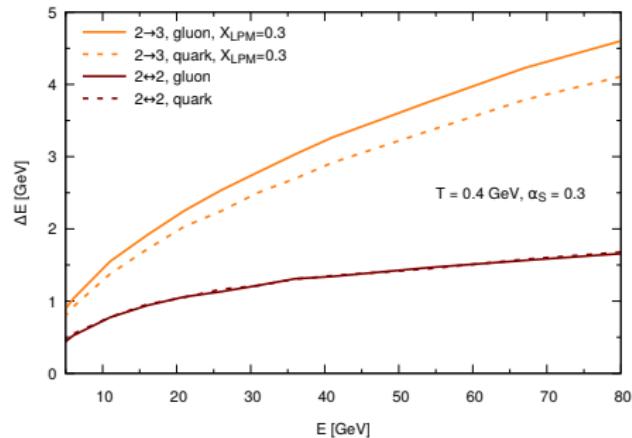
Gunion, Bertsch: Phys. Rev. D25 (1982)
Fochler, Uphoff, Xu, Greiner: Phys. Rev. D88 (2013)

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

Momentum broadening of partons: \hat{q}



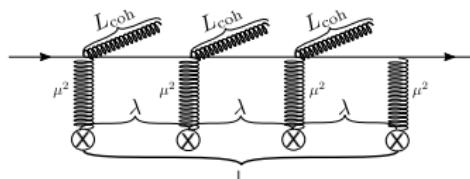
Energy loss of partons in a static medium



Qualitative discussion of LPM effect - gluon spectrum

Bethe-Heitler regime ($L_{\text{coh}} < \lambda$ or $\omega < \omega_{\text{BH}}$)

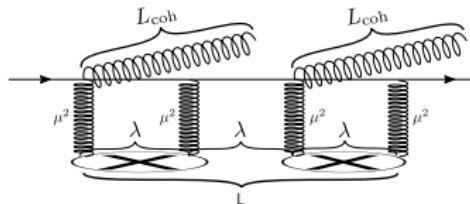
$$\omega \frac{dI}{d\omega dz} \Big|_{\text{BH}} \sim \frac{1}{L} \frac{dI}{d\omega} \Big|_L \sim \frac{N^{\text{incoh}}}{L} \sim \frac{1}{\lambda}$$



LPM regime

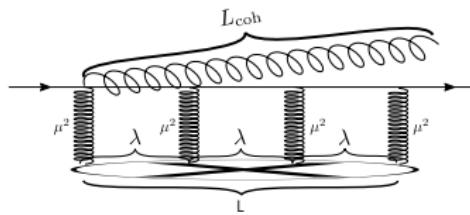
($\lambda < L_{\text{coh}} < L$ or $\omega_{\text{BH}} < \omega < \omega_{\text{fact}}$)

$$\omega \frac{dI}{d\omega dz} \Big|_{\text{LPM}} \sim \frac{1}{L_{\text{coh}}} \frac{dI}{d\omega} \Big|_{L_{\text{coh}}} \sim \frac{1}{\lambda} \sqrt{\frac{\omega_{\text{BH}}}{\omega}}$$



Factorization regime ($L_{\text{coh}} > L$ or $\omega > \omega_{\text{fact}}$)

$$\omega \frac{dI}{d\omega dz} \Big|_{\text{fact}} \sim \frac{1}{L} \frac{dI}{d\omega} \Big|_L \sim \frac{1}{L}$$



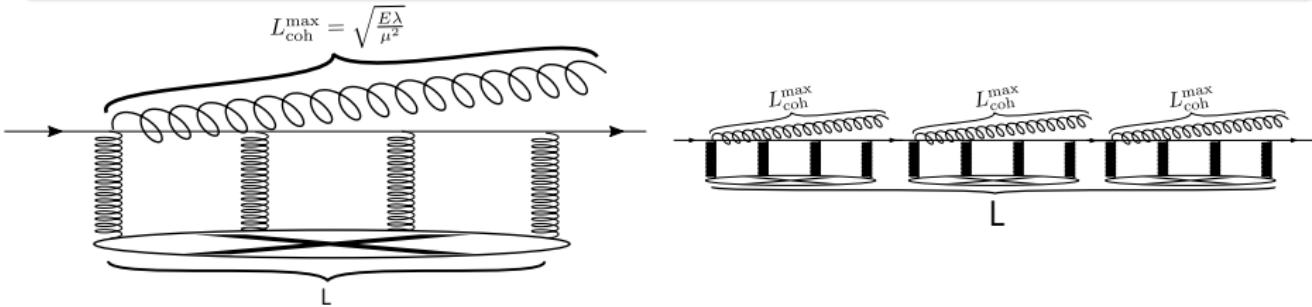
Qualitative discussion of LPM effect - energy loss $\frac{dE}{dz}$

Thin media: $\omega_{\text{fact}} < E$ or $L < L_{\text{coh}}^{\max}$

$$\frac{dE}{dz} = \int_0^{\omega_{\text{BH}}} d\omega \omega \frac{dI}{d\omega dz} \Big|_{\text{BH}} + \int_{\omega_{\text{BH}}}^{\omega_{\text{fact}}} d\omega \omega \frac{dI}{d\omega dz} \Big|_{\text{LPM}} + \int_{\omega_{\text{fact}}}^E d\omega \omega \frac{dI}{d\omega dz} \Big|_{\text{fact}}$$

$$\sim \frac{\mu^2}{\lambda} L$$

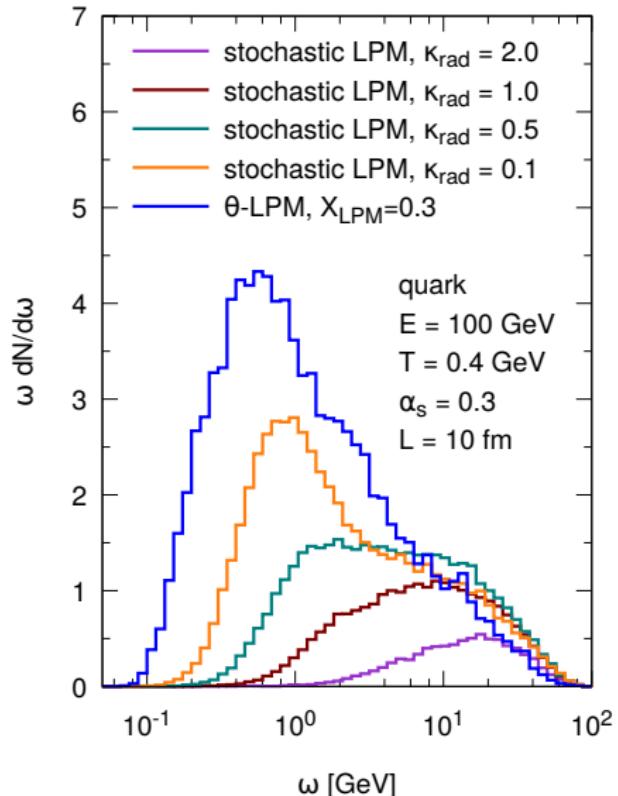
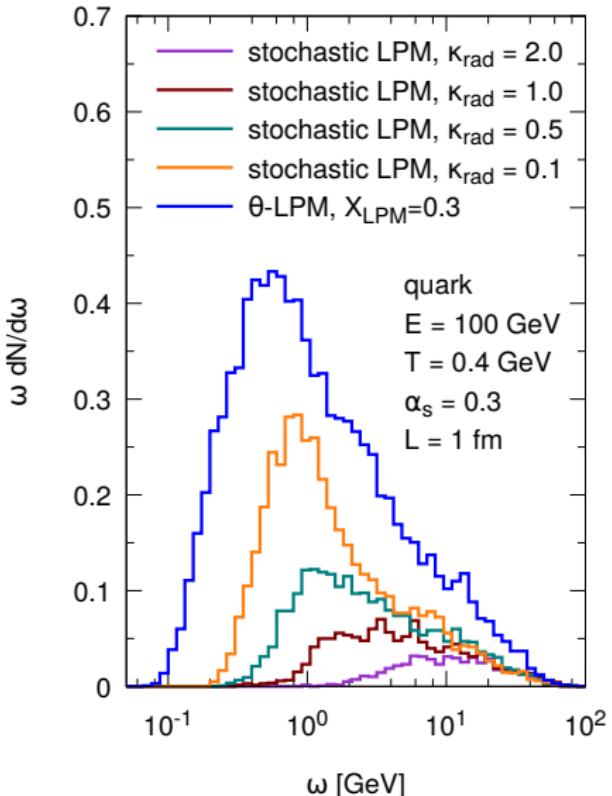
$$L_{\text{coh}}^{\max} = \sqrt{\frac{E\lambda}{\mu^2}}$$



Thick media: $\omega_{\text{fact}} > E$ or $L > L_{\text{coh}}^{\max}$

$$\frac{dE}{dz} = \int_0^{\omega_{\text{BH}}} d\omega \omega \frac{dI}{d\omega dz} \Big|_{\text{BH}} + \int_{\omega_{\text{BH}}}^E d\omega \omega \frac{dI}{d\omega dz} \Big|_{\text{LPM}} \sim \sqrt{\frac{\mu^2}{\lambda} E}$$

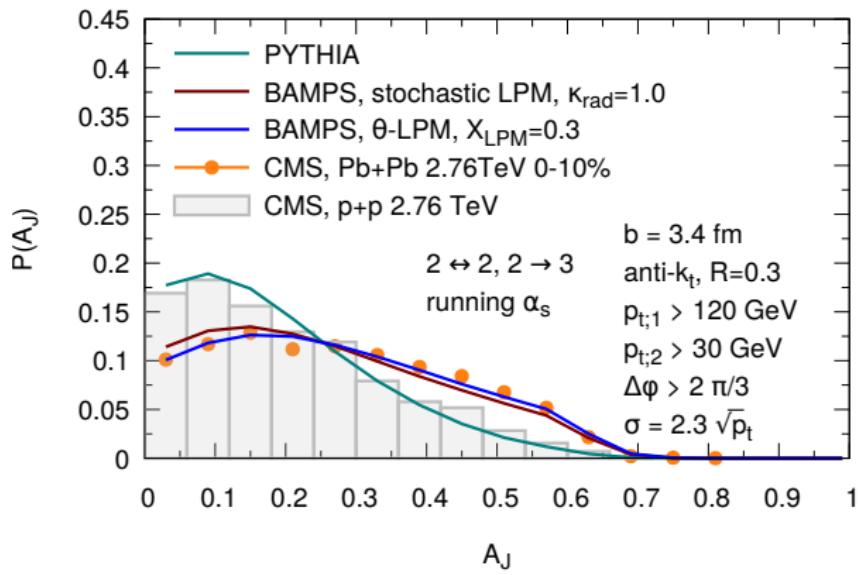
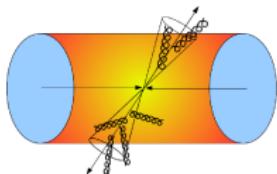
ω spectrum of gluons after τ_f



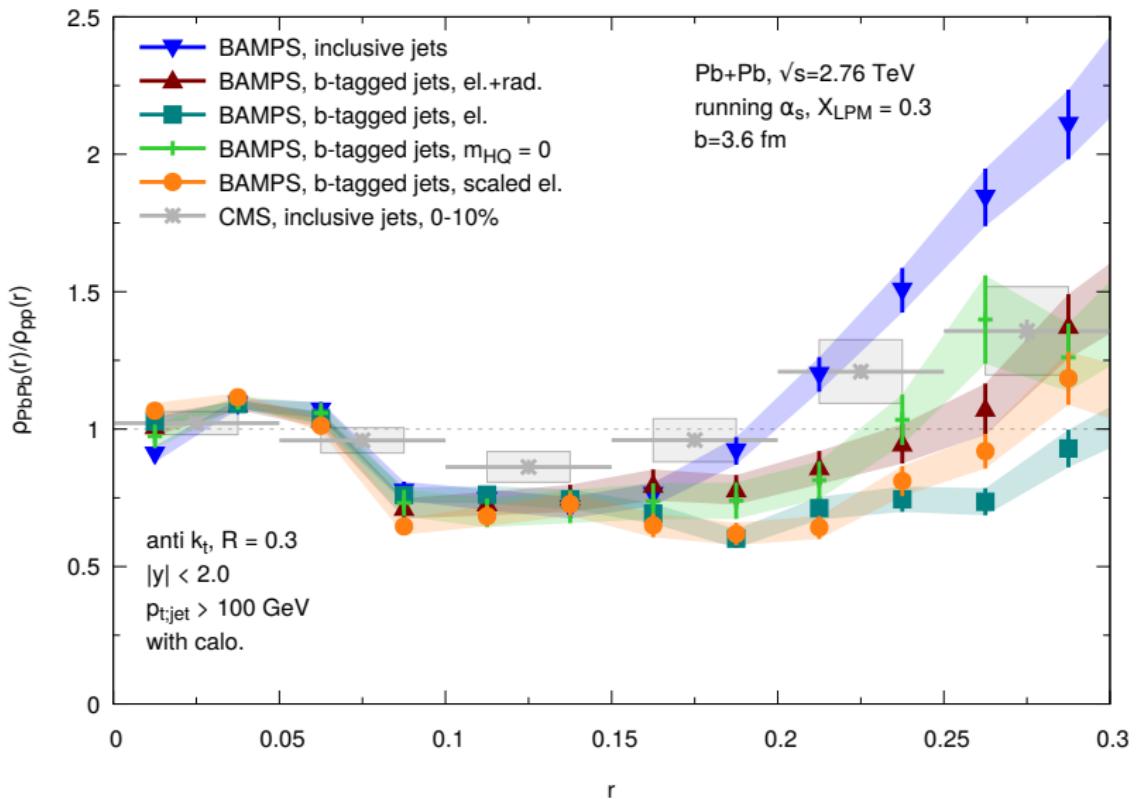
Momentum imbalance A_J of reconstructed di-jets

Definition

$$A_J = \frac{p_{t;\text{leading}} - p_{t;\text{subleading}}}{p_{t;\text{leading}} + p_{t;\text{subleading}}}$$



Jet shapes in a heavy-ion collision



Differential energy loss in a static medium

