Jet quenching beyond the energy loss approach

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

Grigory Ovanesyan

with I. Vitev

arXiv:1103.1074 (JHEP)
arXiv:1109.5619 (PLB)

with Z. Kang, R. Lashof-Regas, P. Saad, I. Vitev arXiv:1405.2612

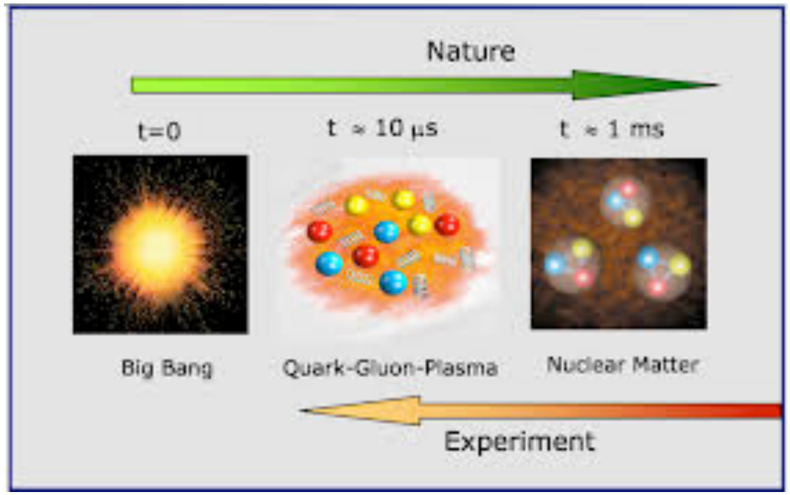
QCD Evolution Workshop, Santa Fe, NM, 2014

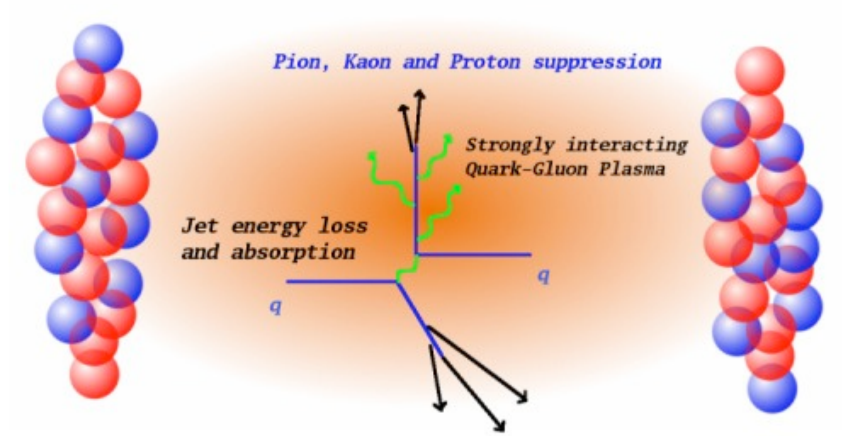
Outline

- 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

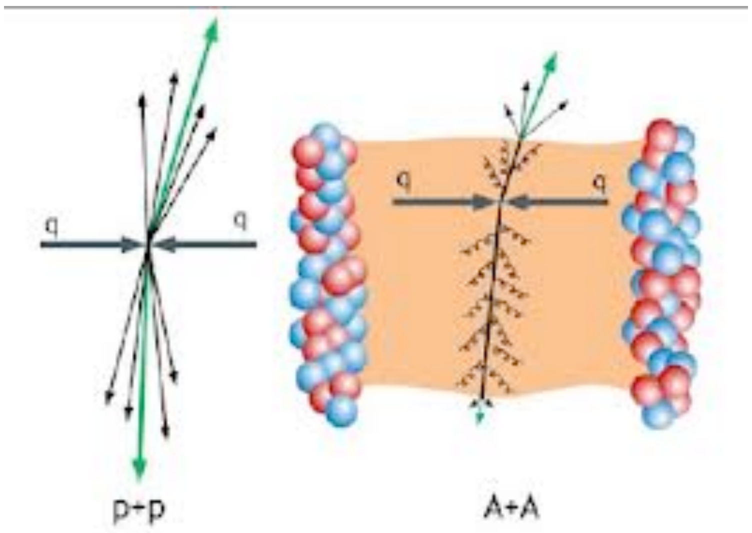
Experimental facilities

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

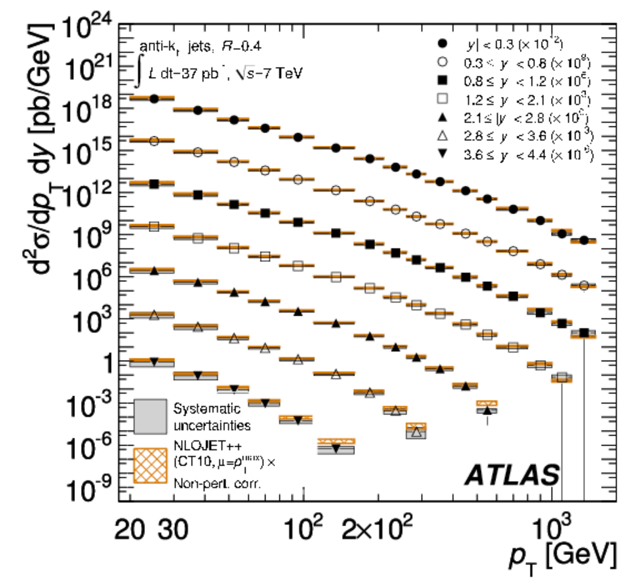
LHC: Pb-Pb, E_{NN}=2.76 TeV

- 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

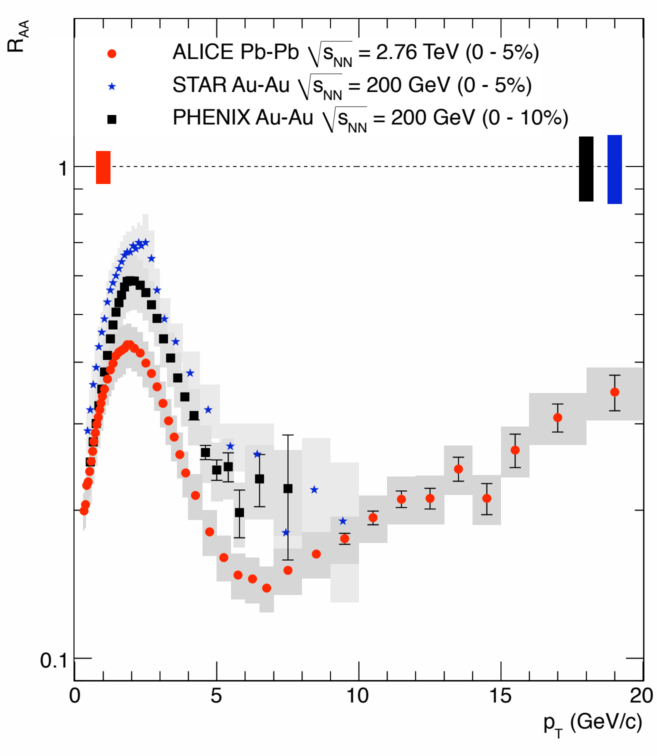


$$R_{AA}(p_T) = \frac{\sigma_{AA}(p_T)}{\langle N_{\rm coll}\rangle \sigma_{pp}(p_T)}$$

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

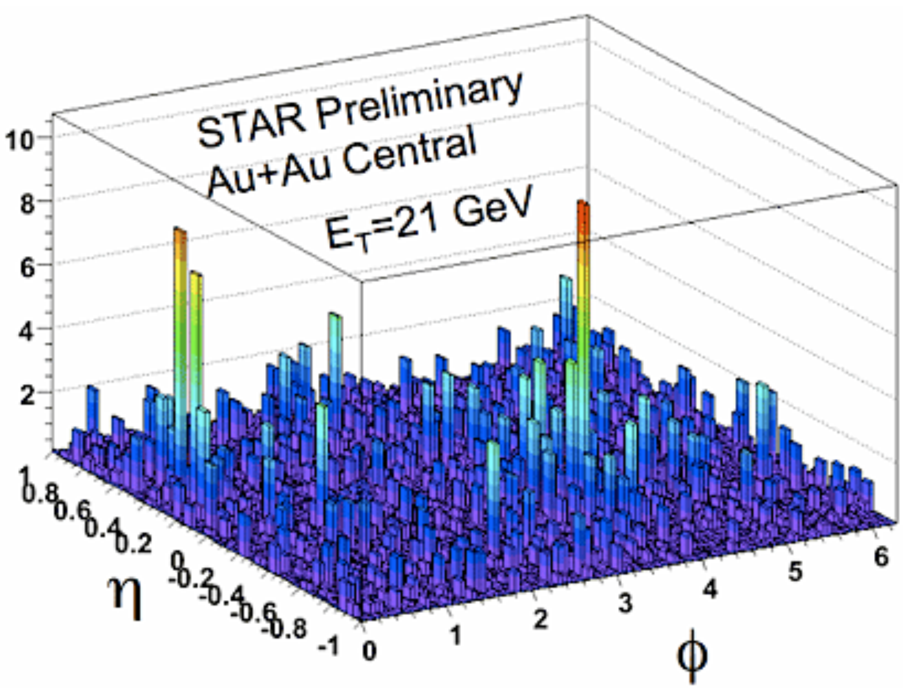
Jet Quenching

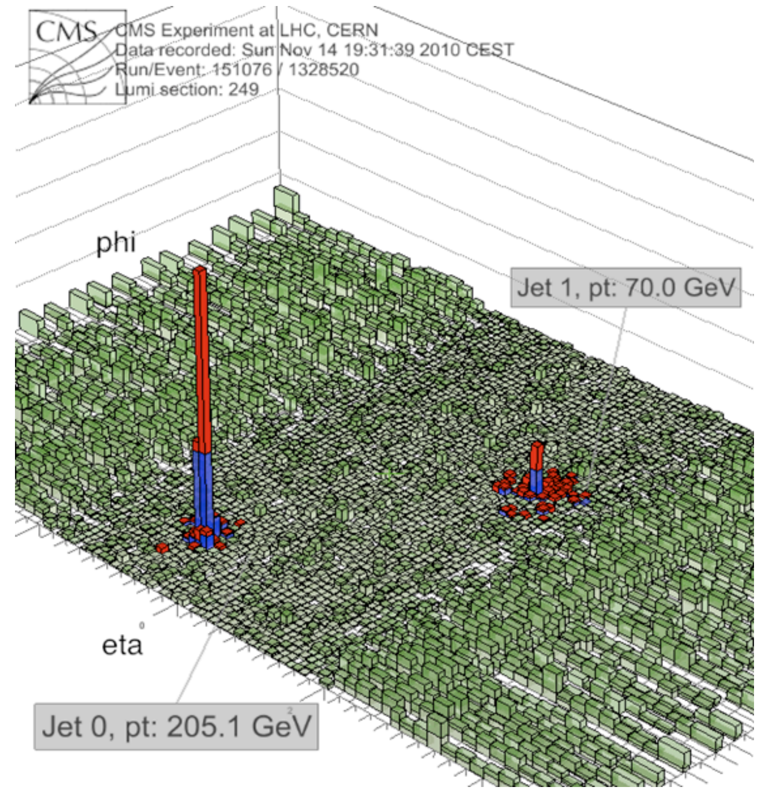
ALICE collaboration, 11-12/2010



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



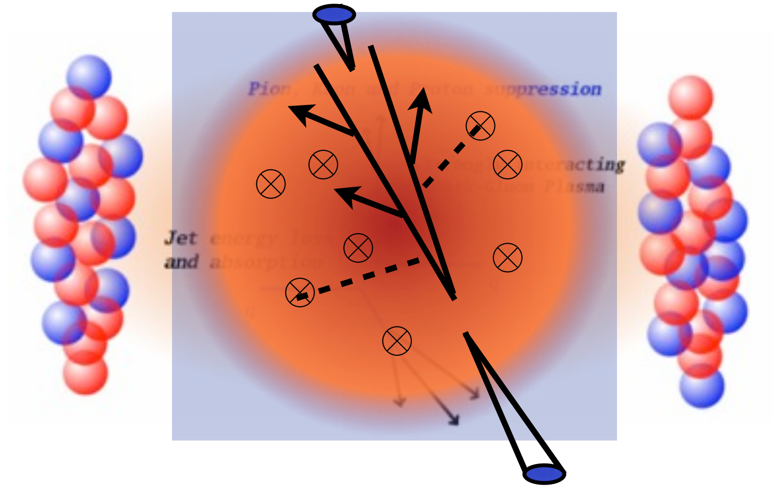


Events at LHC look much more “jetty” than at RHIC even by eye

Gyulassy-Wang model

Gyulassy, Wang, 94

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



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

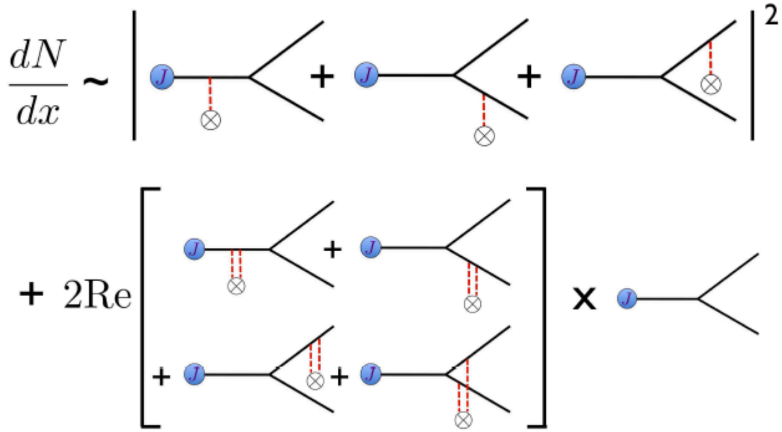
$$v(q) = \frac{4\pi\alpha_s}{q_z^2 + \mathbf{q^2} + \mu^2}$$

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

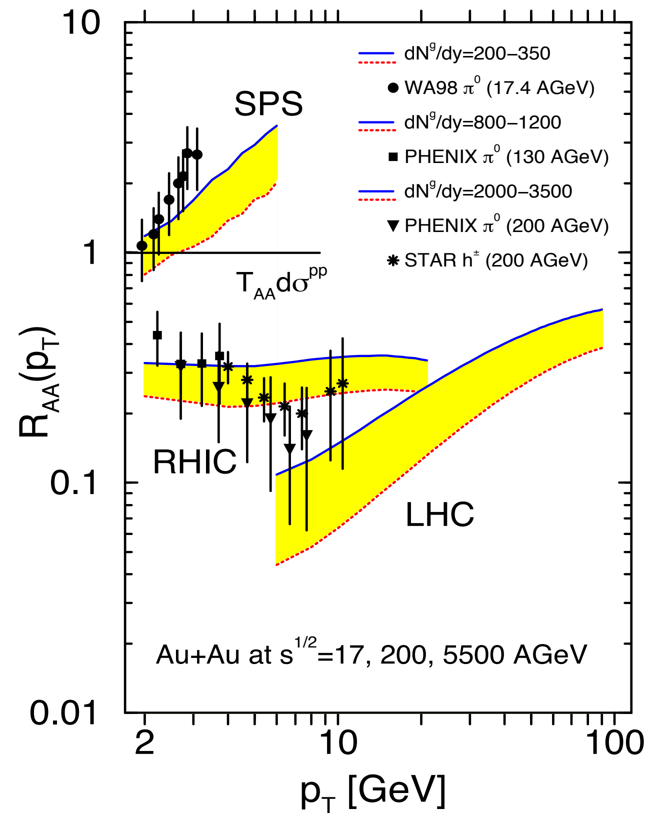
Energy loss approach

GLV approach

$x = Q^+/p^+$



Gyulassy, Levai, Vitev 2002



$$x\frac{dN^g}{dx\,d^2\boldsymbol{k}_\perp}\bigg|_{x\ll 1} = C_F\frac{\alpha_s}{\pi^2}\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{g\ \mathrm{medium}}}{d^2\mathbf{q}_\perp}\left(-2\boldsymbol{B}_1\cdot\boldsymbol{C}_1\right)\left(1-\cos(\omega_1\Delta z)\right)$$

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

Medium-induced splitting functions

GO, I. Vitev

arXiv:1103.1074 (JHEP)

arXiv:1109.5619 (PLB)

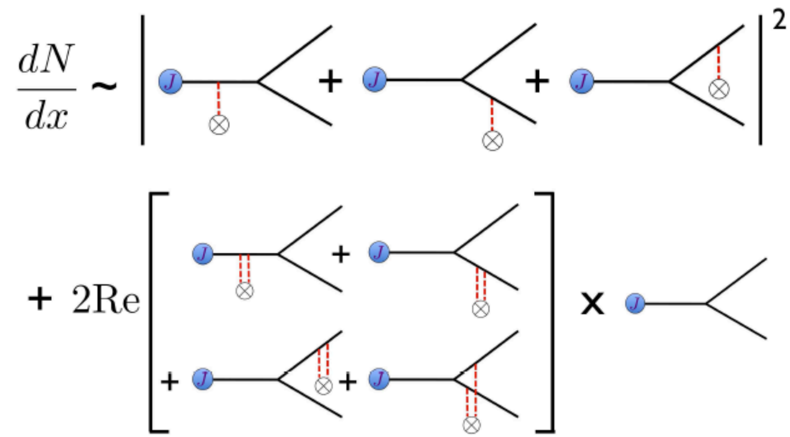
Soft Collinear Effective Theory with Glauber Gluons

Idilbi, Majumder, 2008

GO, Vitev, 2011

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

- 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	✖	✔	✖

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

Gauge invariance explicitly demonstrated

Factorization of the medium-induced splitting from the production proved

All four medium-induced splittings calculated beyond small x approximation

$$\begin{aligned}\left(\frac{dN}{dx\,d^2\boldsymbol{k}_\perp}\right)_{\left\{\begin{smallmatrix} g\to q\bar{q}\\ g\to gg\end{smallmatrix}\right\}} &= \left\{\begin{matrix}\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{matrix}\right\}\int d\Delta z\left\{\begin{matrix}\frac{1}{\lambda_q(z)}\\ \frac{1}{\lambda_g(z)}\end{matrix}\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{matrix}\frac{1}{N_c^2-1}\\ -\frac{1}{2}\end{matrix}\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].\end{aligned}$$

Small x approximation

GO, Vitev, 2011

$$\begin{pmatrix} x\frac{dN_{q\to qg}}{dx} \\ x\frac{dN_{g\to gg}}{dx} \\ x\frac{dN_{g\to q\bar{q}}}{dx} \\ x\frac{dN_{q\to gq}}{dx} \end{pmatrix}_{\mathrm{SCET_G}} \overset{x \to 0}{\approx} \begin{pmatrix} C_F \\ C_A \\ 0 \\ 0 \end{pmatrix} \frac{\alpha_s}{\pi^2}\int d\Delta z \frac{1}{\lambda_g(z)}\int d^2\mathbf{k}_\perp d^2\mathbf{q}_\perp \frac{1}{\sigma_{\mathrm{el}}}\frac{d\sigma_{\mathrm{el}}^{\mathrm{med}}}{d^2\mathbf{q}_\perp}\frac{2\mathbf{k}_\perp\cdot\mathbf{q}_\perp}{\mathbf{k}_\perp^2(\mathbf{k}_\perp-\mathbf{q}_\perp)^2}\left(1-\cos\frac{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2}{xp_0^+}\Delta z\right)$$

Gyulassy, Levai, Vitev 2002

In small x approximation the SCET$_G$ splitting kernels reproduce the GLV splitting functions calculated in pQCD

The next logical step is to understand the phenomenological applications of full x corrections

What to do with these splitting functions ?

- Turns out that these splitting functions cannot be inserted into the traditional energy loss calculations because of flavor changing splittings $g \rightarrow q\bar{q}$; $q \rightarrow gq$
- Thus, need a new framework beyond energy loss approach to incorporate the finite x corrections

Jet Quenching from QCD evolution

with, Z. Kang, R. Lashof-Regas, P. Saad, I. Vitev (arXiv:1405.2612)

Jet quenching from evolution

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

p_T H

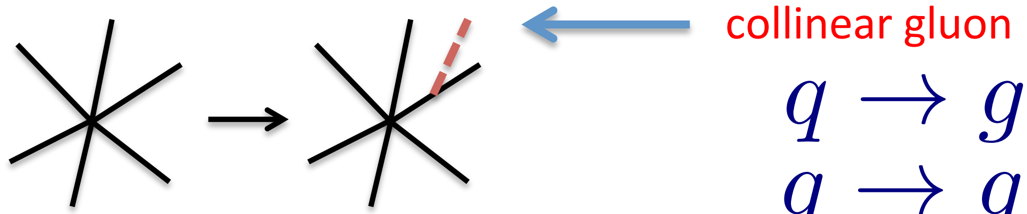
Λ_{QCD} f, D

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:

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

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

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

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

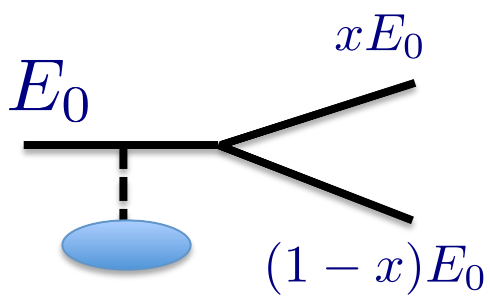
Real emission calculated in GO, Vitev, 2011 using SCET_G

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

Kang, Lashof-Regas, GO, Saad, Vitev, 2014



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

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

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

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

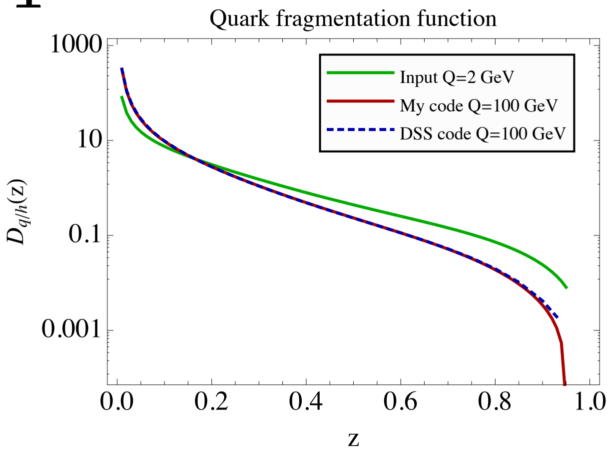
$$g[x,Q,L,\mu] = \int \frac{\mathrm{d}\Delta z}{\lambda_g(\Delta z)} \mathrm{d}^2\boldsymbol{q}_\perp \frac{1}{\sigma_{\mathrm{el}}} \frac{\mathrm{d}\sigma_{\mathrm{el}}^{\mathrm{medium}}}{\mathrm{d}^2\boldsymbol{q}_\perp} \frac{2\,\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp}{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2}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

- 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

Kang, Lashof-Regas, GO, Saad, Vitev, 2014

- Expand the convolution integral around z'=1
- Assume fixed steepness n(z)
- Solve DGLAP equations exactly



$$\frac{\mathrm{d}D(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\,[P(z',Q)]_+\, D\left(\frac{z}{z'},Q\right)$$

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

$$\left\langle \frac{\Delta E}{E}\right\rangle_z = \int_0^{1-z}\mathrm{d}x\, x\,\frac{\mathrm{d}N}{\mathrm{d}x}(x) \xrightarrow{z\to 0} \left\langle \frac{\Delta E}{E}\right\rangle ,$$

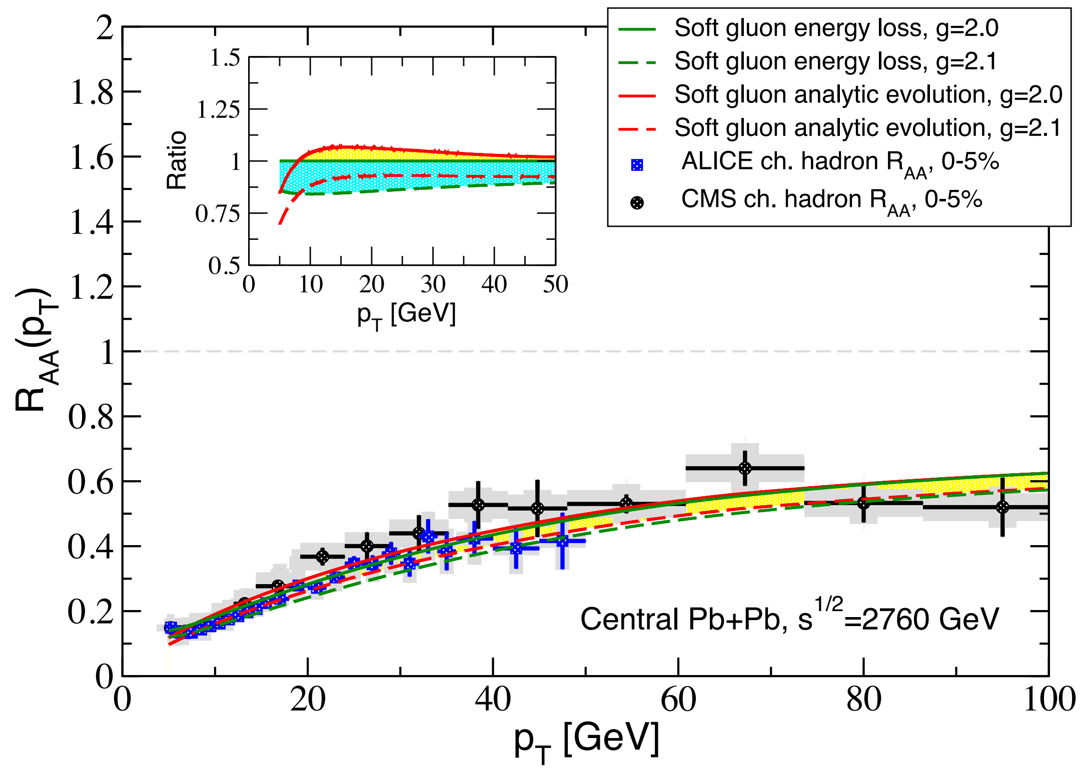
$$\langle N_g\rangle_z = \int_{1-z}^1 \mathrm{d}x\,\frac{\mathrm{d}N}{\mathrm{d}x}(x) \xrightarrow{z\to 1} \langle N_g\rangle ,$$

$$n(z) = -\frac{\mathrm{d}\ln D(z,Q)^{\mathrm{vac}}}{\mathrm{d}\ln z}$$

Comparison I: Energy loss vs Evolution

Kang, Lashof-Regas, GO, Saad, Vitev, 2014

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



- QCD evolution in the small x evolution agrees almost perfectly with energy loss approach (differences at any value of the p_T can be absorbed within 2% change in the jet-medium coupling g)

Virtual pieces

Kang, Lashof-Regas, GO, Saad, Vitev, 2014

GO, Vitev, 2011

$$P_i^{\rm real}(x,\boldsymbol{Q}_\perp;\alpha) = \frac{2\pi^2}{\alpha_s}\,\boldsymbol{Q}_\perp^2\,\frac{{\rm d}N_i(x,\boldsymbol{Q}_\perp;\alpha)}{{\rm d}x\,{\rm d}^2\boldsymbol{Q}_\perp} = P_i^{\rm vac}(x)\,g_i(x,\boldsymbol{Q}_\perp;\alpha)\,.$$

$$P_{q\to qg}(x) = \left[P^{\rm real}_{q\to qg}(x)\right]_+ + A\,\delta(x), \qquad (36)$$

$$P_{g\to gg}(x) = 2C_A\left(\left[\left(\frac{1-2x}{x} + x(1-x)\right) g_2\left(x,\boldsymbol{k}_\perp,L,\mu\right)\right]_+ + \frac{g_2\left(x,\boldsymbol{k}_\perp,L,\mu\right)}{1-x}\right) + B\,\delta(x),$$

$$P_{g\to q\bar q}(x) = P^{\rm real}_{g\to q\bar q}(x), \qquad (37)$$

$$P_{q\to gq}(x) = P^{\rm real}_{q\to gq}(x). \qquad (38)$$

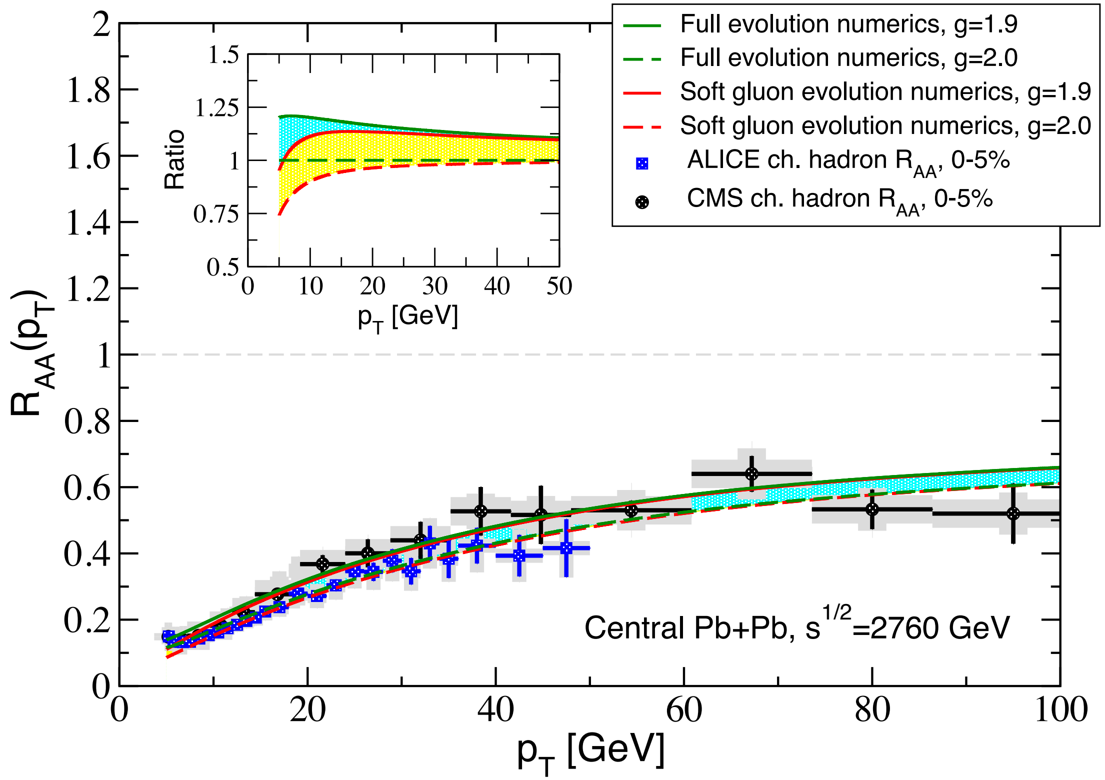
$$A = 0 \qquad (39)$$

$$B = \int {\rm d}x' \left\{2C_A\left(x'\left(\frac{1-2x'}{x'} + x'(1-x')\right) - 1\right) g_2\left(x',\boldsymbol{k}_\perp,L,\mu\right) - 2n_f(1-x')P_{g\to q\bar q}(x')\right\}. \qquad (40)$$

Comparison II: Evolution (full x vs small x)

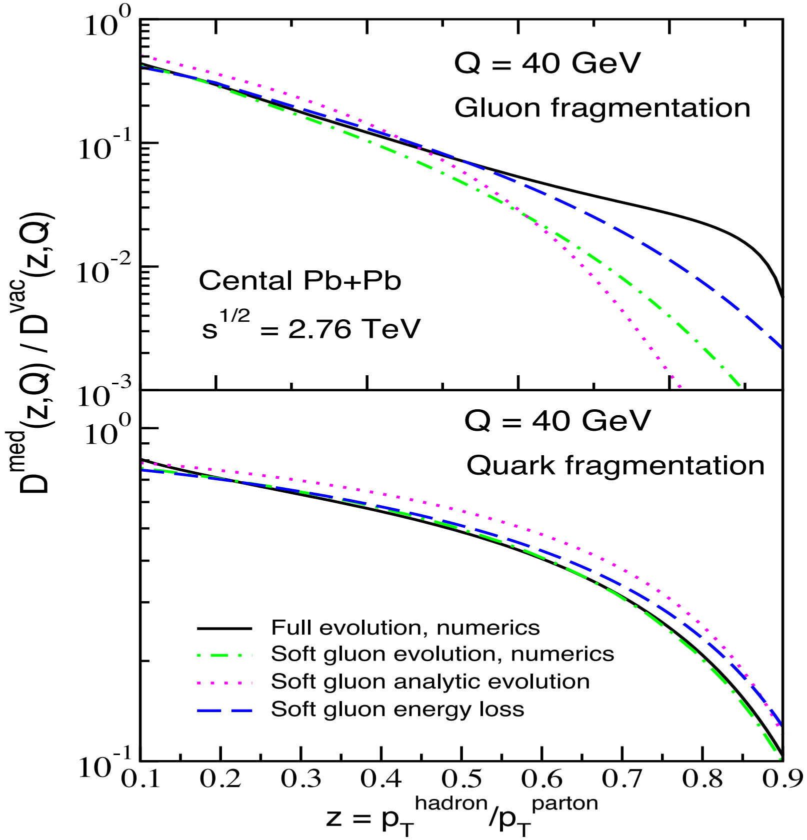
Kang, Lashof-Regas, GO, Saad, Vitev, 2014

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



- QCD evolution using full DGLAP equations in the medium is on top of the small x approximation to evolution above 20 GeV
- At small and intermediate p_T the shape of full x evolution is in better agreement with data from ALICE and CMS

Comparison III: Fragmentation functions



Differences in the fragmentation function calculated with different methods are more visible, especially for the gluon fragmentation function at large values of z. The sensitivity of R_{AA} to this is reduced because the gluon fragmentation function in the medium is more quenched.

Conclusions

- First results on R_{AA} suppression from QCD evolution are promising
- We incorporated the $SCET_G$ calculations of medium-induced splitting kernels into jet quenching phenomenology
- The new method agrees with the energy loss method amazingly accurately (and with data)
- Coupling in the medium is constrained by less than 10% from comparing different theoretical frameworks
- This puts the jet quenching phenomenology on a more solid theoretical grounds