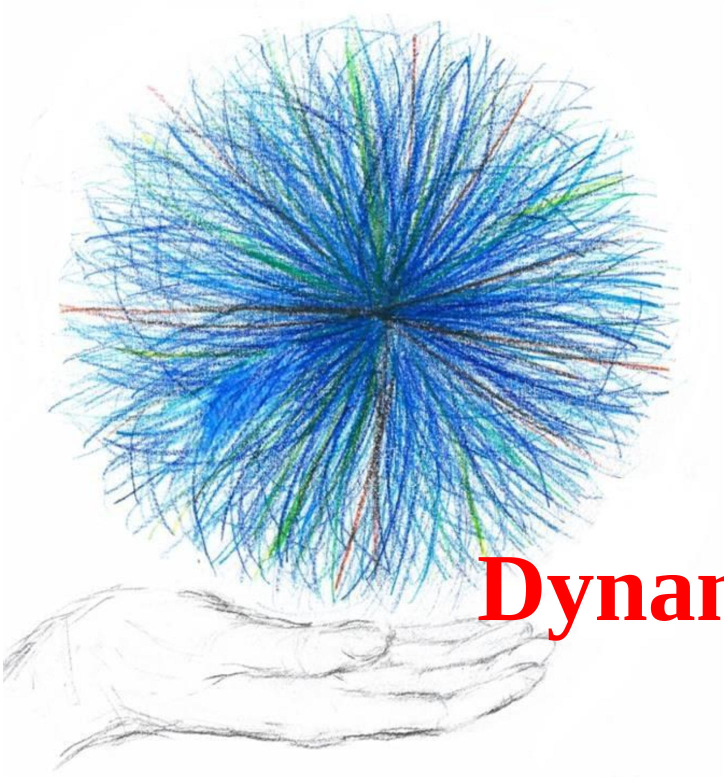


Dynamical energy loss formalism

Magdalena Djordjevic, IPB

In collaboration with: **Bojana Ilic, Dusan Zigic, Stefan Stojku,**
Jussi Auvinen, Igor Salom, Marko Djordjevic and Pasi Huovinen

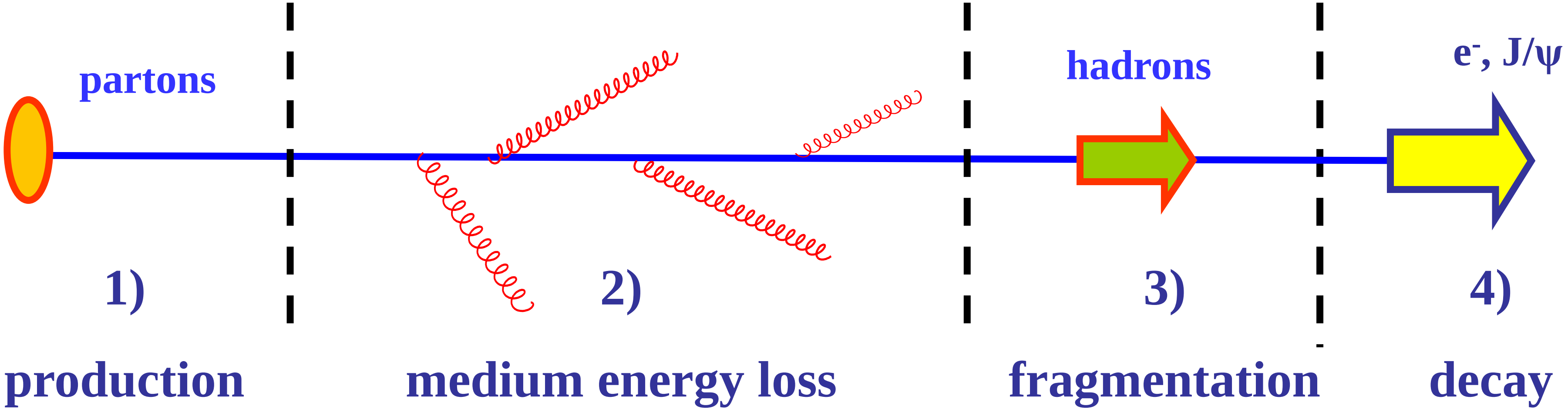
erc European Research Council

МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

Motivation

- Energy loss of high-pt particles traversing QCD medium is an excellent probe of QGP properties.
- Theoretical predictions can be compared with a wide range of data, coming from different experiments, collision systems, collision energies, centralities, observables…
- Can be used together with low-pt theory and experiments to study the properties of created QCD medium, i.e. for precision QGP tomography.

Suppression scheme



partons

hadrons

e^-, J/ψ

1) production

2) medium energy loss

3) fragmentation

4) decay

1) Initial momentum distributions for partons
2) Parton energy loss
3) Fragmentation functions of partons into hadrons
4) Decay of heavy mesons to single e^- and J/ψ.

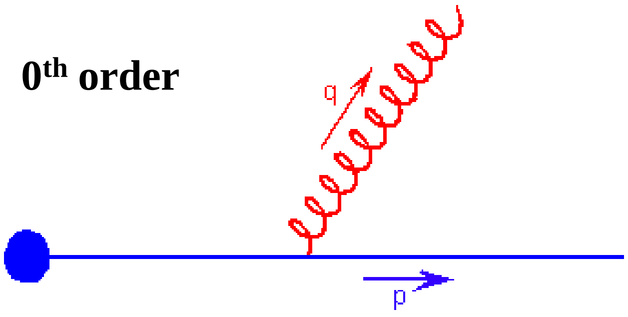
Out of these steps the energy loss is most important!

Energy loss in QGP

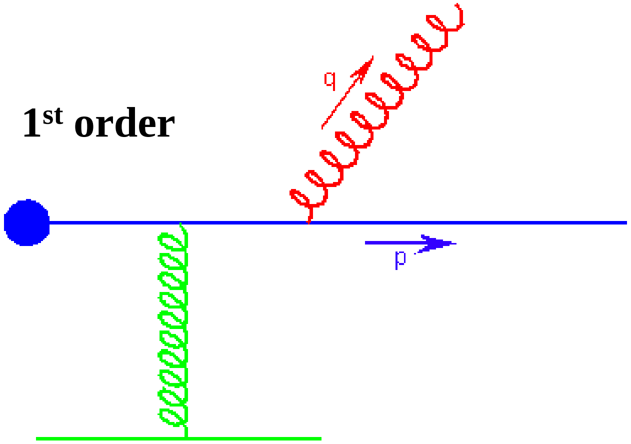
Radiative energy loss

Radiative energy loss comes from the processes in which there are more outgoing than incoming particles:

0th order



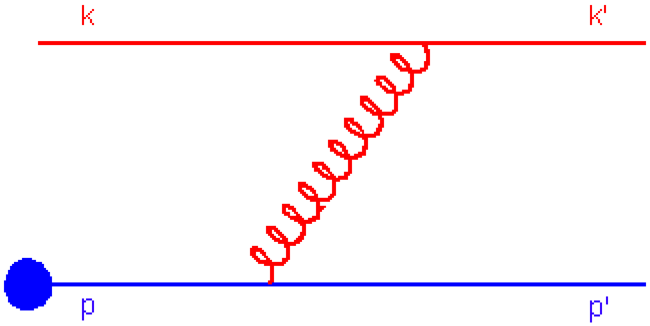
1st order



Collisional energy loss

Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles:

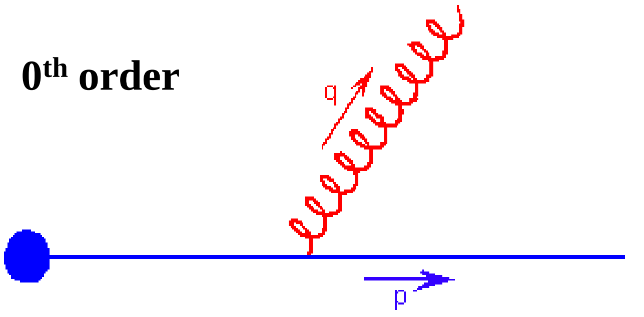
0th order



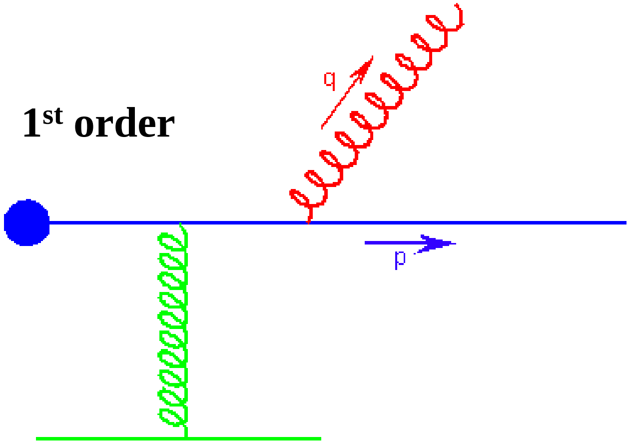
Radiative energy loss

Radiative energy loss comes from the processes in which there are more outgoing than incoming particles:

0^{th} order



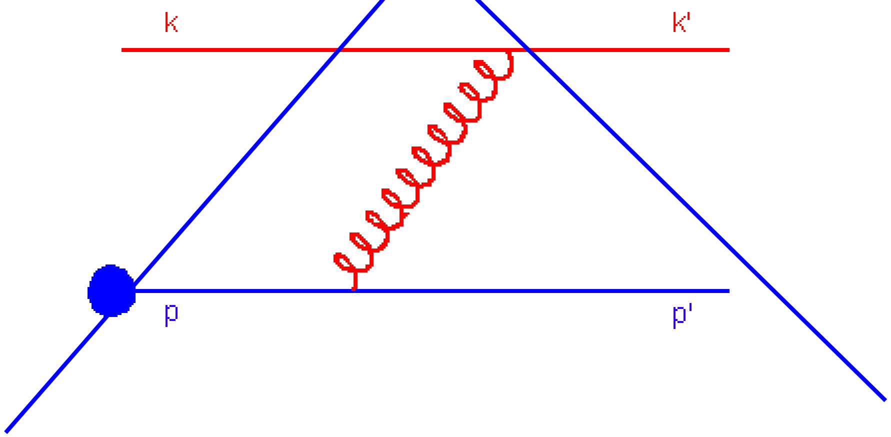
1^{st} order



Collisional energy loss

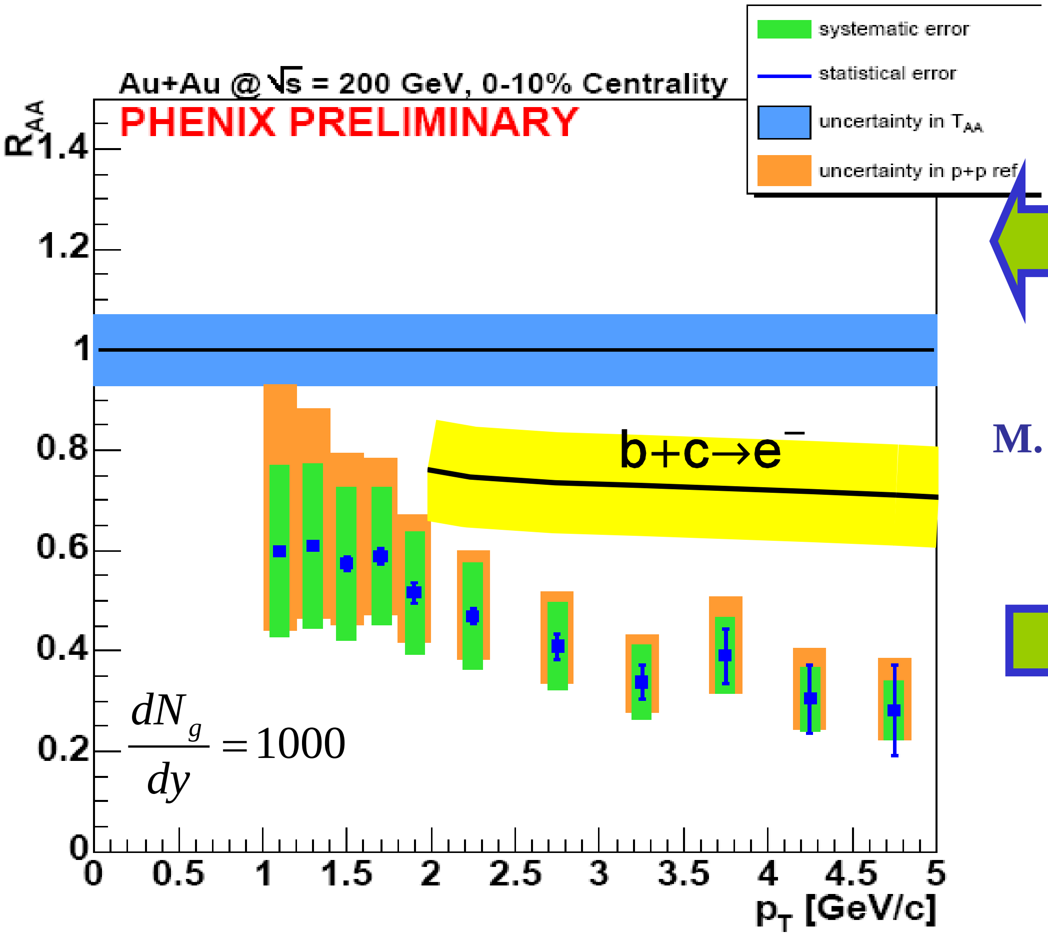
Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles:

0^{th} order



Considered to be negligible compared to radiative!

Heavy flavor puzzle @ RHIC



M. D. et al., Phys. Lett. B 632, 81 (2006)

Radiative energy loss predictions with $dN_g/dy=1000$

M. D. and M. Gyulassy, PRC 2003, PLB 2003, NPA 2004; M. D. PRC 2006;

Disagreement!

Radiative energy loss is not able to explain the single electron data as long as realistic parameter values are taken into account!

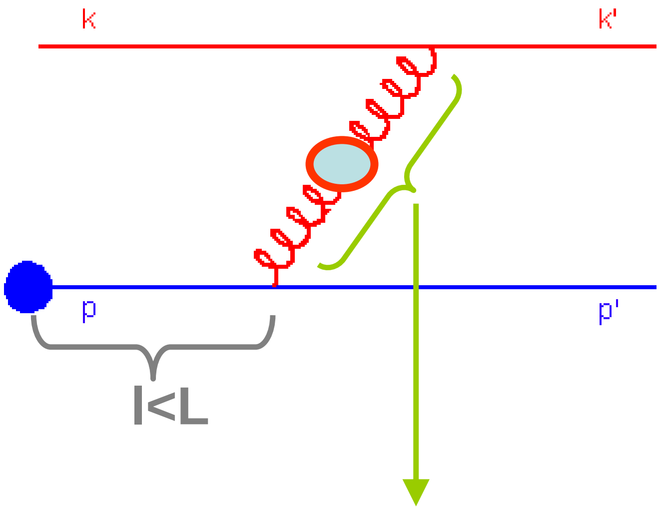
Does the radiative energy loss control the energy loss in QGP?

Is collisional energy loss also important?

Collisional energy loss in a finite size QCD medium

Consider a medium of size L in thermal equilibrium at temperature T.

The main order collisional energy loss is determined from:

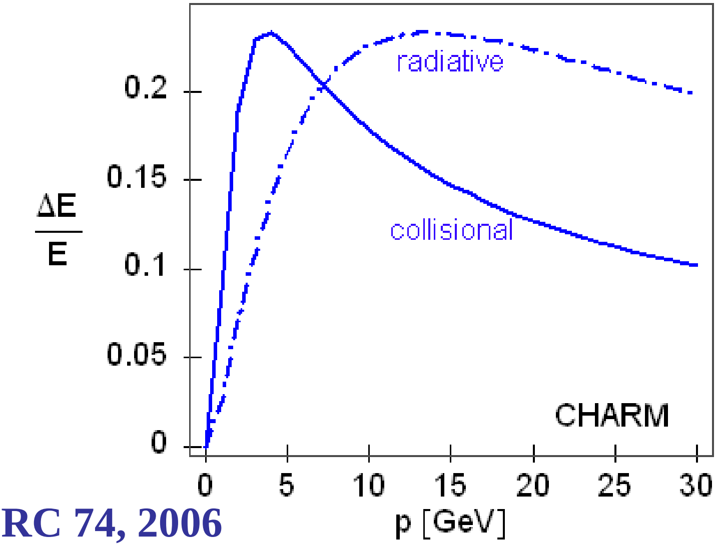


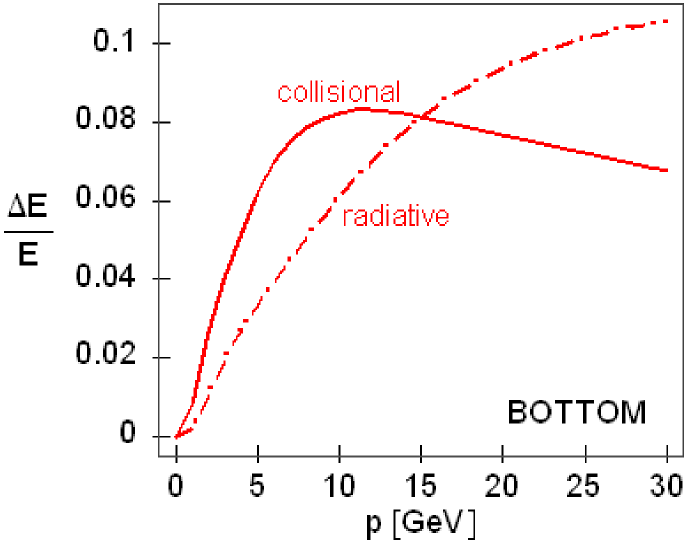
The effective gluon propagator:

$$D^{\mu\nu}(\omega,\vec{\mathrm{q}}) = -P^{\mu\nu}\Delta_T(\omega,\vec{\mathrm{q}}) - Q^{\mu\nu}\Delta_L(\omega,\vec{\mathrm{q}})$$

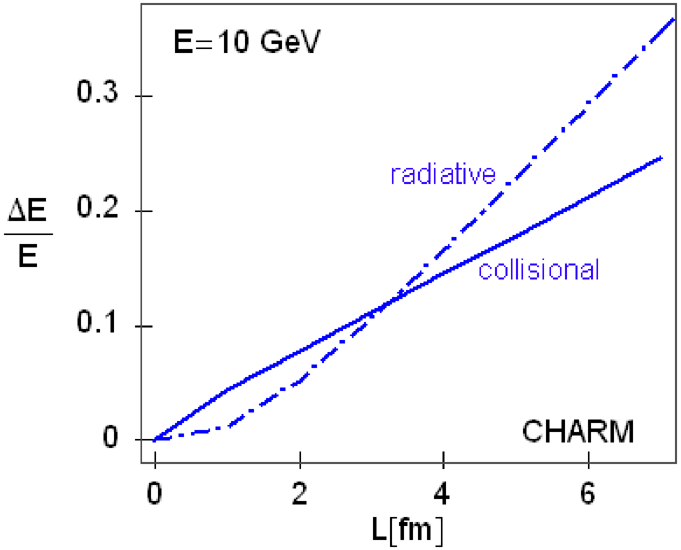
M. D., Phys.Rev.C74:064907,2006

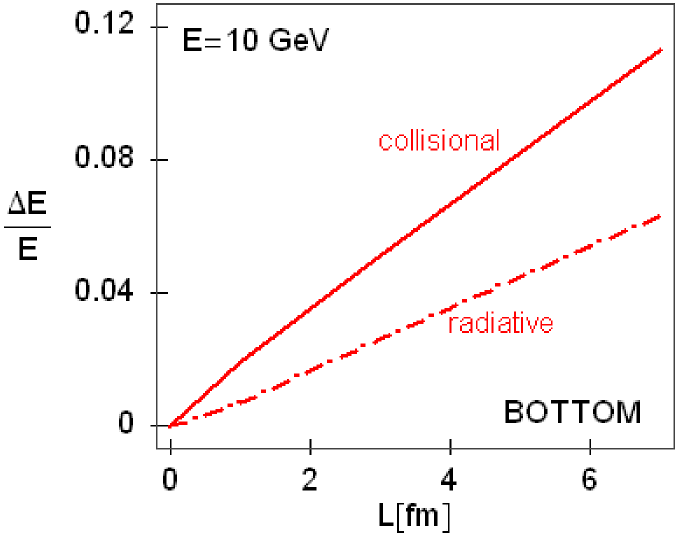
Collisional v.s. medium induced radiative energy loss





M. D., PRC 74, 2006

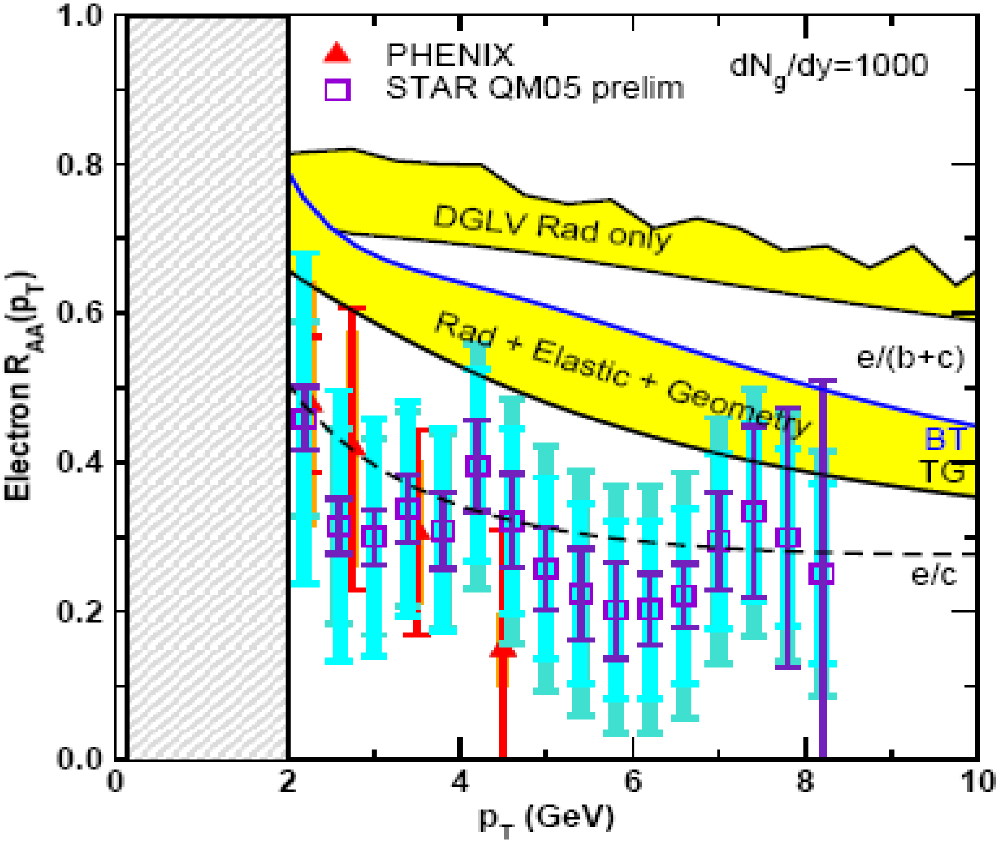




Collisional and radiative energy losses are comparable!

Single electron prediction (collisional + radiative)

(S. Wicks, W. Horowitz, M.D. and M. Gyulassy, Nucl.Phys.A784:426-442,2007)



Inclusion of collisional energy loss leads to better agreement with single electron data.

Non-zero collisional energy loss - a fundamental problem

Static QCD medium approximation (modeled by Yukawa potential).

With such approximation, collisional energy loss has to be exactly equal to zero!

However, collisional and radiative energy losses are shown to be comparable.

Introducing collisional energy loss is necessary, but inconsistent with static approximation!

Static medium approximation should not be used in radiative energy loss calculations!

Dynamical QCD medium effects have to be included!

Our goal

We wanted to compute the light and heavy quark radiative energy loss in dynamical medium of thermally distributed massless quarks and gluons.

Why?

- **To address the applicability of static approximation in radiative energy loss computations.**
- **To compute collisional and radiative energy losses within a consistent theoretical framework which is applicable to both light and heavy flavor.**

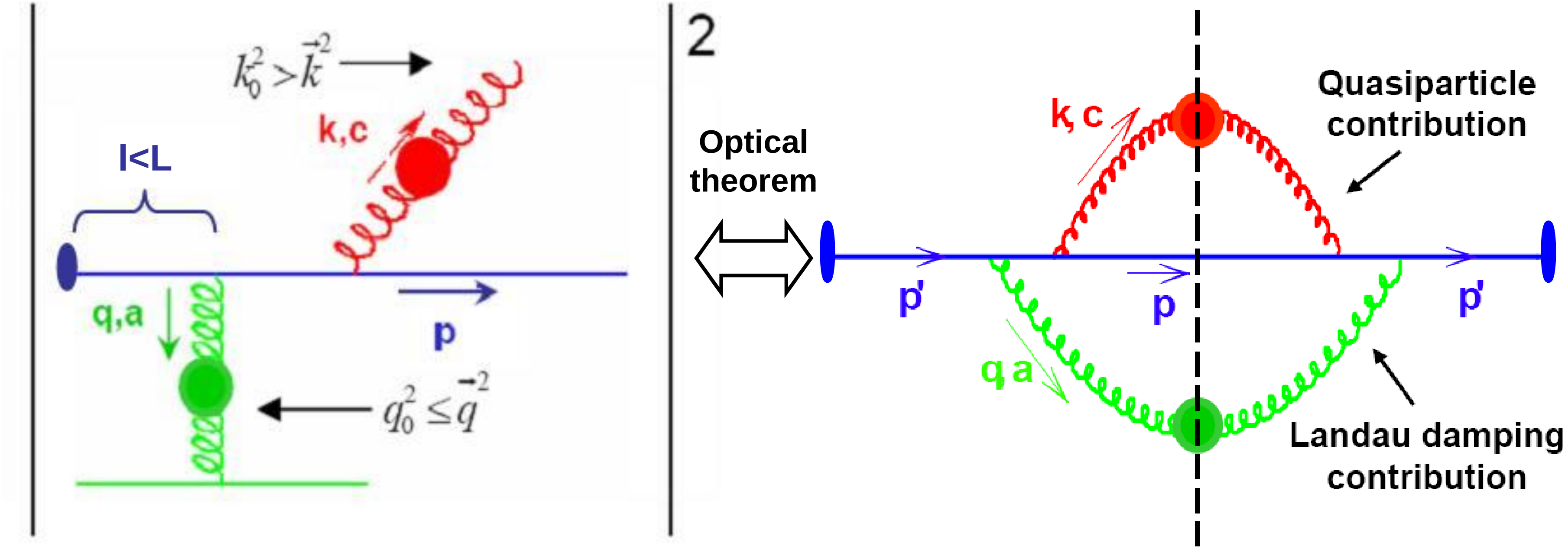
M. D., Phys.Rev.C80:064909,2009 (highlighted in APS physics).

M. D. and U. Heinz, Phys.Rev.Lett.101:022302,2008.

Radiative energy loss in a dynamical medium

We compute the medium induced radiative energy loss for a light and heavy quark to the first (lowest) order in number of scattering centers.

To compute this process, we consider the radiation of one gluon induced by one collisional interaction with the medium.



We consider a medium of finite size L, and assume that the collisional interaction has to occur inside the medium.

The calculations were performed by using two Hard-Thermal Loop approach.

1-HTL gluon propagator:

$$iD^{\mu\nu}(l) = \frac{P^{\mu\nu}(l)}{l^2 - \Pi_T(l)} + \frac{Q^{\mu\nu}(l)}{l^2 - \Pi_L(l)}$$

Cut 1-HTL gluon propagator:

$$D^{>}_{\mu\nu}(l) = -(1+f(l_0))\Big(P_{\mu\nu}(l)\rho_T(l) + Q_{\mu\nu}(l)\rho_L(l)\Big)\,,$$

$$\rho_{L,T}(l) = \underbrace{2\pi\,\delta(l^2 - \Pi_{T,L}(l))}_{\textbf{Radiated gluon}} - \underbrace{2\,\mathrm{Im}\left(\frac{1}{l^2 - \Pi_{T,L}(l)}\right)\theta(1 - \frac{l_0^2}{\vec{\mathrm{l}}^2})}_{\textbf{Exchanged gluon}}$$

For radiated gluon, cut 1-HTL gluon propagator can be simplified to

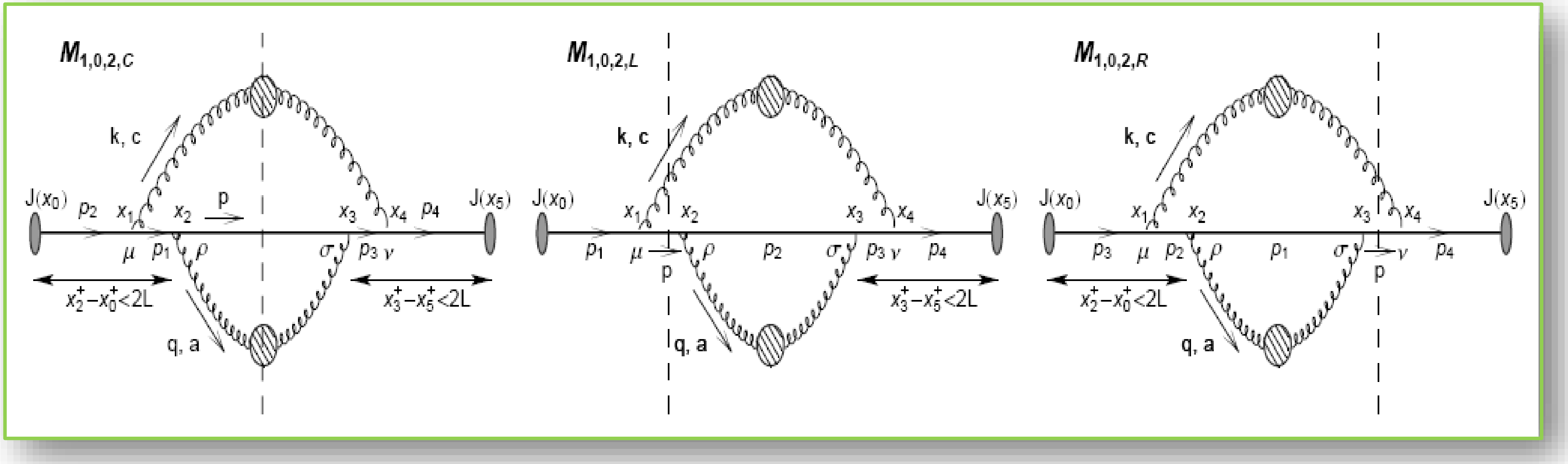
(M.D. and M. Gyulassy, PRC 68, 034914 (2003).

$$D^{>}_{\mu\nu}(k) \approx -2\pi\,\frac{P_{\mu\nu}(k)}{2\omega}\,\delta(k_0 - \omega) \qquad \omega \approx \sqrt{\vec{\mathrm{k}}^2 + m_g^2}\,;\; m_g \approx \mu/\sqrt{2}$$

For exchanged gluon, cut 1-HTL gluon propagator cannot be simplified, since both transverse (magnetic) and longitudinal (electric) contributions will prove to be important.

$$D^{>}_{\mu\nu}(q) = \theta(1 - \frac{q_0^2}{\vec{\mathrm{q}}^2})\,(1 + f(q_0))\,2\,\mathrm{Im}\left(\frac{P_{\mu\nu}(q)}{q^2 - \Pi_T(q)} + \frac{Q_{\mu\nu}(q)}{q^2 - \Pi_L(q)}\right)$$

More than one cut of a Feynman diagram can contribute to the energy loss in finite size dynamical QCD medium:



These terms interfere with each other, leading to the nonlinear dependence of the jet energy loss.

M. D., Phys.Rev.C80:064909,2009 (highlighted in APS physics).

We calculated all the relevant diagrams that contribute to this energy loss

Each individual diagram is infrared divergent, due to the absence of magnetic screening!

The divergence is naturally regulated when all the diagrams are taken into account.

So, all 24 diagrams have to be included to obtain sensible result.

$$\frac{\Delta E_{\mathrm{dyn}}}{E} = \frac{C_R \alpha_s}{\pi} \frac{L}{\lambda_{\mathrm{dyn}}} \int dx \frac{d^2 \mathbf{k}}{\pi} \frac{d^2 \mathbf{q}}{\pi} \frac{\mu^2}{\mathbf{q}^2(\mathbf{q}^2+\mu^2)} \left(1 - \frac{\sin \frac{(\mathbf{k}+\mathbf{q})^2+\chi}{x E^+} L}{\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{x E^+} L}\right)$$
$$\times 2 \frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} \left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} - \frac{\mathbf{k}}{\mathbf{k}^2+\chi}\right),$$

M. D., Phys.Rev.C80:064909,2009 (highlighted in APS physics).

The dynamical energy loss formalism

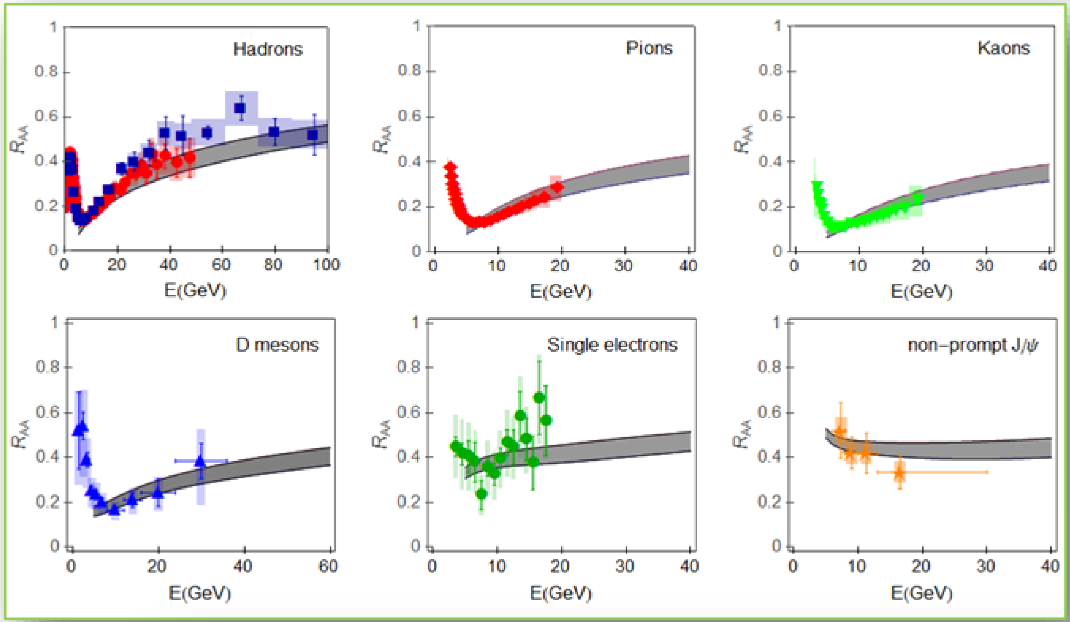
Dynamical energy loss formalism, which has several unique features in the description of high-$p_\perp$ parton medium interactions:

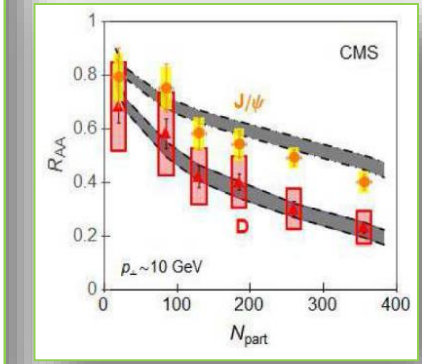
Includes:

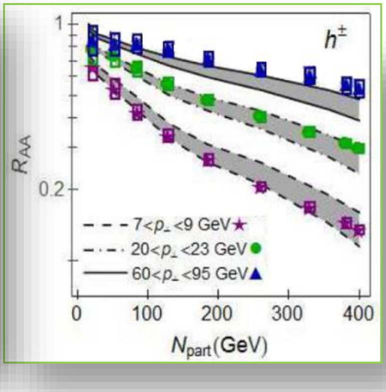
- ***Finite size finite temperature*** **QCD medium of** ***dynamical*** **(moving) partons**
- **Based on finite T field theory and generalized HTL approach**
  M. D., PRC74 (2006), PRC 80 (2009), M. D. and U. Heinz, PRL 101 (2008).
- **Same theoretical framework for both radiative and collisional energy loss**
- ***Applicable to both light and heavy flavor.***
- **Finite magnetic mass effects (M. D. and M. Djordjevic, PLB 709:229 (2012))**
- **Running coupling (M. D. and M. Djordjevic, PLB 734, 286 (2014)).**
- **Relaxed soft-gluon approximation (B. Blagojevic, M. D. and M. Djordjevic, PRC 99, 024901, (2019)). – next talk by Bojana Ilic**

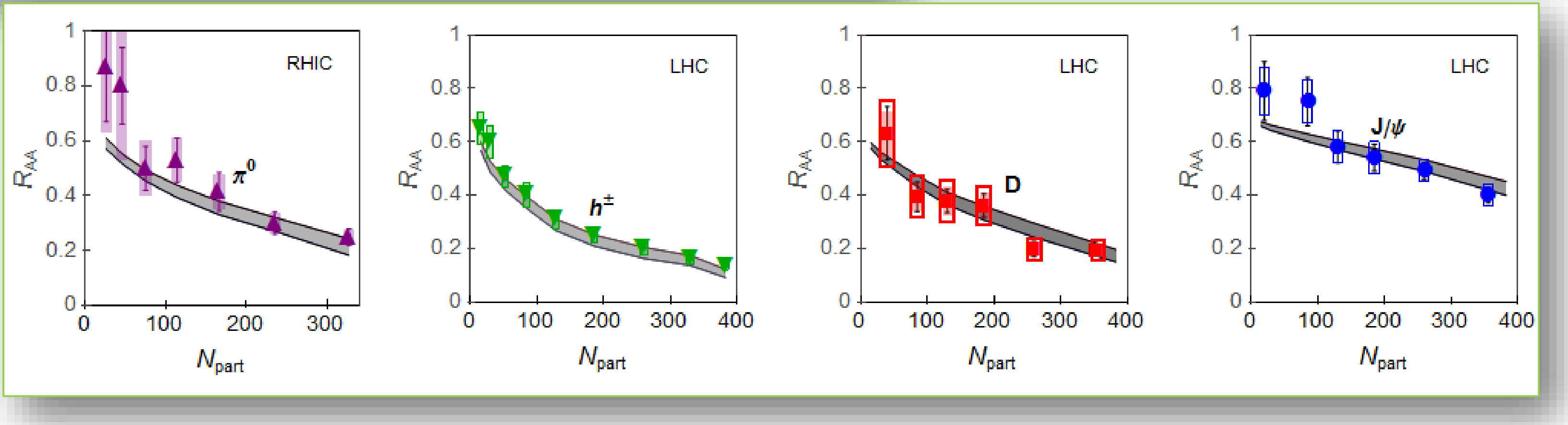
Integrated in a numerical procedure including parton production, fragmentation functions, path-length and multi-gluon fluctuations.

Comparison with experimental data



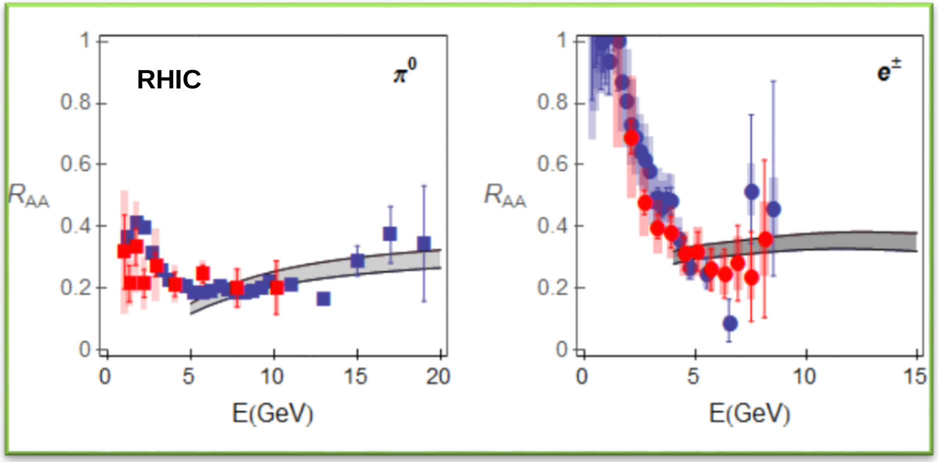


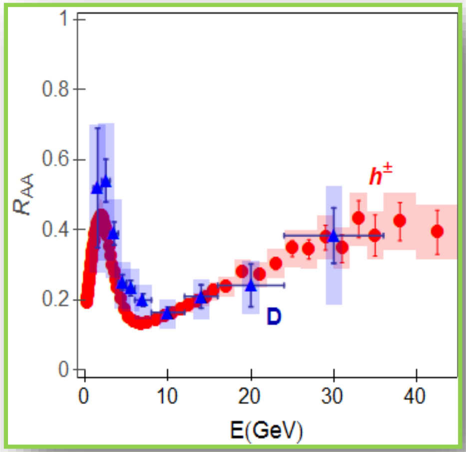


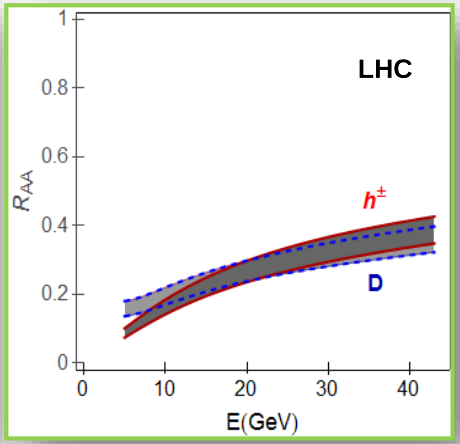


- Explains high pt data for different probes, collision energies, and centralities.
- Agreement obtained by the same model and parameter set, no fitting parameters introduced.

Resolved the longstanding “heavy flavour puzzles at RHIC and LHC”.

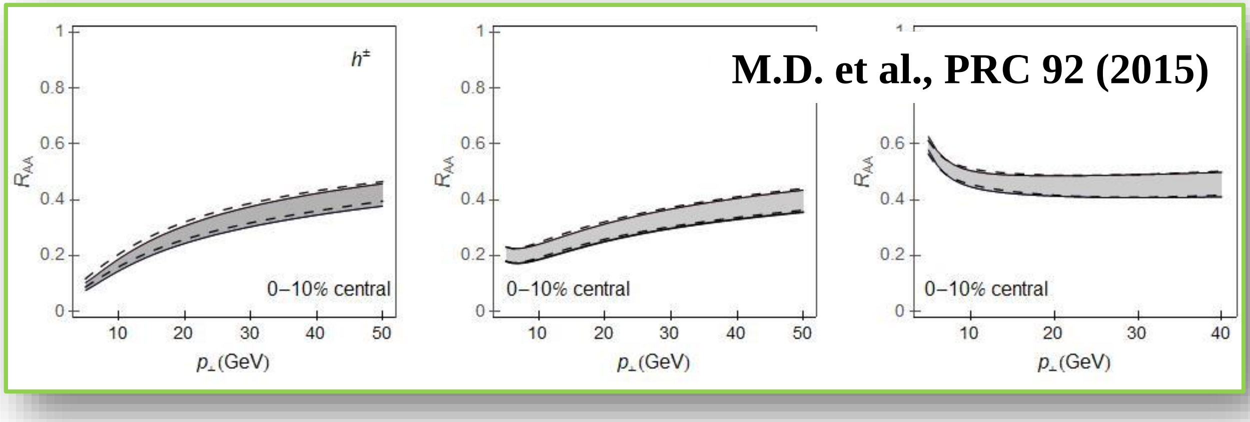




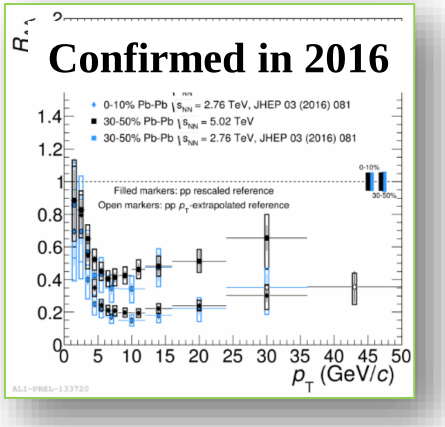


M.D., PRL 112, 042302 (2014)

Clear predictive power!



M.D. et al., PRC 92 (2015)



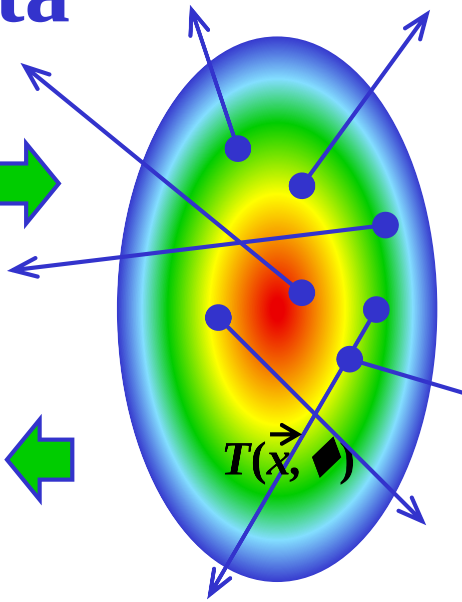
Confirmed in 2016

Obtained comprehensive agreement of predictions with experimental data strongly suggests that the model provides a realistic description of high pt parton-medium interactions.

Next Goal: Inferring bulk QGP properties from high pt theory and data

When high energy particles go through QGP they lose energy

This energy loss is sensitive to QGP properties



Different *bulk* medium parameters lead to different *T*(*x*, ◆)

High *pt* partons can directly probe *T* profiles through energy loss

We can realistically predict this energy loss

High pt probes are powerful tomographic tools

Use them to infer some of bulk QGP properties

To develop the precision QGP tomography tool, we have to

Develop a fully optimized numerical framework, which allows systematic comparison of experimental data and theoretical predictions, obtained by the same formalism, the same parameter set and with no fitting parameters used in model testing.

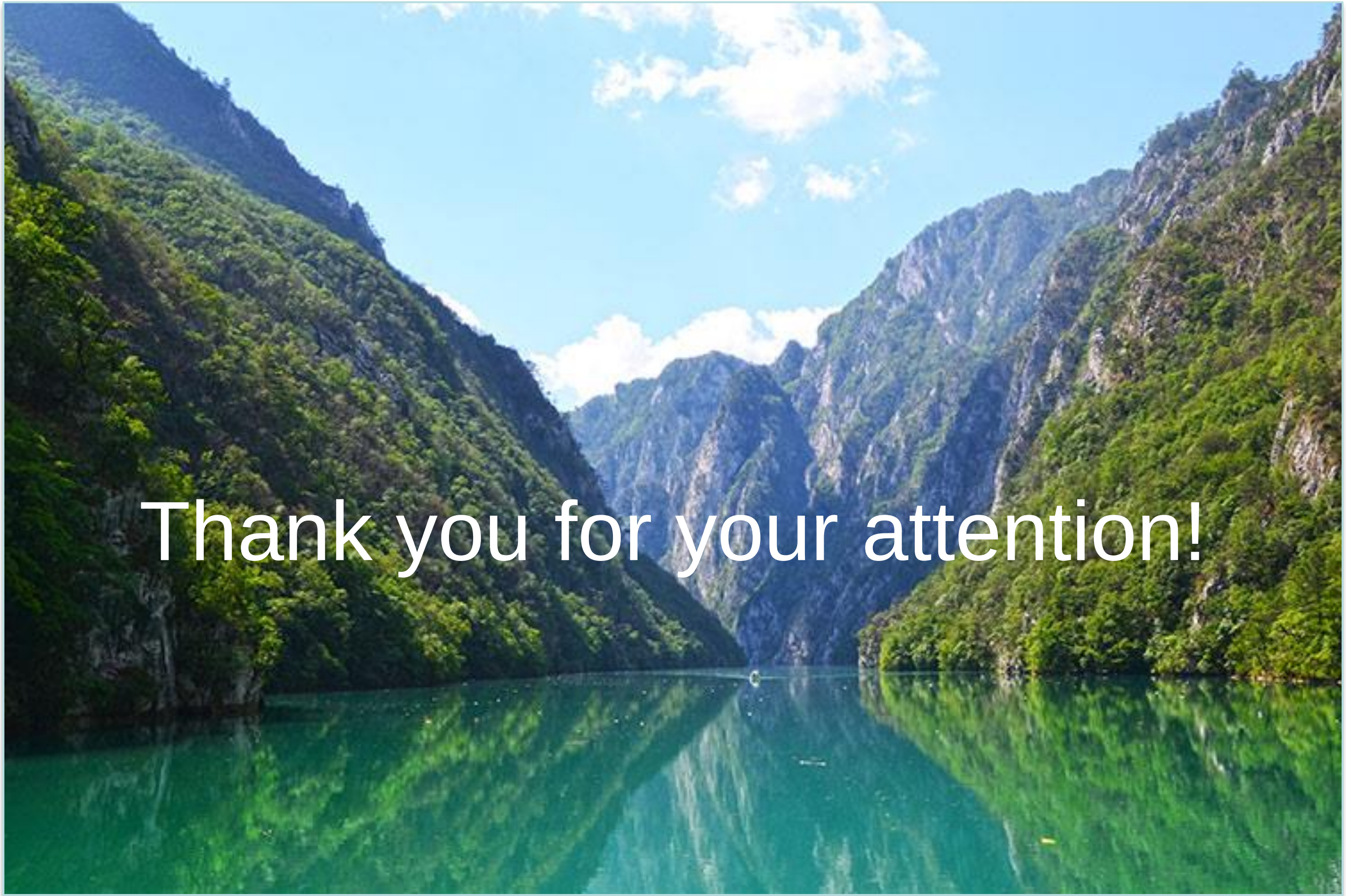
DREENA (Dynamical Radiative and Elastic ENergy loss Approach)

Talk by
Dusan Zigic

First application of DREENA framework and high-pt data to infer the bulk QGP properties:

Propose the observable to directly infer the shape of the QGP droplet from the data.

Talk by
Stefan Stojku



Canyon of river DREENA in Serbia

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