# Jet quenching: probing *arbitrary* medium *perturbatively*

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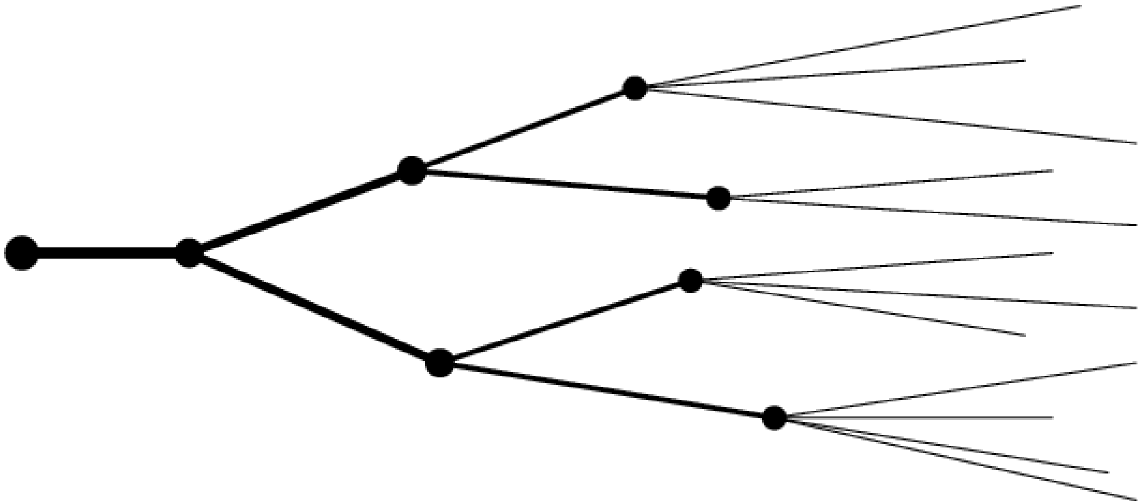
# Setup

- Based on pQCD factorization paradigm
- Assume hard jet weakly coupled to soft medium
- Make no assumption about the medium
- Need a formalism that is independent of underlying structure of the medium
- Need a detailed global analysis: light and heavy flavors
- Working in HT

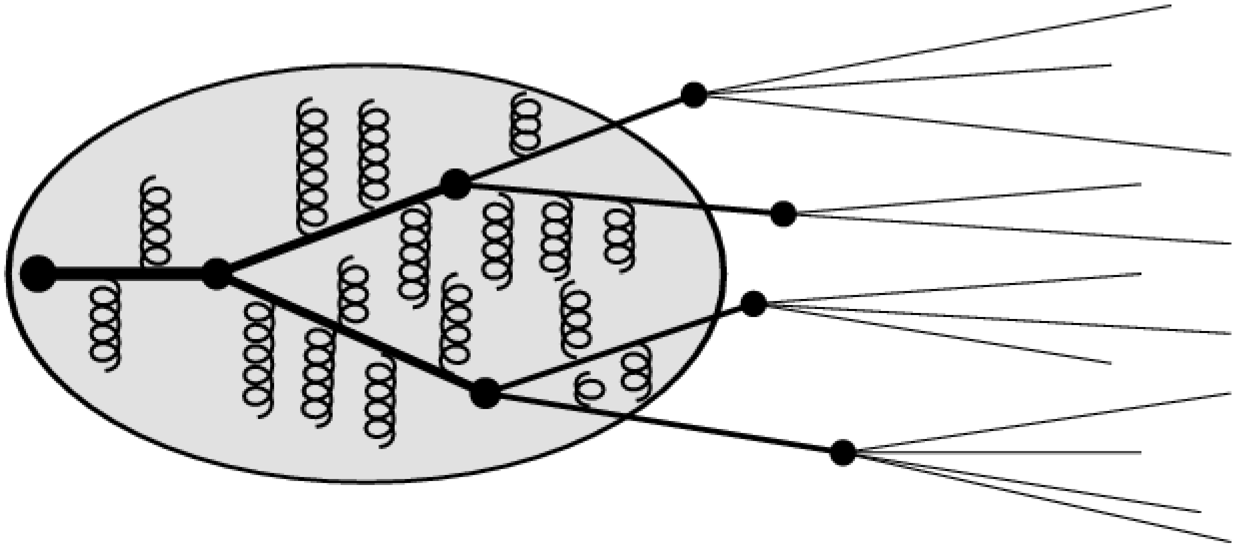
# Vacuum evolution of a hard jet



- A parton/hadron shower from a hard virtual parton
- Factorization of hard perturbative and soft non-perturbative regimes
- Building up virtuality leads to DGLAP Eqs. for FF $D(z,Q^2)$

$$\frac{\partial D_i(z,Q^2)}{\partial \ln Q^2} = \sum_j \frac{\alpha_s}{2\pi} \int_z^1 \frac{dy}{y} P_{i\to j}(y) D_j(\frac{z}{y},Q^2)$$

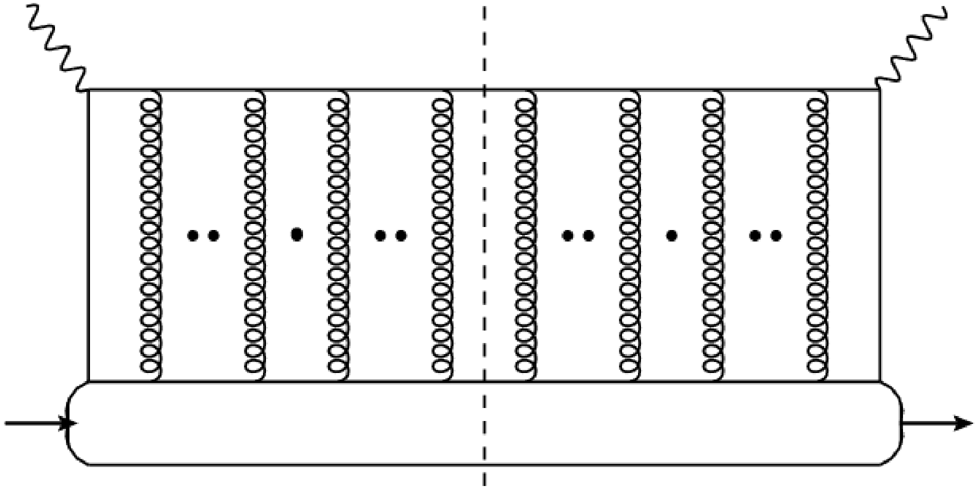
# How does a jet evolve in a medium?



- Multiple scatterings in medium will change the radiation pattern and final hadronic shower
- From vacuum to medium: $D_{vac}(z) \rightarrow D_{med}(z)$
- Studying the change of the jet structure can help to understand the structure of medium

# What are we measuring in medium?

- Partons undergo transverse diffusion & longitudinal momentum loss



**Majumder, arXiv:0810.4697**
**Majumder, Muller, PRC (2008)**

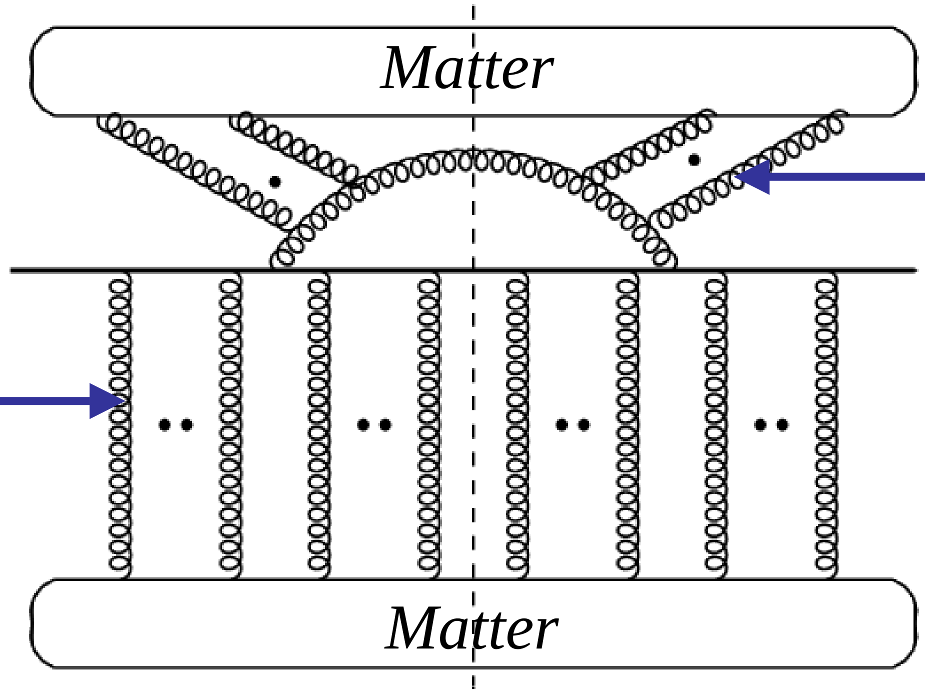
$$\frac{\partial \phi(q^-, \vec{q}_\perp)}{\partial L^-} = \hat{q} \nabla^2_{q_\perp} \phi(q^-, \vec{q}_\perp) + \hat{e} \frac{\partial \phi(q^-, \vec{q}_\perp)}{\partial q^-}$$

$$\hat{q} = \frac{4\pi \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F^{+\mu}(Y^- + y^-) F^+_{\mu,}(Y^-) \rangle$$

$$\hat{e} = \frac{4\pi \alpha_s C_R}{N_c^2 - 1} \int dy^- dy^+ \langle F^{+-}(Y^- + y^-, 0) F^{+-}(Y^-, y^+) \rangle$$

- Can be evaluated in a well defined medium

# A typical diagram

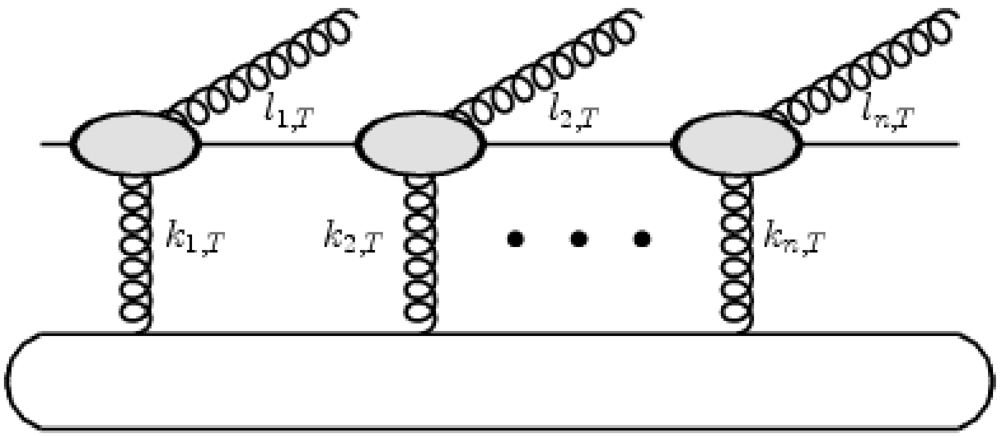



Interaction between radiated gluon & medium

Interaction between hard parton & medium

- In general, should include transverse broadening & longitudinal loss due to multiple scatterings
- But very hard to calculate (different limits are taken in different approaches)

# Single scattering per emission




- $l_T$ ordered for subsequent emissions
- In the limit $k_T << l_T$, DGLAP-like Eqs. for MMFF

$$\frac{\partial \tilde{D}_i(z,Q^2,q^-)|_{\zeta_i}^{\zeta_f}}{\partial \ln Q^2} = \sum_j \frac{\alpha_s}{2\pi}\int_z^1 \frac{dy}{y}\int_{\zeta_i}^{\zeta_f} d\zeta \tilde{P}_{i\to j}(y,\zeta,Q^2,q^-)\tilde{D}_j(\frac{z}{y},Q^2,q^- y)|_{\zeta}^{\zeta_f}$$

*+ vacuum part*

$$\tilde{P}_{i\to j} = \frac{P_{i\to j}(y)}{Q^2}\frac{\hat{q}(\zeta)}{\pi}\left[2 - 2\cos\left(\frac{Q^2(\zeta-\zeta_i)}{2q^- y(1-y)}\right)\right]$$

*qhat = d<p$_T$$^2$>/dL*

**Guo, Wang, PRL, (2000), Majumder, arXiv:0901.4516, Zhang, Wang, Wang, PRL (2005)**

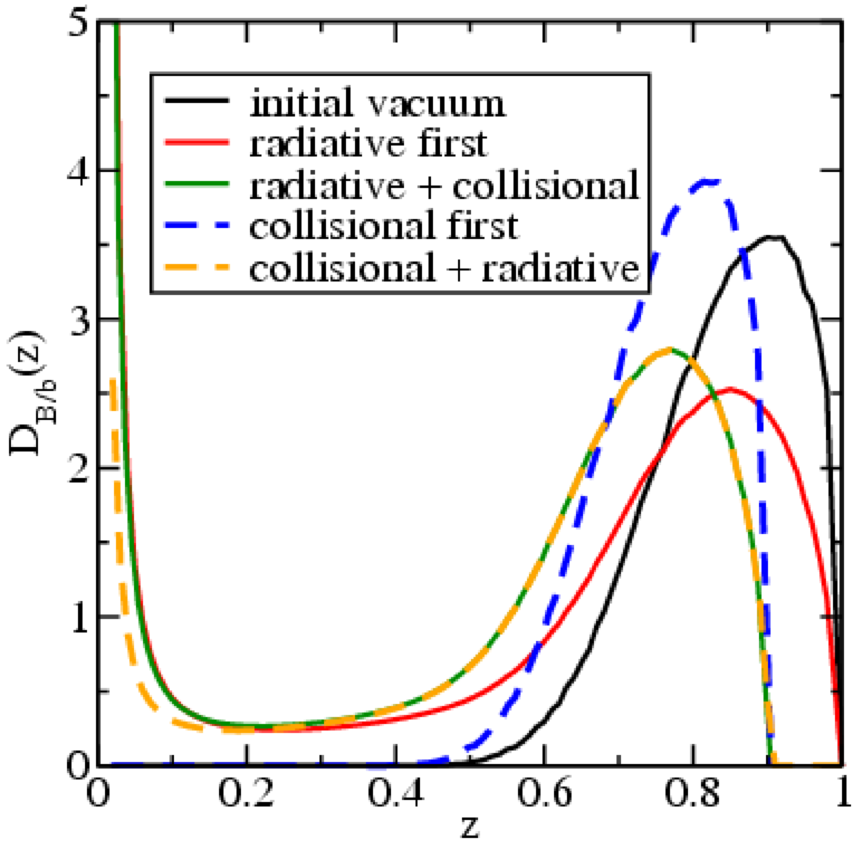
# Add elastic energy loss

- Elastic energy loss suffered by the fast parton is encoded by transport coefficient:

  *ehat = dE/dL*

- Included by shifting the fragmentation function

$$D'(z) = D\left(z/(1-\delta z)\right)/(1-\delta z)$$

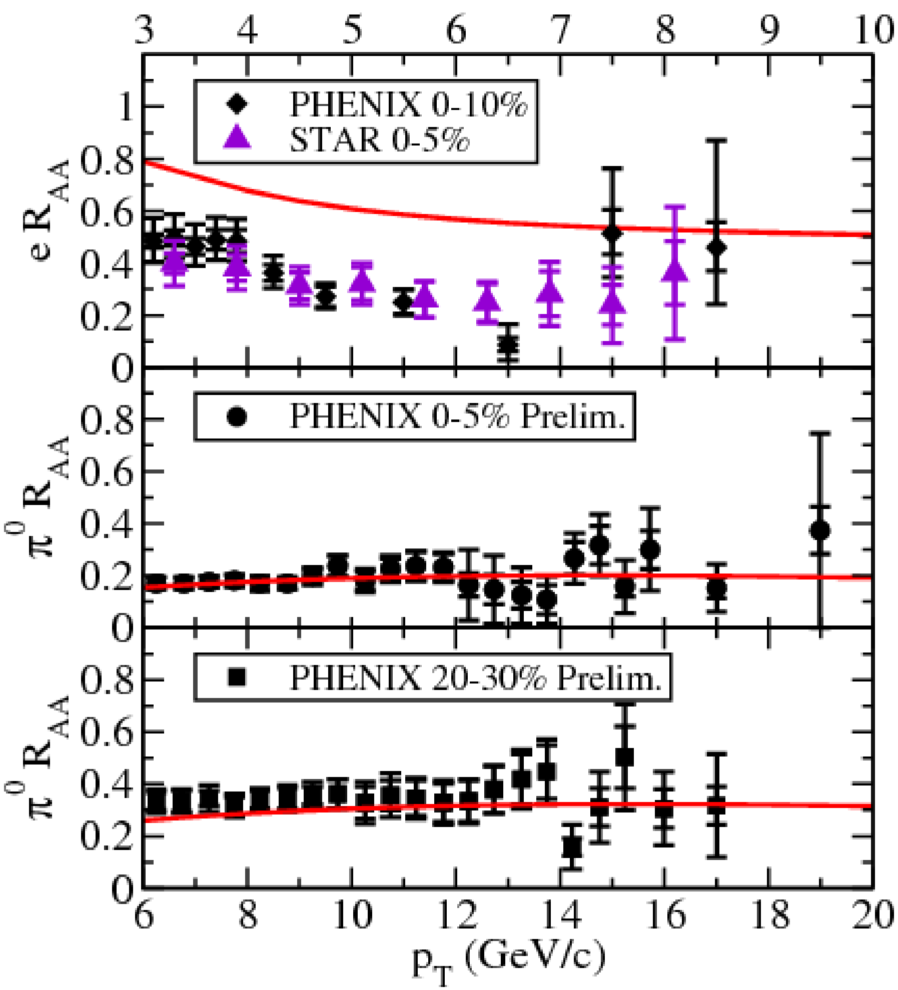


# I: Assuming LO HTL medium

$$\hat{e}_{\rm HTL} = \frac{1}{4} C_R \alpha_s m_D^2 \ln \frac{q_\perp^{\max 2}}{m_D^2},$$

$$\hat{q}_{\rm HTL} = C_R \alpha_s m_D^2 T \ln \frac{q_\perp^{\max 2}}{m_D^2}.$$

- $q_{\max}{}^2 = 4\,E\,T$
- v corrections for heavy quarks (Braaten, Thoma)
- Woods-Saxon profile
- 1D Bjorken expansion
- *qhat/ehat* = 4*T*
- Fit $\pi\ R_{AA}$ for central *b*




**With Majumder, Preliminary**

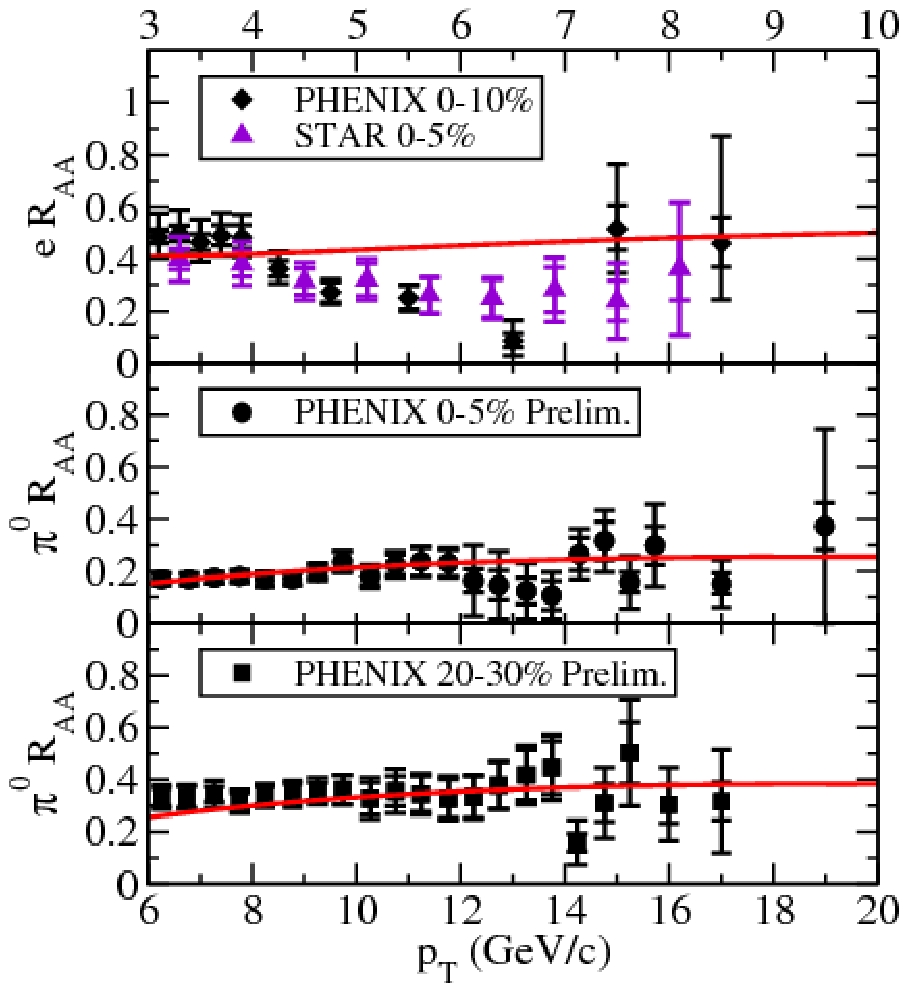
# II: No assumption for medium

$$\hat{e} = \alpha C_R T^2$$

$$\hat{q} = \beta C_R T^3$$

- Fit $\pi$ $R_{AA}$ for different *b* & heavy central e $R_{AA}$
- *ehat*=2.3GeV/fm
  *qhat*=4.3GeV$^2$/fm

  at $T_0$=400MeV for gluon
- *qhat*/*ehat* =5*T*>LO-HTL
- No log and LO-HTL velocity terms




**With Majumder, Preliminary**

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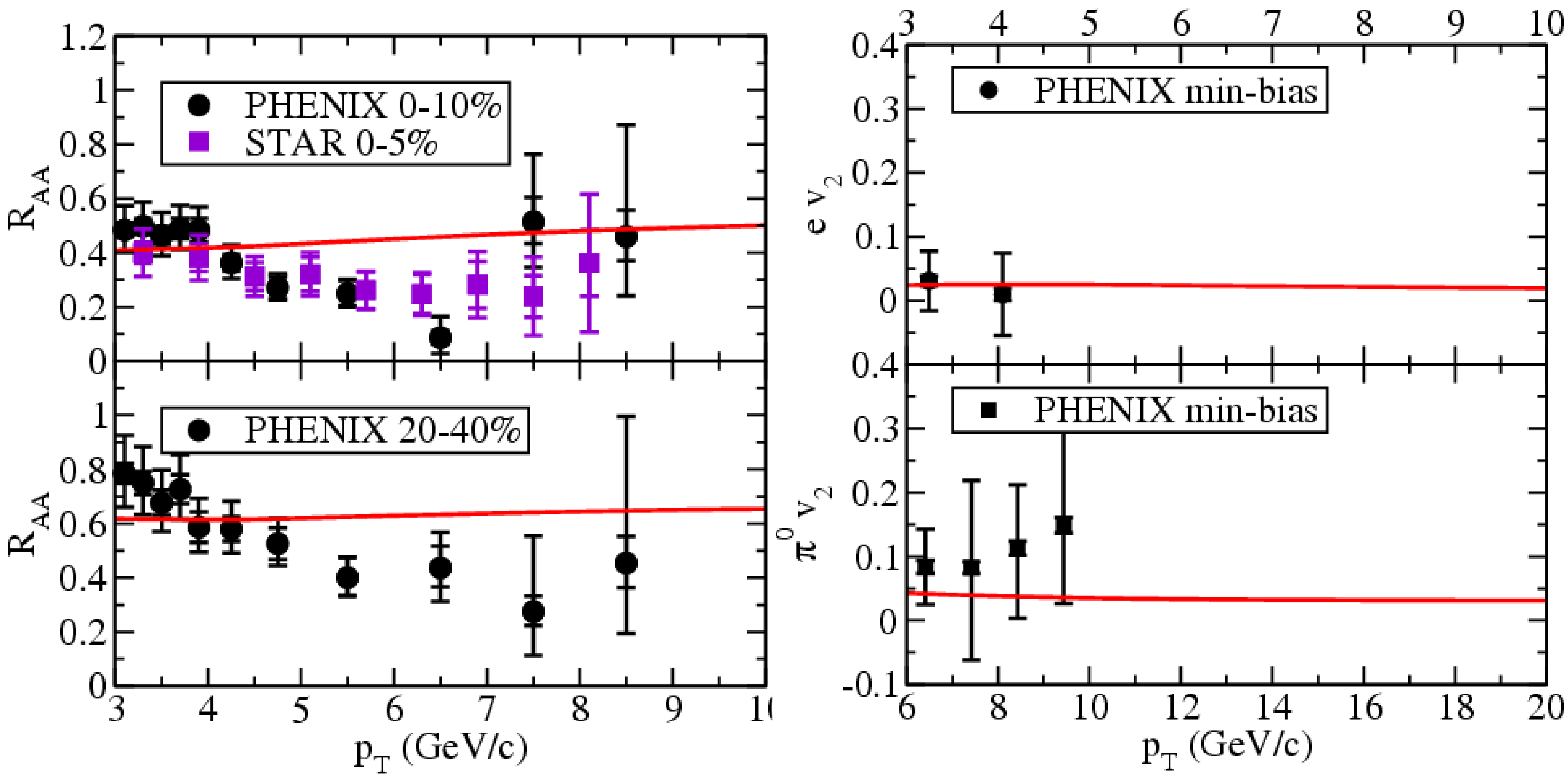



**With Majumder, Preliminary**

# What have we learned so far?

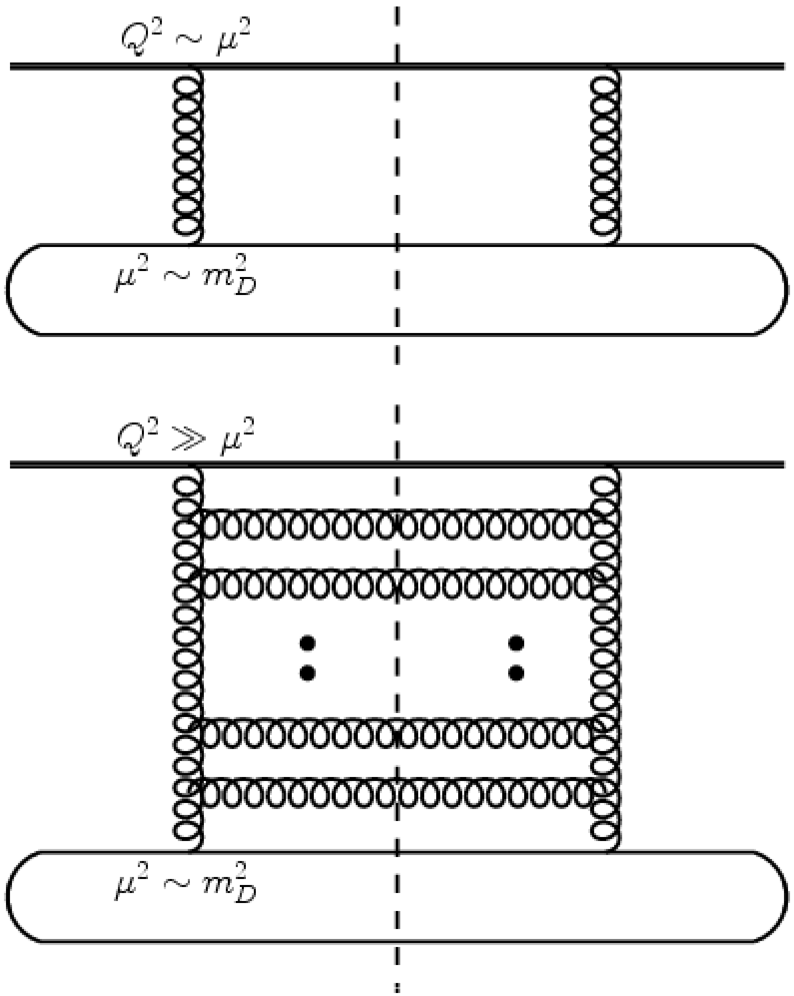
- pQCD-based weak coupling approach is able to describe both light and heavy flavor suppressions
- LO HTL description of the medium is not favored by the data
- What can/should we do next?

# $Q^2$ evolution of *ehat* and *qhat*

- The number of the targeted gluons are enhanced at a large scale

- Need to incorporate $Q^2$ dependence of transport coefficients in the formalism

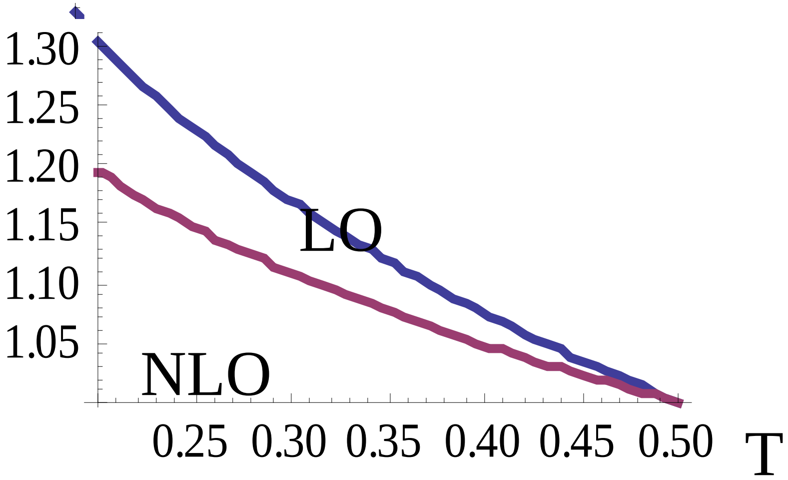
- Room for LO-HTL




**Casalderrey-Solana, Wang, PRC (2007)**

# NLO HTL calculation

- LO: $$\hat{q} = \frac{g^4 T^3 C_s}{2\pi}\left[1.28 \log\left(\frac{q_\perp^{\max}}{4T}\right) + \underline{0.71}\right]$$
- NLO: $$\hat{q} = \frac{g^4 T^3 C_s}{2\pi}\left[1.28 \log\left(\frac{q_\perp^{\max}}{4T}\right) + \underline{1.25}\right]$$




- *qhat* increases from LO to NLO
- We also need *ehat*!

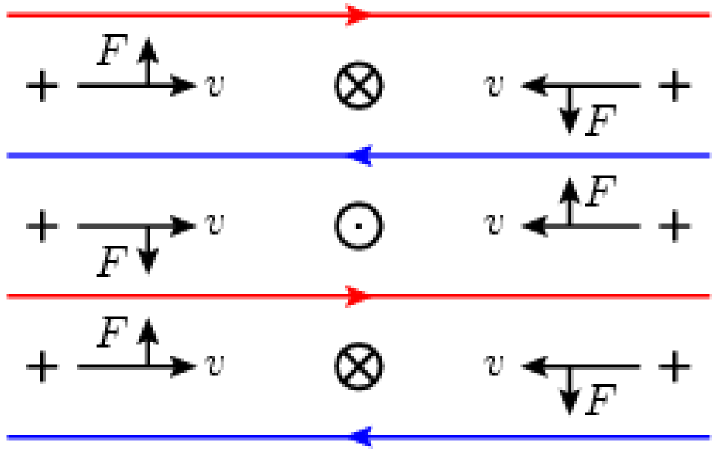
**Caron-Hout, arXiv:0811.1603; NPA (2009)**

# Effect from non-equilibrium

- Eloss is different in pre-equilibrium stage

- The unstable modes in an anisotropic medium can lead to the growth of the momentum broadening

- Does *ehat* grow in the same way?




**Baier, Mehta-Tani, PRC (2008); Majumder, Muller, Mrowczynski, arXiv:0903.3683**

# Strongly coupled medium

- *qhat* for *N* = 4 SYM using AdS/CFT correspondence:

$$\hat{q}_{\mathrm{SYM}} = \frac{\pi^2}{a}\sqrt{\lambda}T^3 = \frac{\pi^{3/2}\Gamma(\frac{3}{4})}{\Gamma(\frac{5}{4})}\sqrt{\lambda}T^3 \approx 26.69\sqrt{\alpha_{\mathrm{SYM}}N_c}T^3$$

**Liu, Rajagopal, Wiedemann, PRL (2006)**

=4.5, 10.6, 20.7GeV$^2$/fm for *T*=300, 400, 500MeV

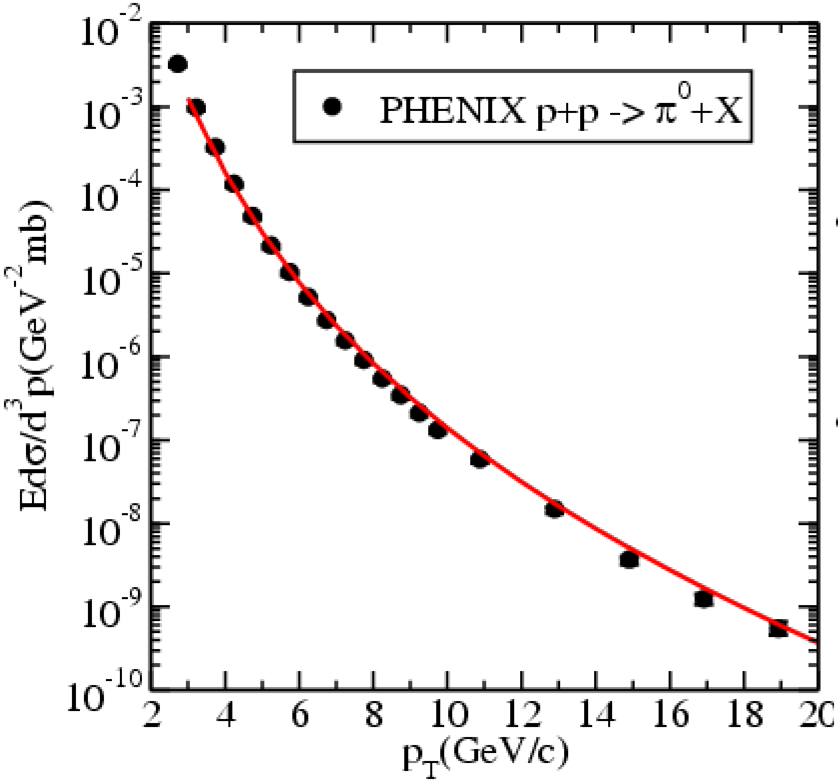
- *qhat* might change if the theory is made more QCD-like
- Again we also need *ehat*

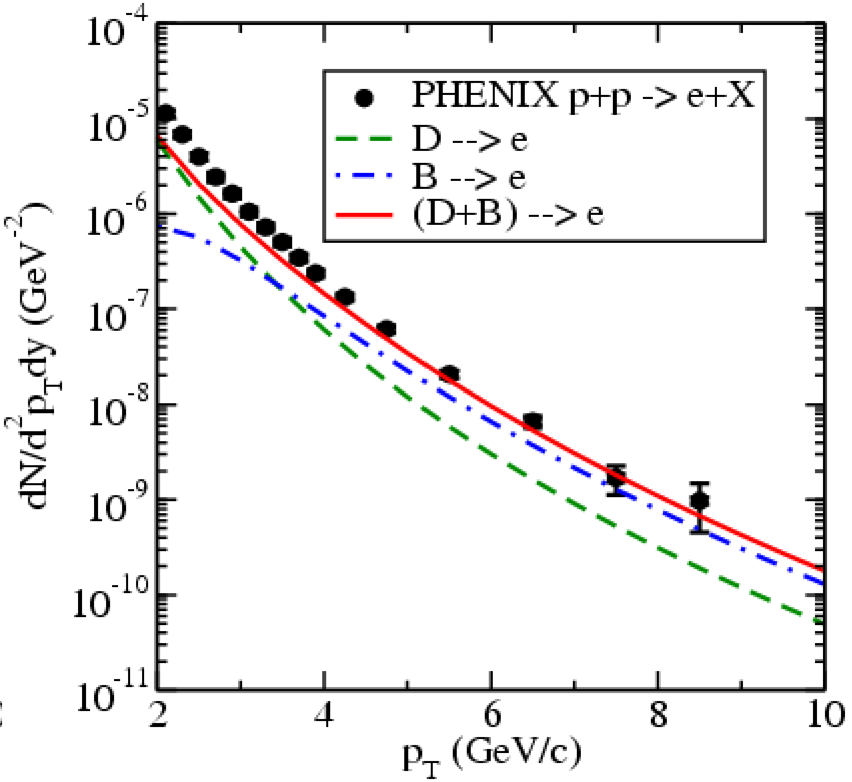
# Summary

- **Perturbative QCD and weak coupling approach can explain jet modification data**

- Calculation of transport coefficients needs to go beyond LO HTL
  - $Q^2$ evolution of transport coefficients
  - NLO HTL
  - Non-equilibrium effect
  - Strongly coupled medium

# Baseline: p+p


PHENIX p+p -> π0+X
Edσ/d3p(GeV-2mb)
pT(GeV/c)


PHENIX p+p -> e+X
D --> e
B --> e
(D+B) --> e
dN/d2pTdy (GeV-2)
pT (GeV/c)