(Improved) Jet Quenching Theory

Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

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arXiv:1103.1074 (JHEP)

arXiv:1109.5619 (PLB)

with, Z. Kang, R. Lashof-Regas, P. Saad, I. Vitev (in progress)

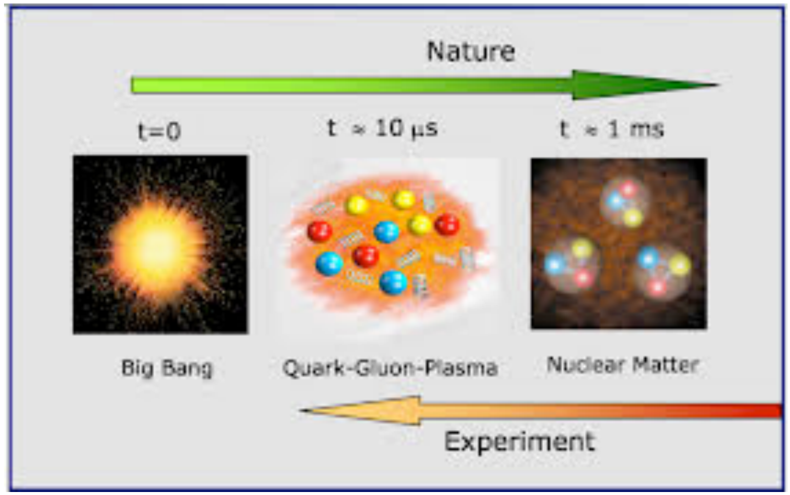
Boston Jet Physics Workshop, January 22, 2014, MIT

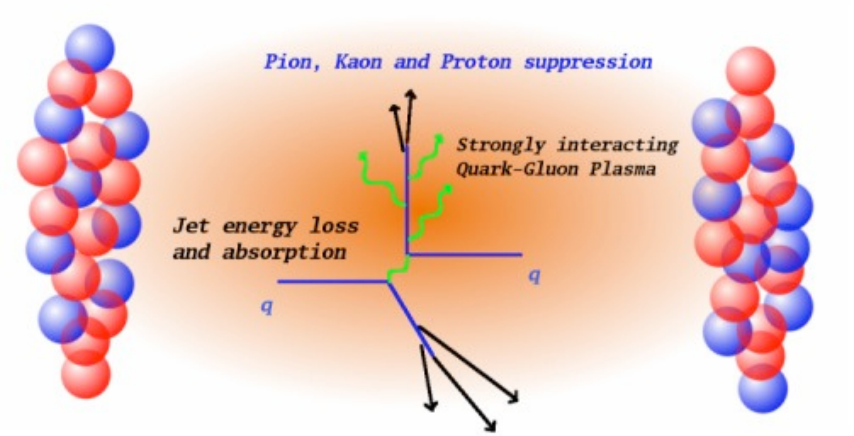
Outline

- Introduction
- Medium-induced splitting functions
- Jet quenching from QCD evolution
- Conclusions

Introduction

Motivation to study heavy ion collisions





- QCD predicts the existence of Quark Gluon Plasma (QGP)
- Recreate in laboratory conditions the matter that was present in the Early Universe, microseconds after the Big Bang

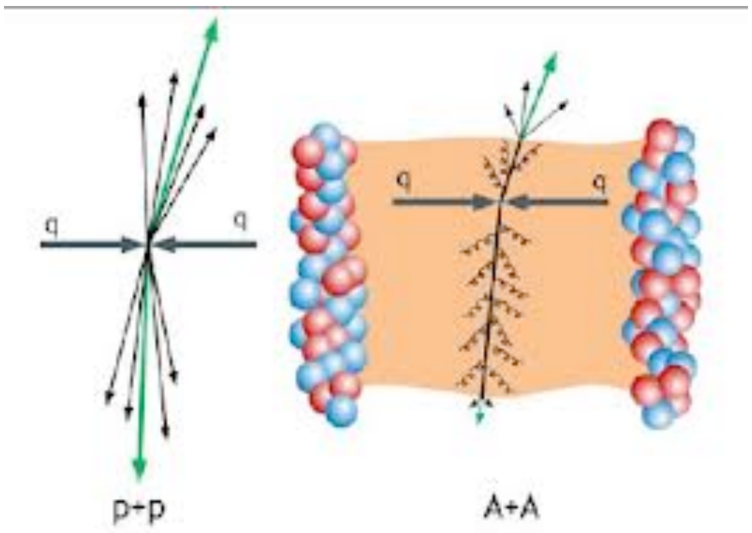
Experimental facilities

RHIC: Au-Au, E_{NN}=20-200 GeV

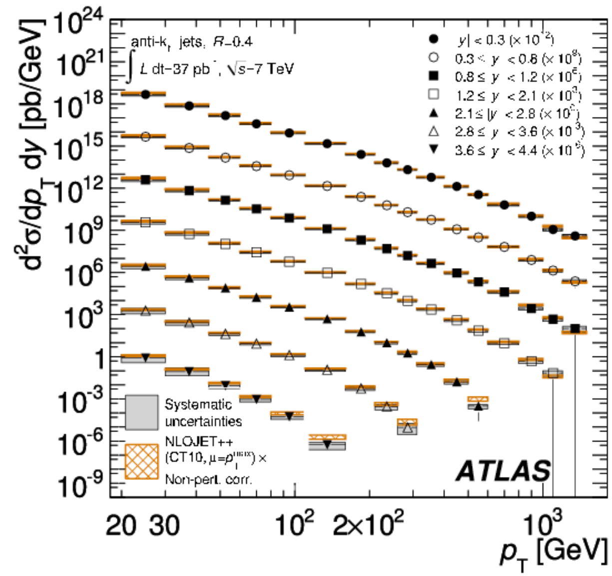
LHC: Pb-Pb, E_{NN}=2.76 TeV

- LHC has confirmed at much higher energies the qualitative features found in RHIC data
- Jet Quenching clearly observed in both experiments

Jet Quenching



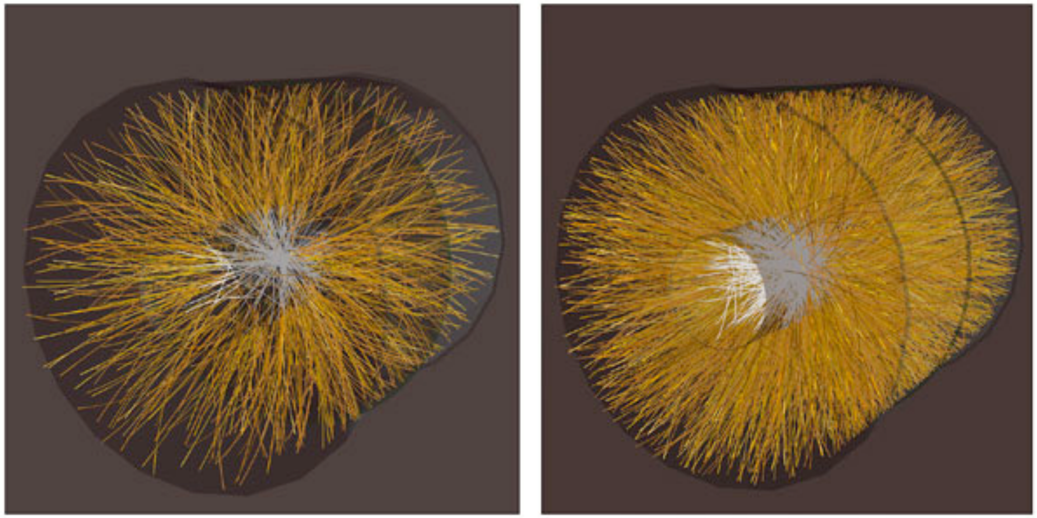
Inclusive production of jets
LHC, 7 TeV



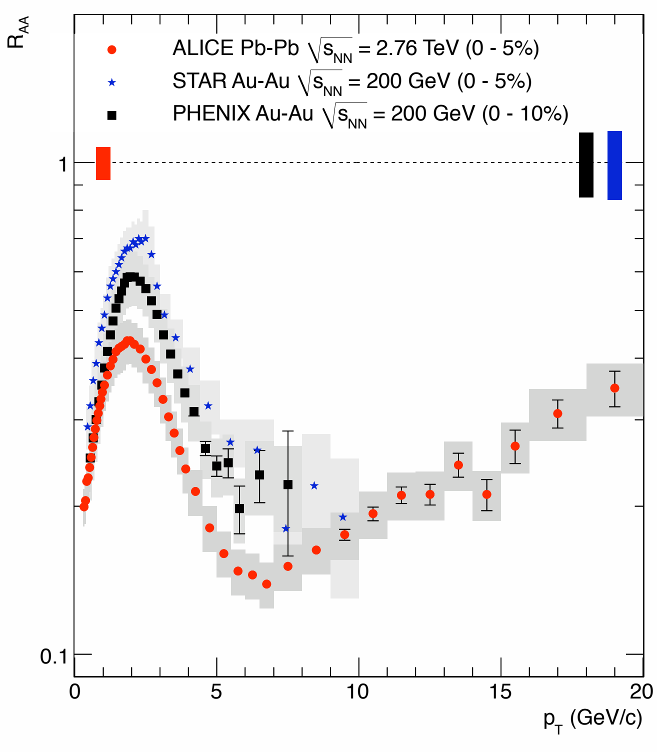
$$R_{AA}(p_T) = \frac{\sigma_{AA}(p_T)}{\langle N_{\rm coll}\rangle \sigma_{pp}(p_T)}$$

Measuring a suppressed nuclear modification factor is observational evidence for jet quenching in heavy ion collisions

Jet Quenching

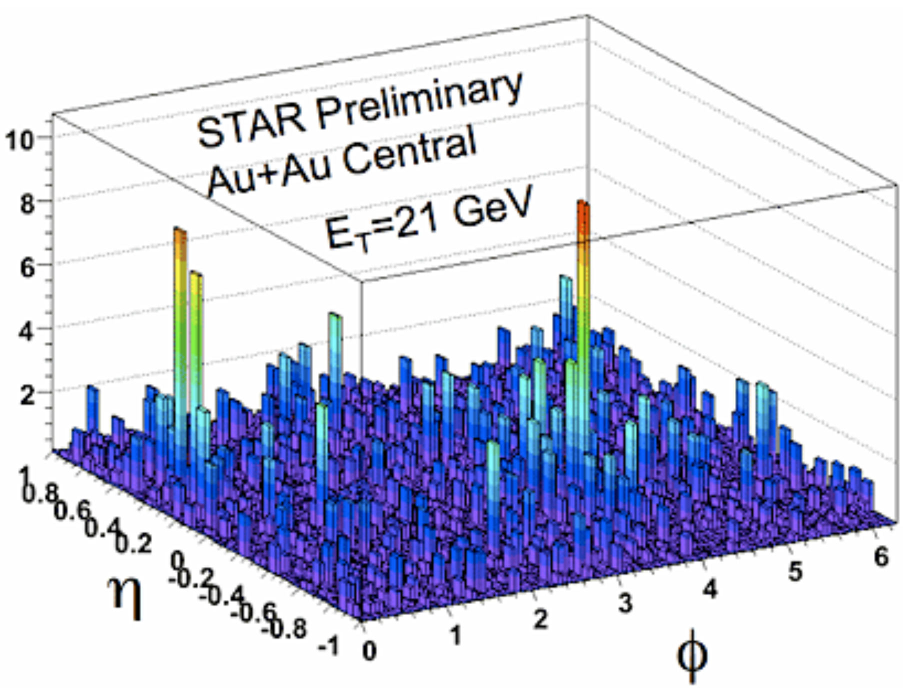


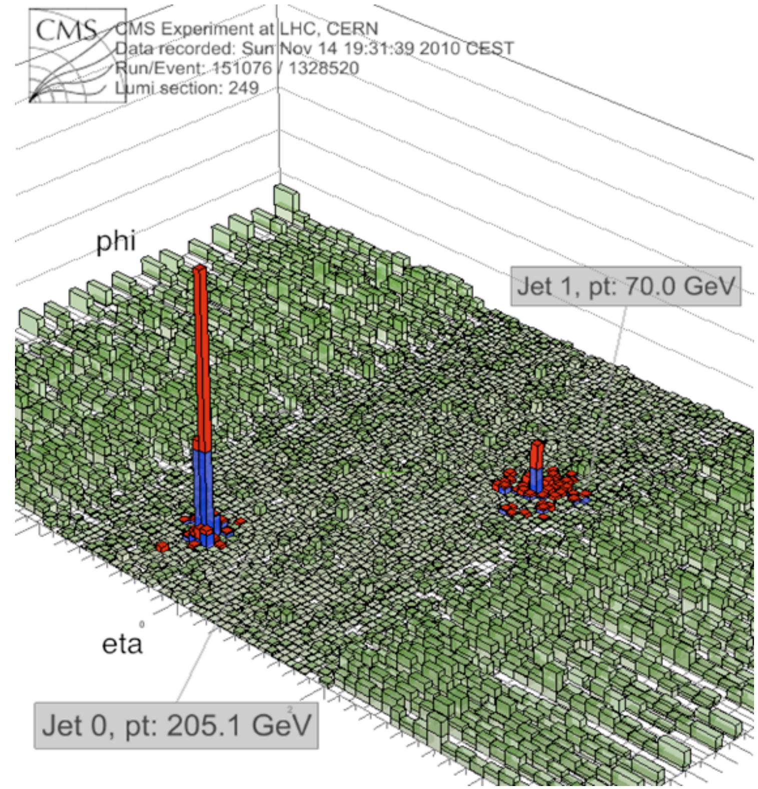
ALICE collaboration, 11-12/2010



Data from RHIC and LHC on R_{AA} both show suppression compared to 1, as a strong indication of final state effects in the medium created in heavy ion collisions

Jets at RHIC vs LHC



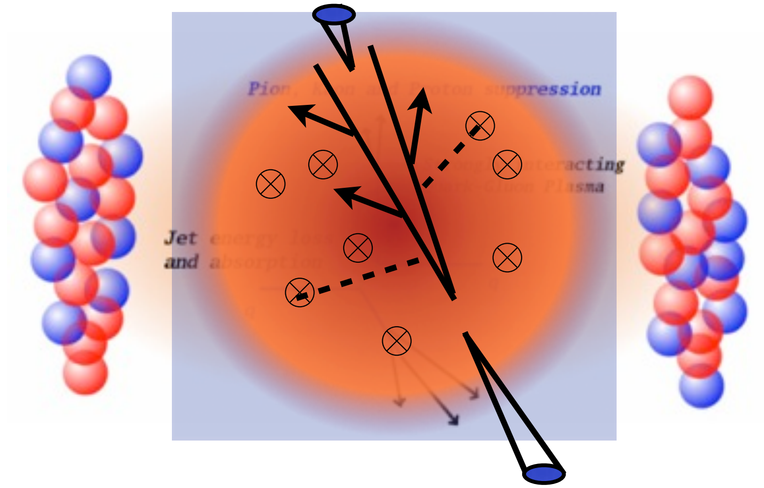


Events at LHC look much more "jetty" than at RHIC even by eye

Gyulassy-Wang model

Gyulassy, Wang, 94

- The medium is modeled with a finite number of scattering centers with static Debye-screened potential



$$H = \sum_{n=1}^{N} H(q; x_n) = 2\pi\delta(q^0)\, v(q) \sum_{n=1}^{N} \mathrm{e}^{iqx_n}\, T^a(R) \otimes T^a(n)$$

$$v(q) = \frac{4\pi\alpha_s}{q_z^2 + \mathbf{q^2} + \mu^2}$$

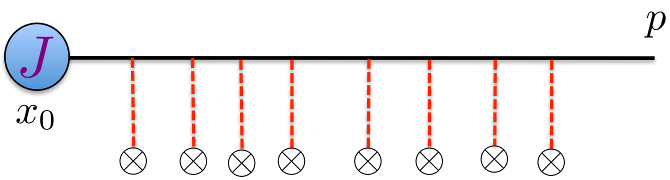
- The momentum scaling of the exchange gluon is that of the Glauber gluon: $q(\lambda^2, \lambda^2, \lambda)$

Gyulassy-Levai-Vitev reaction operator

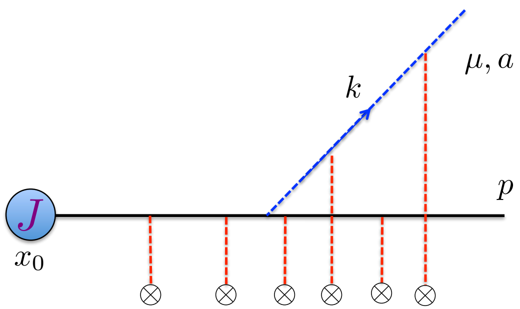
Gyulassy, Levai, Vitev, 00

$$\hat{R}_n = \hat{D}_n^\dagger \hat{D}_n + \hat{V}_n + \hat{V}_n^\dagger$$

Jet broadening



Radiative energy loss



Other applications:
meson dissociation, electromagnetic energy loss

- Using GLV approach both R_{AA} and di-hadron(jet) imbalance have been successfully predicted

Energy loss approach, valid in the limit x << 1

Medium-induced splitting functions

GO, I. Vitev

arXiv:1103.1074 (JHEP)

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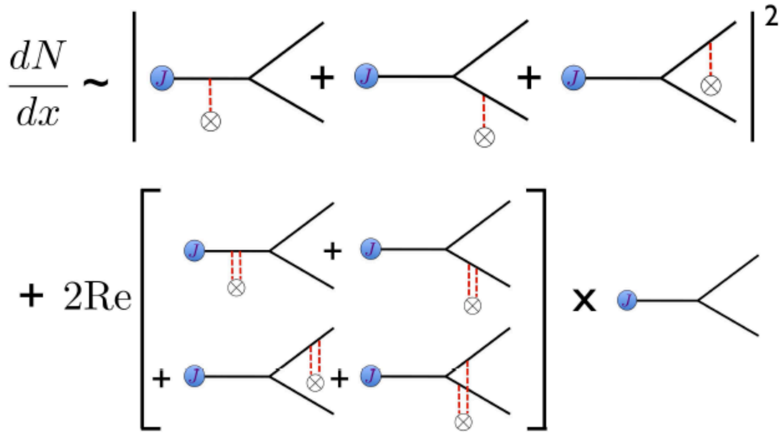
SCET$_G$

GO, Vitev, 2011

Soft Collinear Effective Theory with Glauber Gluons

$$\mathcal{L}_{\mathrm{G}}\left(\xi_n, A_n, \eta\right) = \sum_{p,p',q} \mathrm{e}^{-i(p-p'+q)x} \left(\bar{\xi}_{n,p'} \Gamma^{\mu,a}_{\mathrm{qqA_G}} \frac{\bar{\not{n}}}{2} \xi_{n,p} - i \Gamma^{\mu\nu\lambda,abc}_{\mathrm{ggA_G}} \left(A^c_{n,p'}\right)_\lambda \left(A^b_{n,p}\right)_\nu \right) \bar{\eta}\, \Gamma^{\delta,a}_{\mathrm{s}}\, \eta\, \Delta_{\mu\delta}(q)$$



- Glauber gluons are needed to describe t-channel exchanges between jets and medium quasi-particles
- Emission of collinear particles is described by SCET Lagrangian
- Allows for calculations beyond the small x limit

Results

GO, Vitev, 2011

	R_ξ	A^+	Hyb.
W^+	✔	✖	✖
T_n	✖	✔	✖

Gauge invariance explicitly demonstrated

Factorization of the medium-induced splitting from the production proved

All four medium-induced splittings calculated beyond small x approximation

$$\left(\frac{dN}{dx d^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp} \left[-\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)^2 + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\right) \right.$$
$$\times (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z])$$
$$+\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z]) + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\right)\cos[\Omega_4\Delta z]$$
$$\left. +\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\cos[\Omega_5\Delta z] + \frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) \right].$$

$$\left(\frac{dN}{dx d^2\boldsymbol{k}_\perp}\right)_{\left\{\begin{array}{c} g\to q\bar{q} \\ g\to gg \end{array}\right\}} = \left\{\begin{array}{c} \frac{\alpha_s}{2\pi^2} T_R\left(x^2+(1-x)^2\right) \\ \frac{\alpha_s}{2\pi^2} 2C_A\left(\frac{x}{1-x} + \frac{1-x}{x} + x(1-x)\right) \end{array}\right\} \int d\Delta z \left\{\begin{array}{c} \frac{1}{\lambda_q(z)} \\ \frac{1}{\lambda_g(z)} \end{array}\right\} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp}$$
$$\times\left[2\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + 2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\left(\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) \right.$$
$$+\left\{\begin{array}{c} \frac{1}{N_c^2-1} \\ -\frac{1}{2} \end{array}\right\}\left(2\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\right) + 2\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\right)\cos[(\Omega_1-\Omega_2)\Delta z]\right.$$
$$+2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\cos[(\Omega_1-\Omega_3)\Delta z] + 2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cos[(\Omega_2-\Omega_3)\Delta z]$$
$$\left.\left. -2\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\right)\cos[\Omega_4\Delta z] - 2\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\cos[\Omega_5\Delta z]\right)\right].$$

Jet Quenching from QCD evolution

with, Z. Kang, R. Lashof-Regas, P. Saad, I. Vitev (in progress)

Jet quenching from evolution

$$R_{AA}(p_T) = \frac{H(\mu, p_T) \otimes f(\mu) \otimes f(\mu) \otimes D^{\rm med}(\mu)}{H(\mu, p_T) \otimes f(\mu) \otimes f(\mu) \otimes D(\mu)}$$

p_T —— H

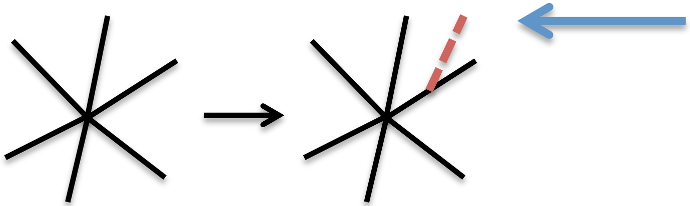
$\Lambda_{\rm QCD}$ —— f, D

The simplest choice is:

$$\mu = p_T$$

- With this scale choice the Hard function need not be evolved. The PDF's and the Fragmentation function need to be evolved from low to high scale
- Because medium-induced splitting is a final state effect, PDF's need to be evolved with vacuum (Altarelli-Parisi) splitting functions
- The Fragmentation function needs to be evolved with medium-induced splitting function
- Can we predict R_{AA} suppression from QCD evolution?
- This method will allow to include consistently inclusion of finite x corrections

Collinear splitting functions



$\mathrm{d}\sigma_n \qquad \mathrm{d}\sigma_{n+1}$

$$q \to gq$$
$$g \to gg$$
$$g \to q\bar{q}$$

DGLAP
Gribov, Lipatov, 1972
Altarelli, Parisi, 1977
Dokshitzer, 1977

$$|\mathcal{M}_{a_1,a_2,\ldots}(p_1,p_2,\ldots)|^2 \simeq \frac{2}{s_{12}}\, 4\pi\mu^{2\epsilon}\alpha_{\mathrm{S}}\, \mathcal{T}^{ss'}_{a,\ldots}(p,\ldots)\, \hat{P}^{ss'}_{a_1a_2}(z,k_\perp;\epsilon)$$

- The collinear splitting functions are process independent
- The virtual contribution is extracted from momentum and flavor conservation sum rules

$$\langle \hat{P}_{gg}(z;\epsilon)\rangle \;=\; 2C_A\, \left[\frac{z}{1-z} + \frac{1-z}{z} + z(1-z)\right]$$

Evolution equations

The form of the evolution equations is same as the traditional Altareli-Parisi evolution equations:

$$\frac{\mathrm{d}f_q(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)f_q\left(\frac{z}{z'},Q\right)+P_{g\to q\bar{q}}(z',Q)f_g\left(\frac{z}{z'},Q\right)\right\},$$

$$\frac{\mathrm{d}f_{\bar{q}}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)f_{\bar{q}}\left(\frac{z}{z'},Q\right)+P_{g\to q\bar{q}}(z',Q)f_g\left(\frac{z}{z'},Q\right)\right\},$$

$$\frac{\mathrm{d}f_g(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{g\to gg}(z',Q)f_g\left(\frac{z}{z'},Q\right)\right.$$
$$\left.+P_{q\to gq}(z',Q)\left(f_q\left(\frac{z}{z'},Q\right)+f_{\bar{q}}\left(\frac{z}{z'},Q\right)\right)\right\}.$$

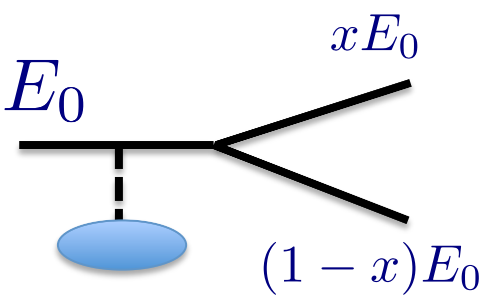
$P=P_{vac}+P_{med}$

Real emission calculated in GO, Vitev, 2011

For the Fragmentation function we need to include in addition to vacuum evolution, the medium-induced splitting terms.

Similarly to the vacuum case the virtual pieces we determine from the momentum and flavor sum rules

Small x limit of splitting functions



$$P_{q\to qg} = \frac{2C_F}{x_+} + \left(\frac{2C_F}{x} g[x,Q,L,\mu]\right)_+ ,$$

$$P_{g\to gg} = \frac{2C_A}{x_+} + \left(\frac{2C_A}{x} g[x,Q,L,\mu]\right)_+ ,$$

$$P_{g\to q\bar{q}} = 0,$$

$$P_{q\to gq} = 0,$$

$$g[x,Q,L,\mu] = \int \frac{\mathrm{d}\Delta z}{\lambda_g(\Delta z)} \mathrm{d}^2\boldsymbol{q}_\perp \frac{1}{\sigma_{\rm el}} \frac{\mathrm{d}\sigma_{\rm el}^{\rm medium}}{\mathrm{d}^2\boldsymbol{q}_\perp} \frac{2\,\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp}{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2}\left[1-\cos\frac{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2}{xp_0^+}\Delta z\right]$$

- In the small x limit only two splittings survive
- From flavor and momentum sum rules we get that the splitting is given by a plus function
- Keeping finite x corrections one needs to keep all four splittings. Delta function pieces do not vanish.

Evolution in the small x limit

- Expand the convolution integral around z'=1
- Assume fixed steepness n(z)
- Solve RG equations exactly
- Steepness of PDF's forces the z to be a function of p_T

$$\frac{\mathrm{d}D(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'} P(z',Q)\left(\frac{1}{z'}D(z/z',Q) - D(z,Q)\right)$$
$$\approx \frac{\alpha_s}{\pi}\left(1 + z\frac{\partial}{\partial z}\right) D(z,Q)\int_z^1 \mathrm{d}z'\,(1-z')\,P(z',Q).$$

$$D(z,Q) = \mathrm{e}^{-(n(z)-1)\left\langle\frac{\Delta E}{E}\right\rangle_z} D(z,Q_0).$$

$$n(z) = -\frac{\mathrm{d}\ln D(z)}{\mathrm{d}\ln z}$$

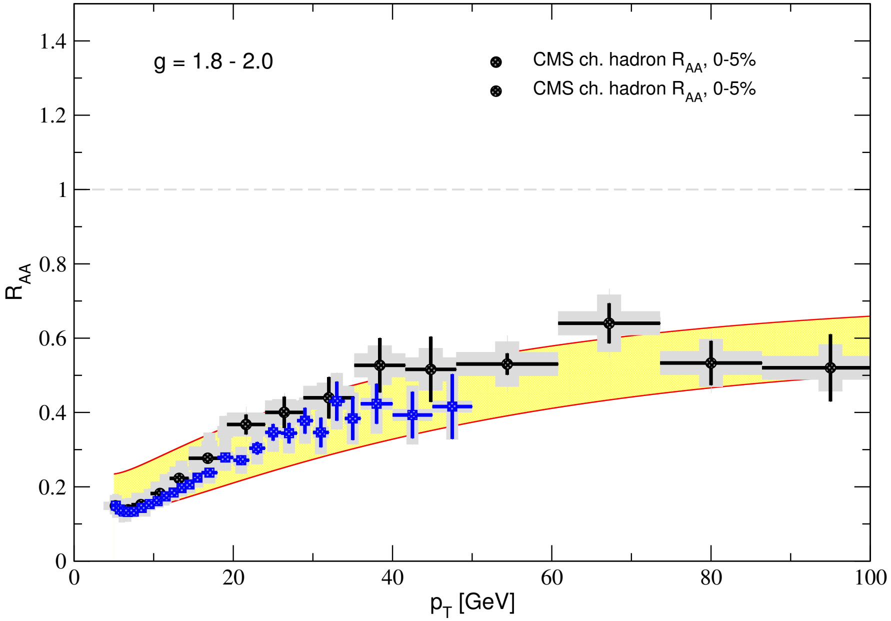
Approximate analytical prediction for nuclear modification factor:

$$R_{AA}(p_T) \approx \mathrm{e}^{-n_{\mathrm{eff}}(p_T)\left\langle\frac{\Delta E}{E}\right\rangle},$$

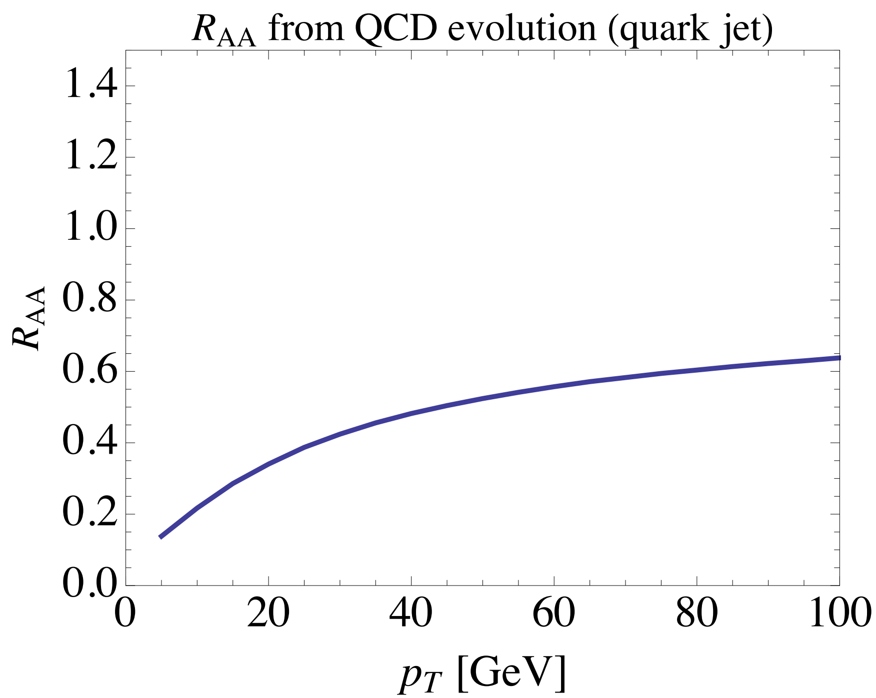
$$n_{\mathrm{eff}}(p_T) = (n(z)-1)\frac{\left\langle\frac{\Delta E}{E}\right\rangle_z}{\left\langle\frac{\Delta E}{E}\right\rangle},$$

Preliminary results

Energy loss approach:



QCD evolution (n_{eff}=4):



- Preliminary results show that QCD evolution gives the correct shape for the nuclear modification factor
- In reality n_{eff} is by itself a function of p_T. Needs to be checked how the shape is affected
- Straightforward to include finite x corrections. Work in progress. Stay tuned.

Conclusions

- We derived the virtual pieces of medium-induced splitting functions from sum rules
- First results on R_{AA} suppression from QCD evolution are promising
- This new method allows consistent inclusion of finite x corrections for the jet quenching phenomenology
- Putting jet quenching phenomenology on more solid theoretical grounds