



AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

Jet quenching from Soft Collinear Effective Theory

Grigory Ovanesyan

arXiv:1512.00006

[arXiv:1509.02936](#)

[arXiv:1405.2612](#) (PRL)

[arXiv:1304.3497](#) (JHEP)

[arXiv:1109.5619](#) (PLB)

[arXiv:1103.1074](#) (JHEP)

GO, Ringer, Vitev

Chien, Emerman, Kang, GO, Vitev

Kang, Lashof-Regas, GO, Saad, Vitev

Fickinger, GO, Vitev

GO, Vitev

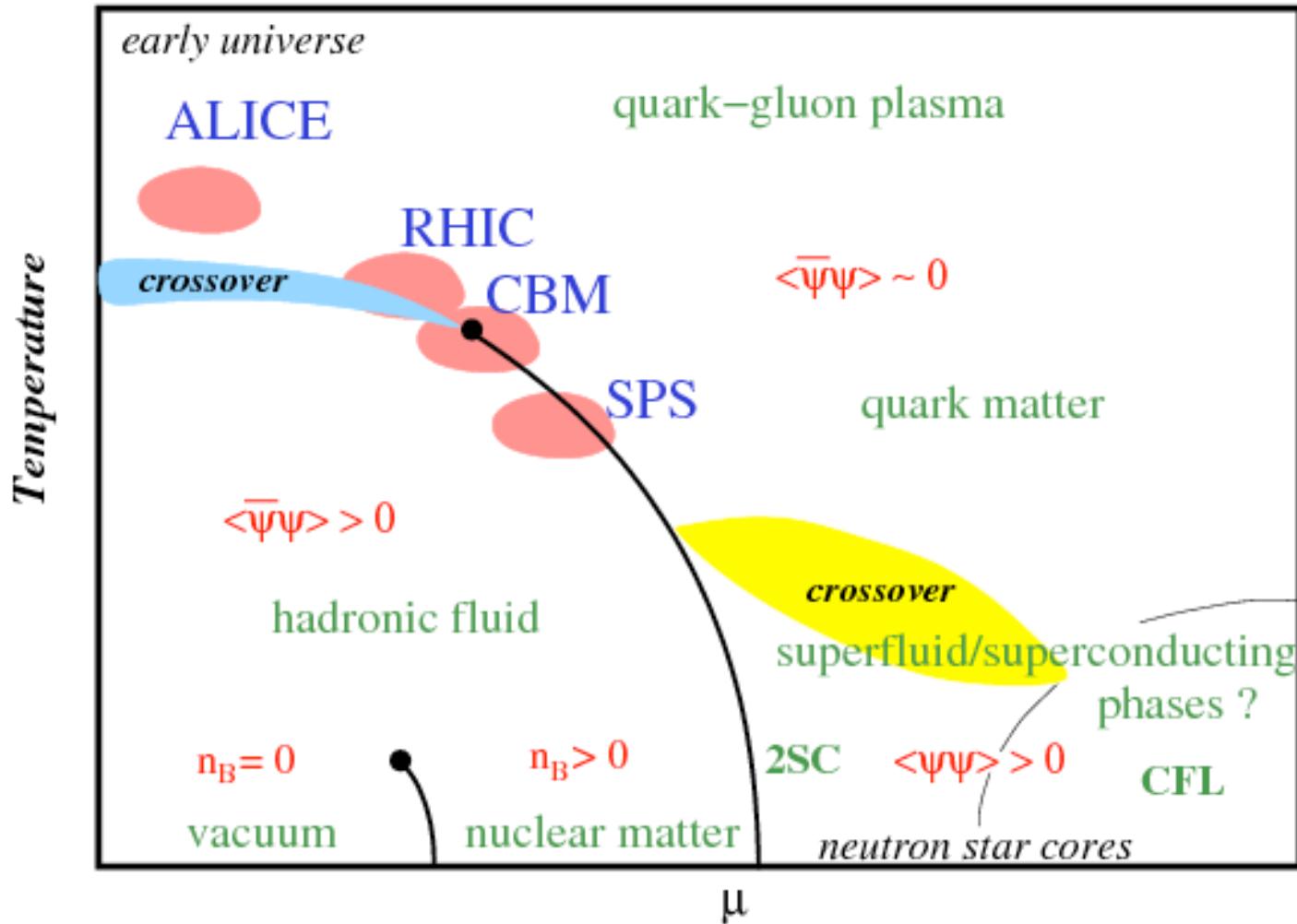
GO, Vitev

Friday, January 12, 2016,
Jets and Heavy Flavor Workshop, Santa Fe, NM

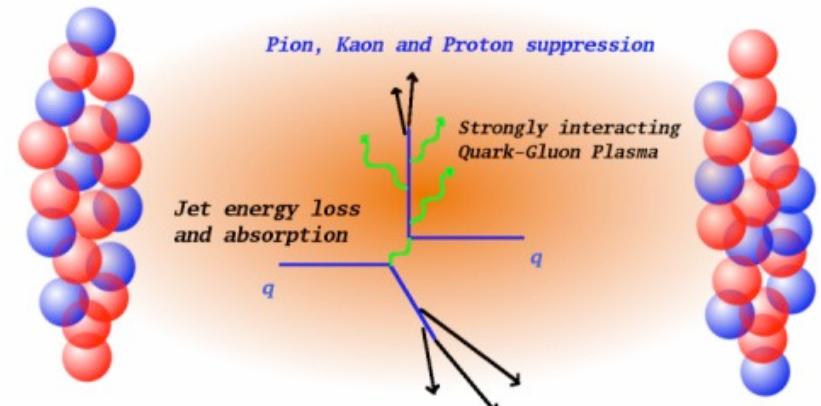
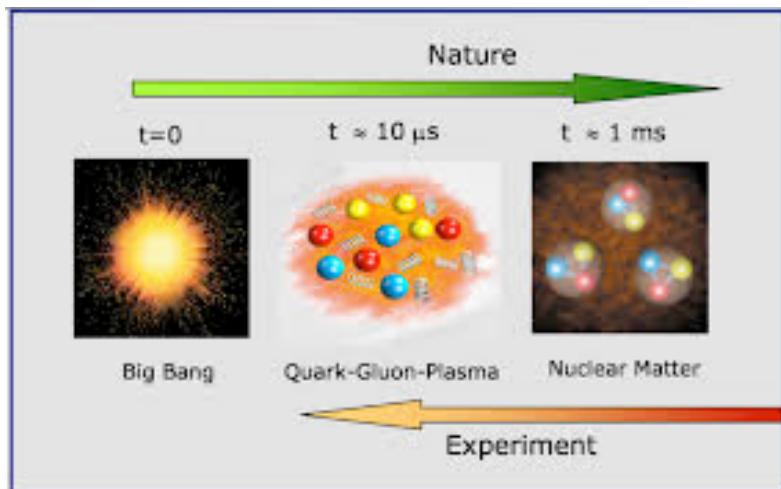
Outline

- Motivation
- SCET_G : Effective Theory for Jets in dense QCD matter
- Jet quenching from QCD evolution
- Initial-state splitting functions in cold nuclear matter
- Conclusions

Phase diagram of QCD



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, $E_{NN}=20\text{-}200 \text{ GeV}$

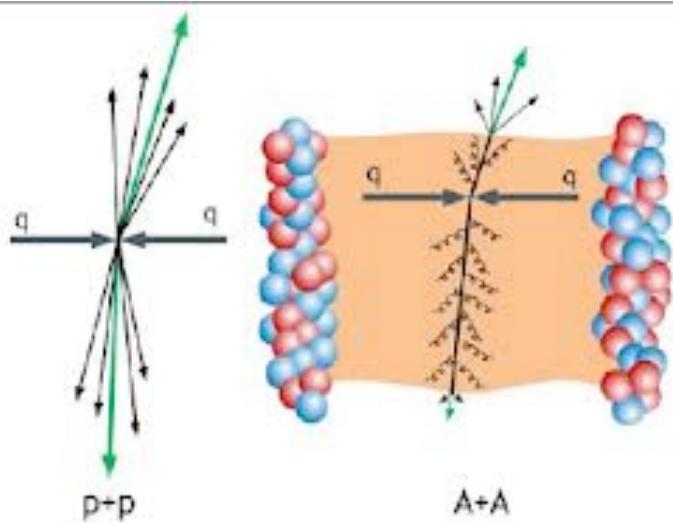


LHC: Pb-Pb, $E_{NN}=2.76 \text{ TeV}$



- LHC has confirmed at much higher energies the jet quenching data from RHIC
- QGP created in both experiments

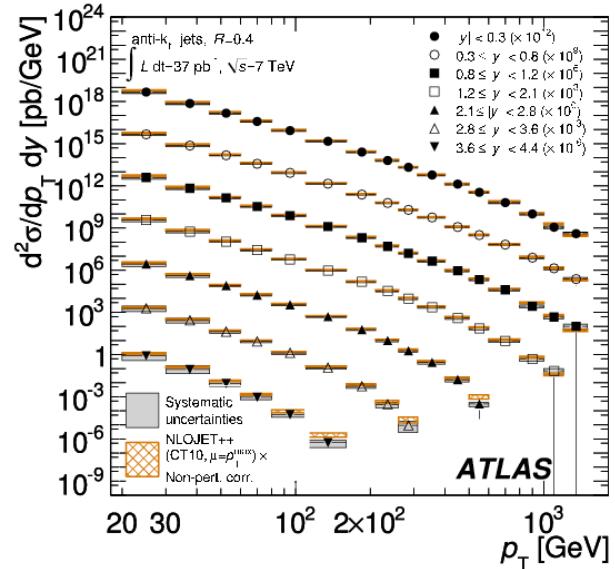
Jet Quenching



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

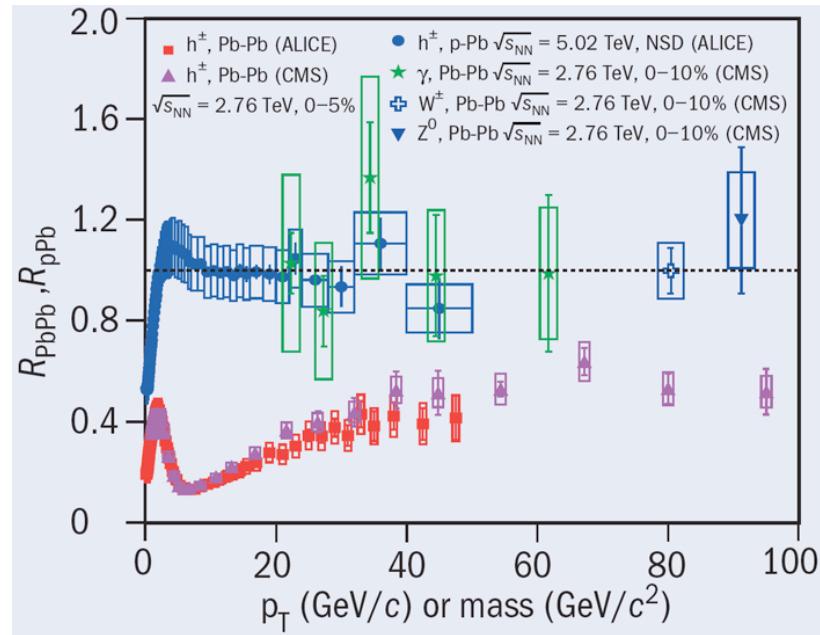
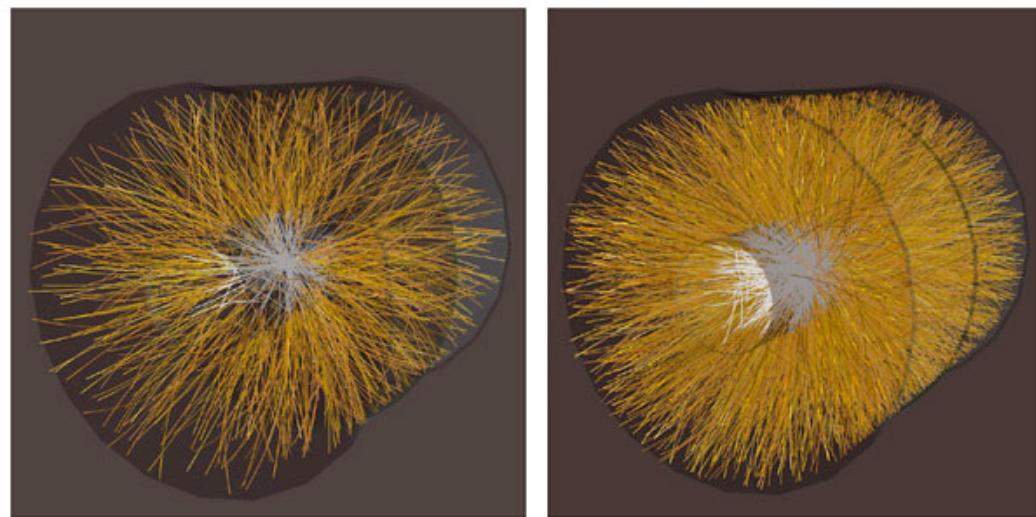
Measuring a suppressed nuclear modification factor is observational evidence for jet quenching in heavy ion collisions

Inclusive production of jets
LHC, 7 TeV



Jet quenching can be described as a combination of energy loss and the steepness of the production cross section

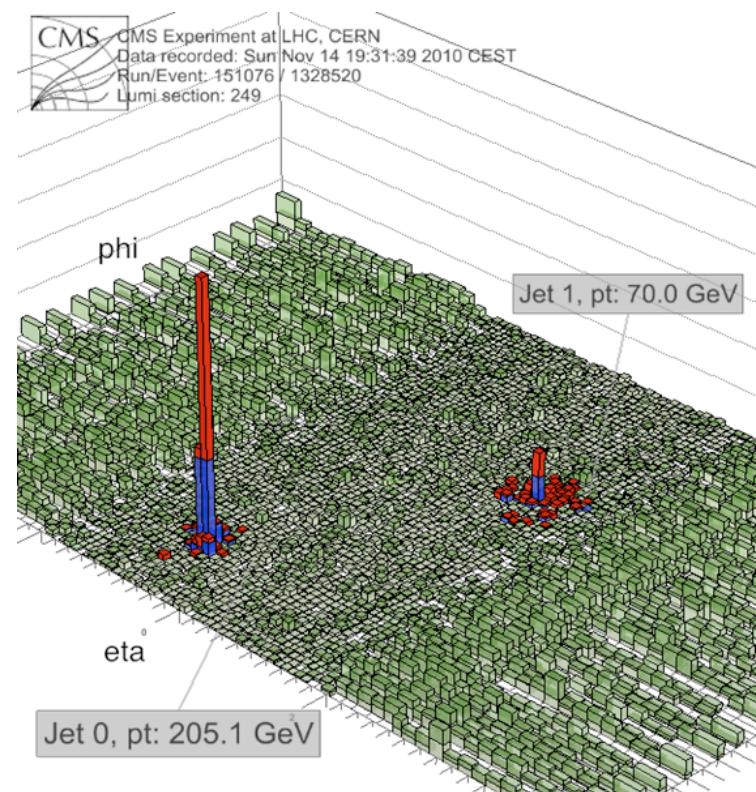
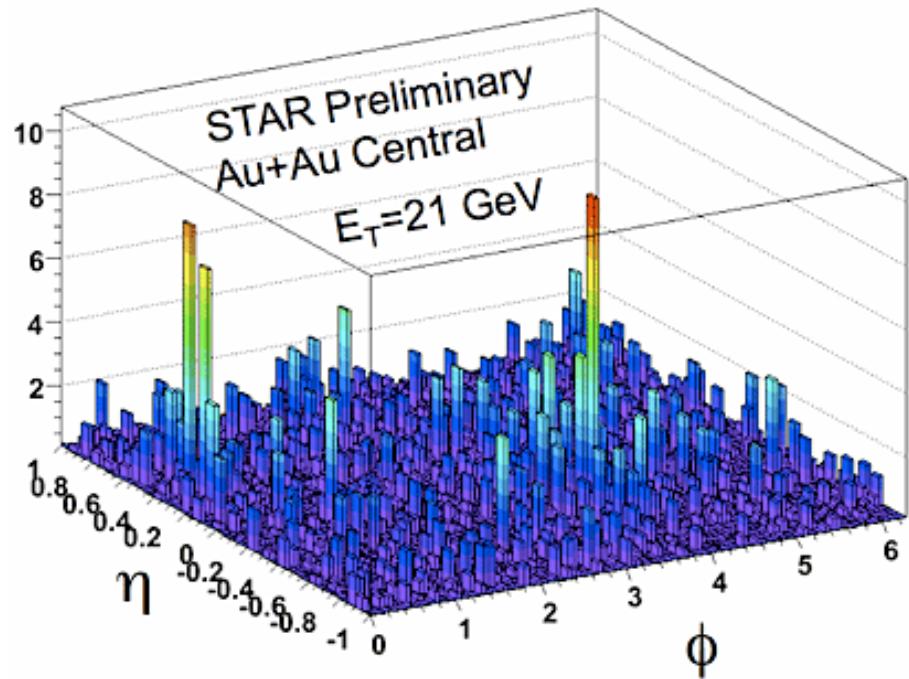
Jet Quenching



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

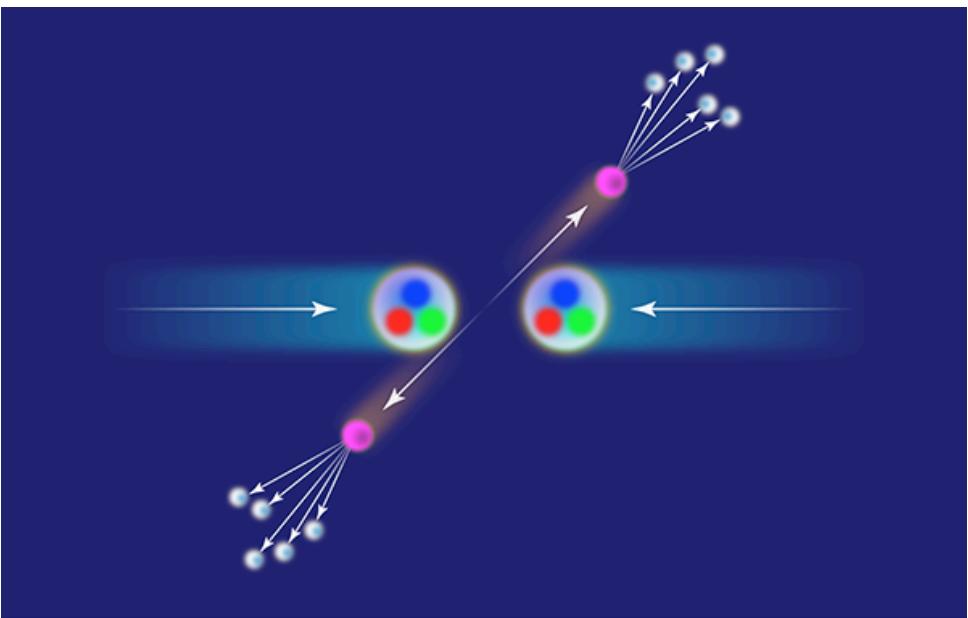
Similar data on photons has no such suppression

Jets at RHIC vs LHC

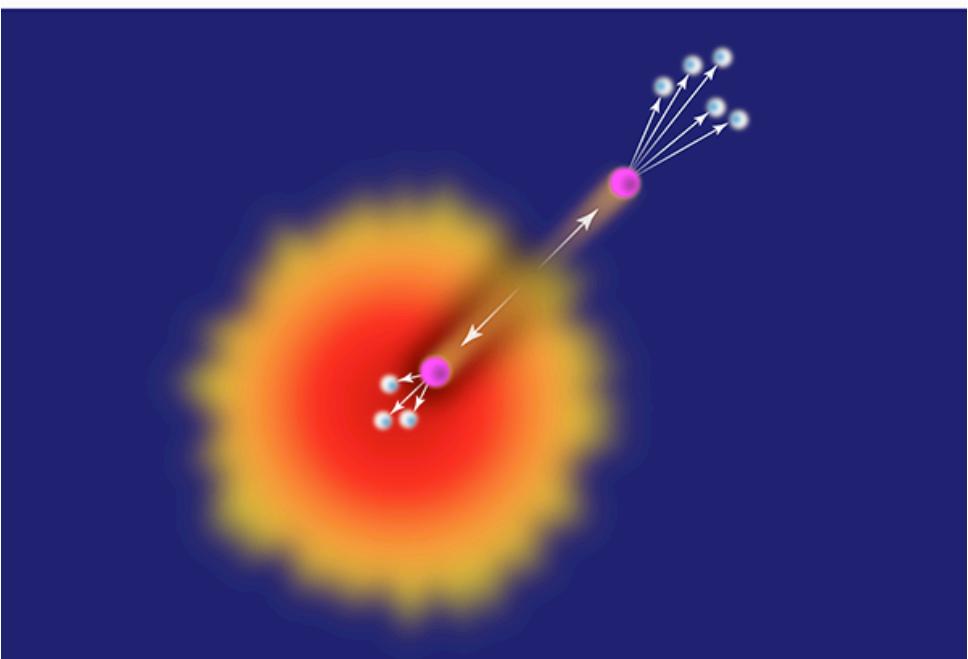


Events at LHC look much more “jetty” than at RHIC even by eye

Asymptotic freedom tells us that high-pT observables can be described using perturbative QCD



Jet quenching for high-pT data can be described using perturbative QCD, and a model for the medium.



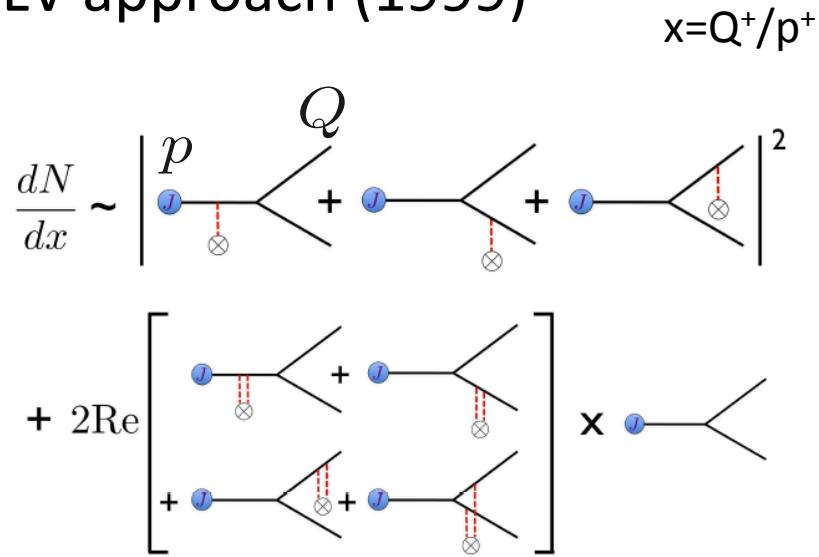
Baier-Dokshitzer-Mueller-Peigne-Schiff (BDMPS) 1996
Gyulassy-Levai-Vitev (GLV) 1999
Higher Twist 2000
Arnold-Moore-Yaffe (AMY) 2001
B.G. Zakharov (1995)

Variety of approaches, each of the methods uses slightly different kinematical assumptions/approximations.

Eventually all methods converged roughly within a factor of 2

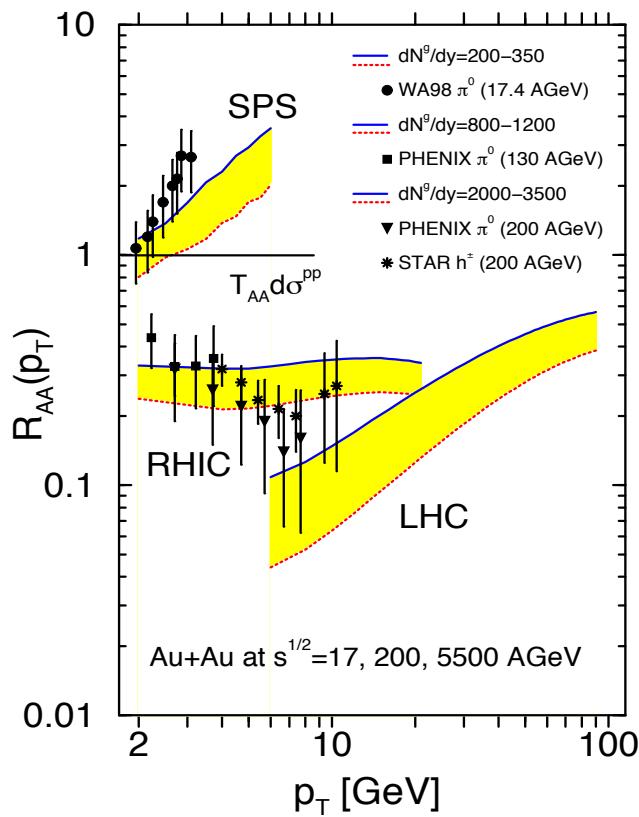
Energy loss approach

GLV approach (1999)



$$x \frac{dN^g}{dxd^2k_\perp} \Big|_{x \ll 1} = C_F \frac{\alpha_s}{\pi^2} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2q_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^g \text{medium}}{d^2q_\perp} (-2\mathbf{B}_1 \cdot \mathbf{C}_1) (1 - \cos(\omega_1 \Delta z))$$

Gyulassy, Levai, Vitev 2002

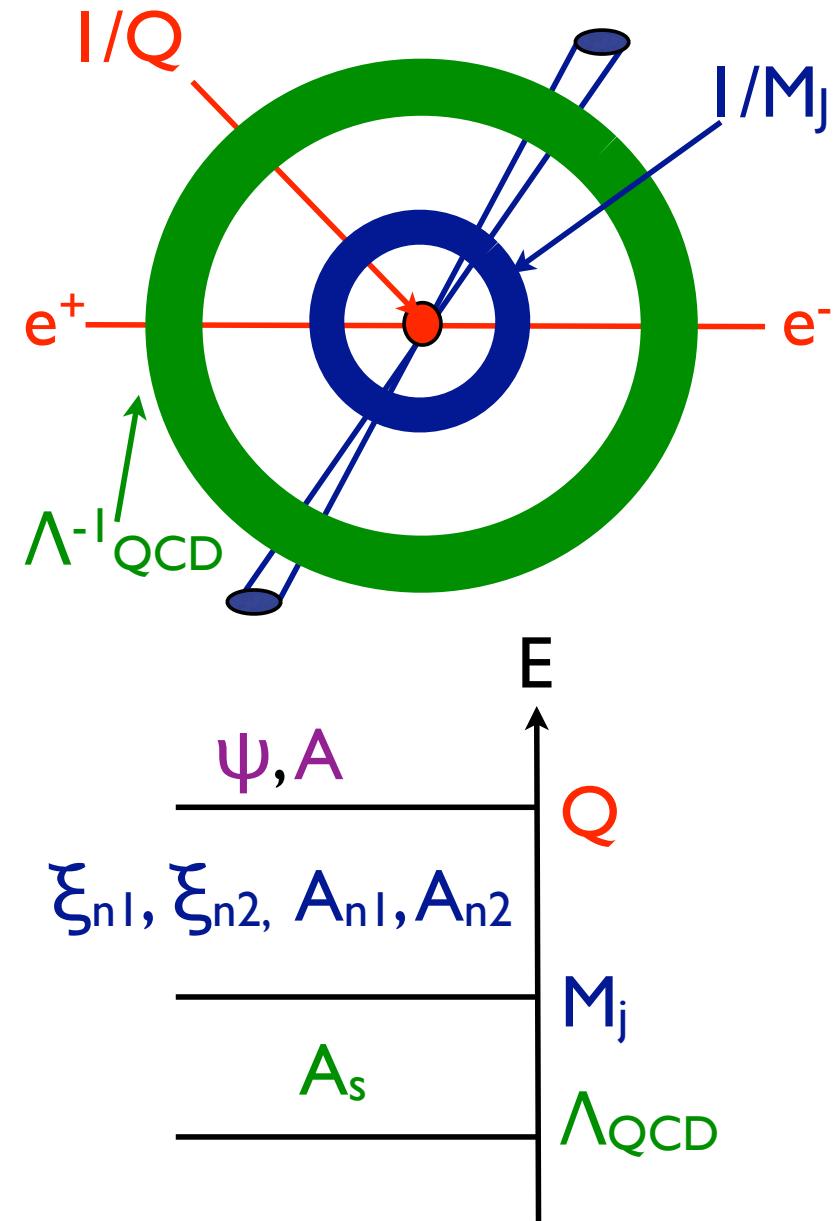


Energy loss approach, valid in the limit $x \ll 1$

Two relevant splittings $g \rightarrow gg$ and $q \rightarrow qg$ (remaining 2 suppressed by x)

$SCET_G$: Effective Theory for Jets in dense QCD matter

Soft Collinear Effective Theory



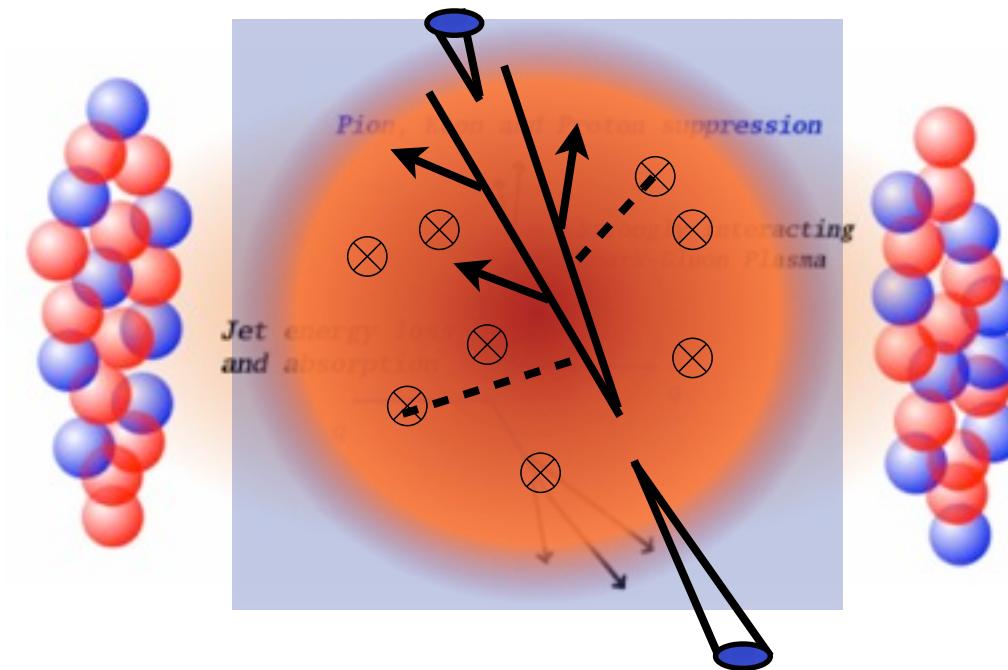
Bauer, Fleming, Luke, Pirjol, Stewart, (00-01)

- Clear separation of scales between **hard emission**, **collinear** splittings and **soft radiation**
- In **SCET** the small parameter λ describes how close to the jet axis the collinear emissions occur
- Power counting of **SCET** requires couplings between **collinear quarks**, **gluons**, and **soft gluons**

Need to include **Glauber** gluons
to **SCET**

Soft Collinear Effective Theory is not enough!

Gyulassy-Wang model of QGP, 1994



Collinear branchings in the parton shower correctly captured by SCET
Elastic scattering with medium quasiparticles are not included (need to go beyond SCET)

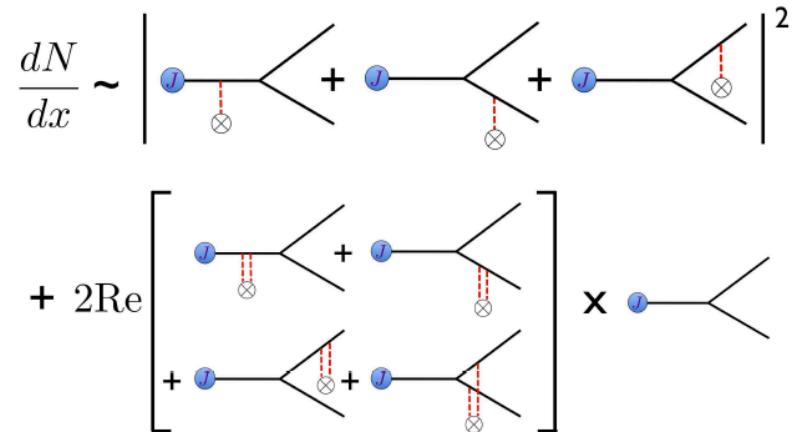
Momentum scaling of the t-channel gluon: $q \sim (\lambda^2, \lambda^2, \lambda)$ (Glauber gluon)

Soft Collinear Effective Theory with Glauber Gluons

$$\mathcal{L}_{\text{SCET}_G} = \mathcal{L}_{\text{SCET}} + \mathcal{L}_G (\xi_n, A_n, \eta)$$

Idilbi, Majumder, 2008
D'Eramo, Liu, Rajagopal, 2010
GO, Vitev, 2011

- 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

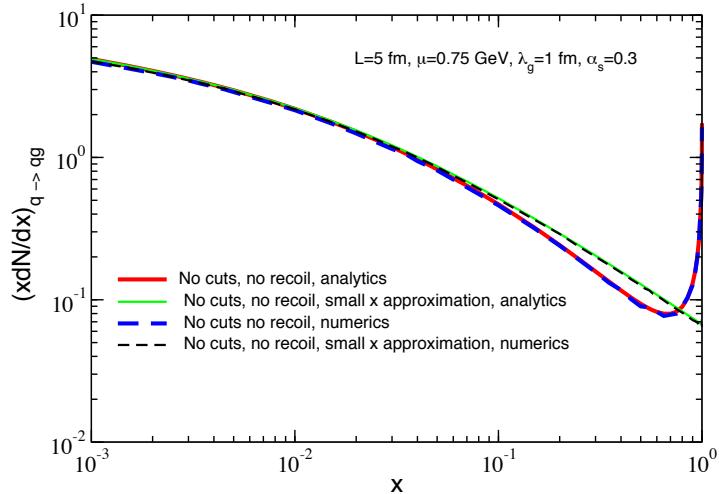


Applications of SCET_G

- Gauge invariance explicitly demonstrated
- Factorization of the medium-induced splitting from the production proved
- All four medium-induced splittings calculated beyond small x approximation
- In the small x limit only two splittings survive and they are in agreement with GLV expressions

GO, Vitev, 2011

$q \rightarrow qg$ (full x)



What to do with these splitting functions ?

- These splitting functions cannot be inserted into the traditional energy loss calculations because of flavor changing processes

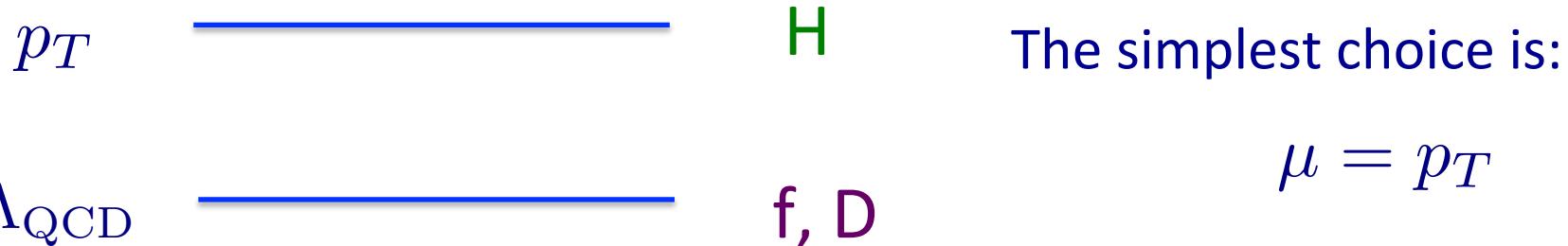
$$g \rightarrow q\bar{q} \quad q \rightarrow gq$$

- Need a new framework beyond energy loss approach to incorporate the **finite x** corrections
- This was achieved recently using the QCD evolution approach to jet quenching

Jet quenching from QCD evolution

Jet quenching from evolution

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



- 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 finite x corrections

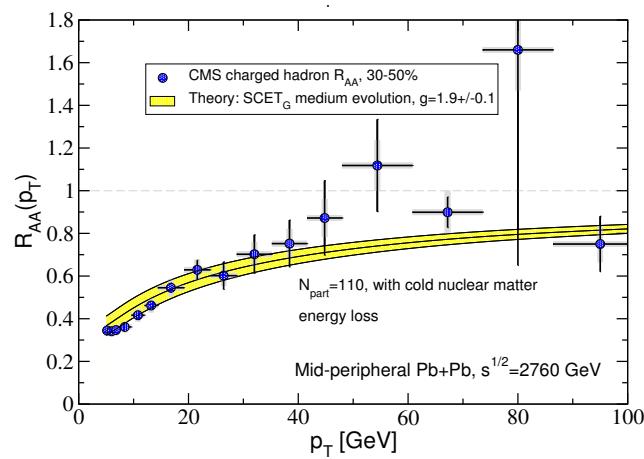
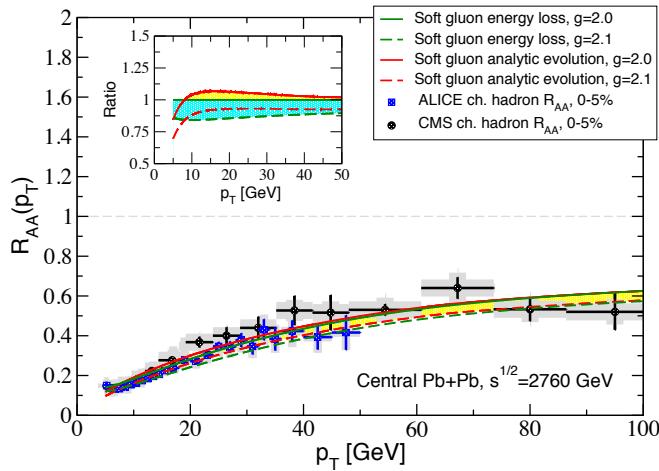
SCET_G+QCD evolution

Deng, Wang, 2009 (medium DGLAP)

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

Chien, Emerman, Kang, Ovanesyan, Vitev, 2015

(medium DGLAP+SCET_G)



$$\frac{dD_{h/q}(z, Q)}{d \ln Q} = \frac{\alpha_s(Q)}{\pi} \int_z^1 \frac{dz'}{z'} \left[P_{q \rightarrow qg}(z') D_{h/q}\left(\frac{z}{z'}, Q\right) + P_{q \rightarrow gg}(z') D_{h/g}\left(\frac{z}{z'}, Q\right) \right],$$

- The full \times SCET_G calculations of medium-induced splitting functions implemented in the QCD evolution (DGLAP) equations
- A consistent framework to go beyond energy loss approach and include flavor changing processes
- Comparison of theory to LHC data for different centralities, including cold nuclear matter effects
- Predictions for LHC run II

Evolution in the small x limit

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

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

- Expand the convolution integrand around $z'=1$
- Assume fixed steepness $n(z)$ (approximately true)
- Solve DGLAP equations exactly

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

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

$$\left\langle \frac{\Delta E}{E} \right\rangle_z = \int_0^{1-z} dx x \frac{dN}{dx}(x) \xrightarrow{z \rightarrow 0} \left\langle \frac{\Delta E}{E} \right\rangle,$$

$$\langle N_g \rangle_z = \int_{1-z}^1 dx \frac{dN}{dx}(x) \xrightarrow{z \rightarrow 1} \langle N_g \rangle,$$

Initial-state splitting functions in cold nuclear matter

Initial state interactions in heavy ion collisions

GO, Ringer, Vitev, 2015

$$\frac{dN}{dx} \sim \left| \text{---} \begin{array}{c} \diagup \\ \otimes \\ \diagdown \end{array} J + \text{---} \begin{array}{c} \diagup \\ \otimes \\ \diagdown \end{array} J + \text{---} \begin{array}{c} \diagup \\ \otimes \\ \diagdown \end{array} J \right|^2$$

$$+ 2\text{Re} \left[\begin{array}{c} \text{---} \begin{array}{c} \diagup \\ \otimes \\ \diagdown \end{array} J + \text{---} \begin{array}{c} \diagup \\ \otimes \\ \diagdown \end{array} J \\ + \text{---} \begin{array}{c} \diagup \\ \otimes \\ \diagdown \end{array} J + \text{---} \begin{array}{c} \diagup \\ \otimes \\ \diagdown \end{array} J \end{array} \right] \times \text{---} \begin{array}{c} \diagup \\ \otimes \\ \diagdown \end{array} J$$

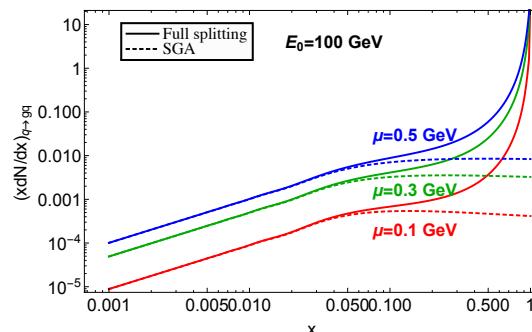
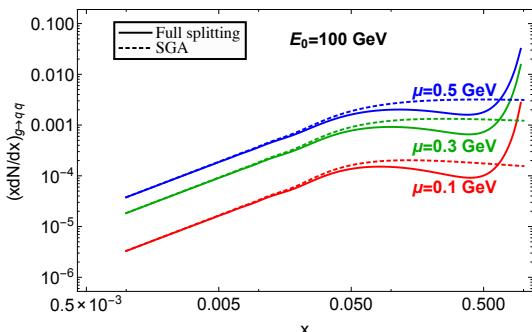
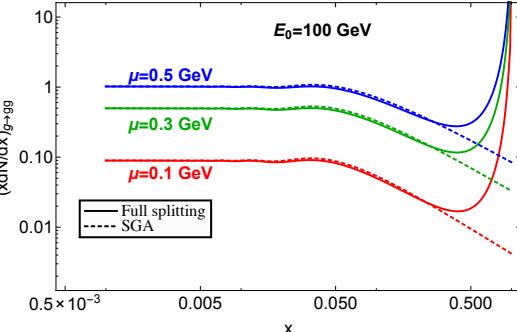
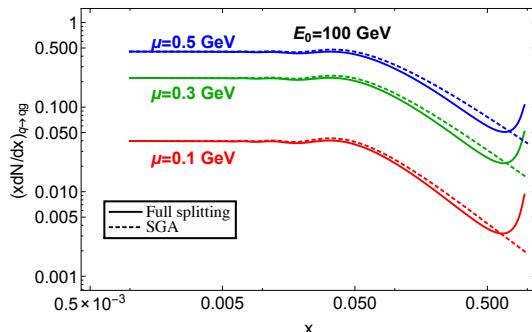
x is fraction of the energy released
in the splitting process

- So far in the phenomenology we treated the final-state effects using SCET_G and QCD evolution
- The initial state effects were still treated using the energy loss approach
- Using SCET_G we can go beyond small x approximation
- “simple calculation”

$$A_\perp = k_\perp, \quad B_\perp = k_\perp - xq_\perp,$$

$$C_\perp = k_\perp - q_\perp,$$

$$\Omega_1 - \Omega_2 = \frac{B_\perp^2}{x(1-x)p^+}, \quad \Omega_3 = \frac{A_\perp^2}{x(1-x)p^+},$$



Results

- Analytical result for initial state medium splitting function $q \rightarrow qg$
- Numerical results for all four splittings

$$\left(\frac{dN}{dx d^2\mathbf{k}_\perp} \right)_{q \rightarrow qg}$$

$$= C_F \frac{\alpha_s}{2\pi^2} \frac{1 + (1-x)^2}{x} \int \frac{dz}{\lambda_g(z)} d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2\mathbf{q}_\perp} \left[\frac{B_\perp}{B_\perp^2} \cdot \left(\frac{B_\perp}{B_\perp^2} - \frac{C_\perp}{C_\perp^2} \right) (1 - \cos(\Omega_1 - \Omega_2)\Delta z) \right.$$

$$\left. + \frac{1}{C_\perp^2} - \frac{1}{A_\perp^2} + \frac{A_\perp}{A_\perp^2} \cdot \left(\frac{A_\perp}{A_\perp^2} - \frac{C_\perp}{C_\perp^2} \right) (1 - \cos \Omega_3 \Delta z) - \frac{1}{N_c^2} \frac{B_\perp}{B_\perp^2} \cdot \left(\frac{B_\perp}{B_\perp^2} - \frac{A_\perp}{A_\perp^2} \right) (1 - \cos(\Omega_1 - \Omega_2)\Delta z) \right]$$

Initial state interactions

- Using SCET_G we calculated all medium-induced initial-state splitting kernels valid beyond previously known approximations
- Even though at the amplitude level initial and final state splitting functions are related via crossing symmetry, integration over Glauber gluon momenta leads to a different interference pattern
- The next step is to include the effect of these results on the QCD evolution applied to the PDFs in heavy ion collisions
- Will give us a self-consistent robust framework for jet quenching phenomenology based on EFT+QCD evolution

Conclusions

- Using effective field theories allowed us for a robust and precise method for jet quenching phenomenology that is based on EFT+QCD evolution
- Description of RHIC and LHC data by the new method is very good over a wide p_T range and different centralities
- The next step is to combine both the initial and final-state effects into the jet quenching phenomenology beyond small x . Stay tuned...