Jet Energy Loss in AMY

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in collaboration with

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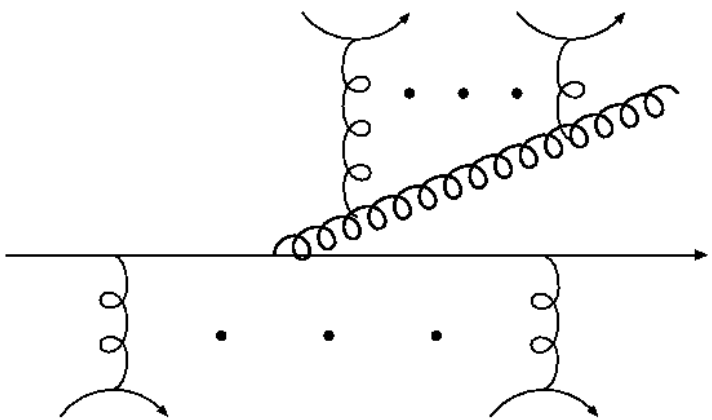
Outline

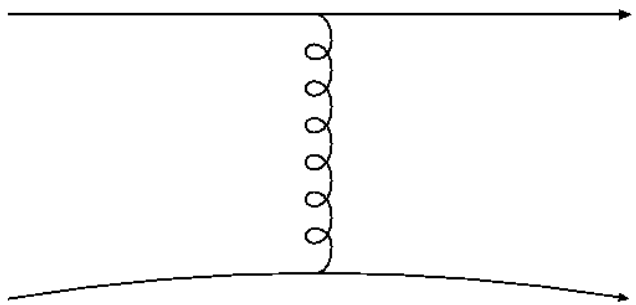
- **Overview of AMY approach**
  - **radiative & collisional jet energy loss**
- **Results for brick problem**
  - **partonic level & hadronic level**
- **Summary**

The issue

- **Jet interacts with QGP and loses energy:**

- **Two energy loss mechanisms: inelastic and elastic**





- **Several formalisms developed, I will focus on AMY.**

Methodology

- **Evolve jet distributions by a set of coupled equations**

$$\frac{dP_j(E,t)}{dt} = \sum_{ab}\int d\omega \left[P_a(E+\omega,t)\frac{d\Gamma_{a\to j}(E+\omega,\omega)}{d\omega dt} - P_j(E,t)\frac{d\Gamma_{j\to b}(E,\omega)}{d\omega dt}\right]$$

- **Partonic rates from finite temperature QCD theory**
  - $\Gamma_{tot} = \Gamma_{inel} + \Gamma_{el}$
  - **Inelastic: resum infinite number of gluon self-energy diagrams**
  - **Elastic: implemented as drag and diffusion**
- **Partons after evolution fragment into hadrons**

$$\sigma_{\rm hadron} \sim \sigma_{\rm parton} \otimes \text{parton evolution in medium} \otimes D_{\rm vacuum}$$

- **Medium-modified FF:** $\tilde{D}_{h/j}(z) = \sum_{j'}\int dp_{j'}\frac{z'}{z}P(p_{j'}|p_j)D_{h/j'}(z')$

$$\sigma_{\rm hadron} \sim \sigma_{\rm parton} \otimes \tilde{D}_{\rm medium}$$

- **AMY (Arnold, Moore and Yaffe), JHEP 0111, 057 (2001); JHEP 0112, 009 (2001); JHEP 0206, 030 (2002).**
- **Qin, Ruppert, Gale, Jeon, Moore and Mustafa, PRL 100, 072301 (2008)**
- **Qin, Ruppert, Turbide, Gale, Nonaka and Bass, PRC 76, 064907 (2007)**
- **Turbide, Gale, Jeon and Moore, PRC 72, 014906 (2005)**

What is included?

- **Partonic transition rates at leading order in α_s**
- **Dynamical medium, including HTL screening and thermal dispersion corrections**
- **Resum infinite scatterings, smooth interpolation between Bethe-Heitler limit and LPM limit**
- **Solve evolution equations for the entire distributions**
- **Keep track of subsequent evolutions of daughters**
- **Includes elastic energy loss**
- **Includes both emission and absorption processes**
- **All processes explicitly preserve detailed balance**

Limitations

- **QGP is assumed thermalized**
- **Perturbative treatment, high temperature $T \to \infty$, weak coupling limit $g \ll 1$**
- **Hard partons come in on-shell, no virtuality evolution, no interference between vacuum and medium radiation**
- **Partonic rates determined for an extended medium**
  - **Valid for $L \gg l_{coh} = \omega/k_\perp^2 = (\lambda\omega/\mu^2)^{1/2}$**
  - **Bound for radiated energy: $\omega \ll E_{fact} = \mu^2 L^2/\lambda$**
- **Not complete for rare high-energy radiation**
  - **RHIC: $\mu \sim 0.5$GeV, L~5fm, $\lambda \sim 1$fm $\Longrightarrow E_{fact} \sim 30$GeV**
- **But many low-energy emissions are more important to R_{AA} in HIC due to initial deep falling spectra (while E-loss more dominated by rare high-energy emissions)**

A simple example

- Assume initially a power law spectrum $dN/dp = 1/p^8$

- Consider two cases both with 20% of energy loss
- (1) 20% of particles lose all their energy, 80% no energy loss
  - Final $dN/dp = (1-0.2)/p^8 = 0.8/p^8$
  - $R_{AA} = 0.8$
- (2) All particles lose 20% of their energy
  - Final $dN/dp = 1/[p/(1-0.2)]^8 = 0.8^8/p^8$
  - $R_{AA} = 0.8^8=0.2$

- R_{AA} is more sensitive to many soft emissions
- Only using average energy loss is not enough, and can be very wrong!

Brick results on partonic level

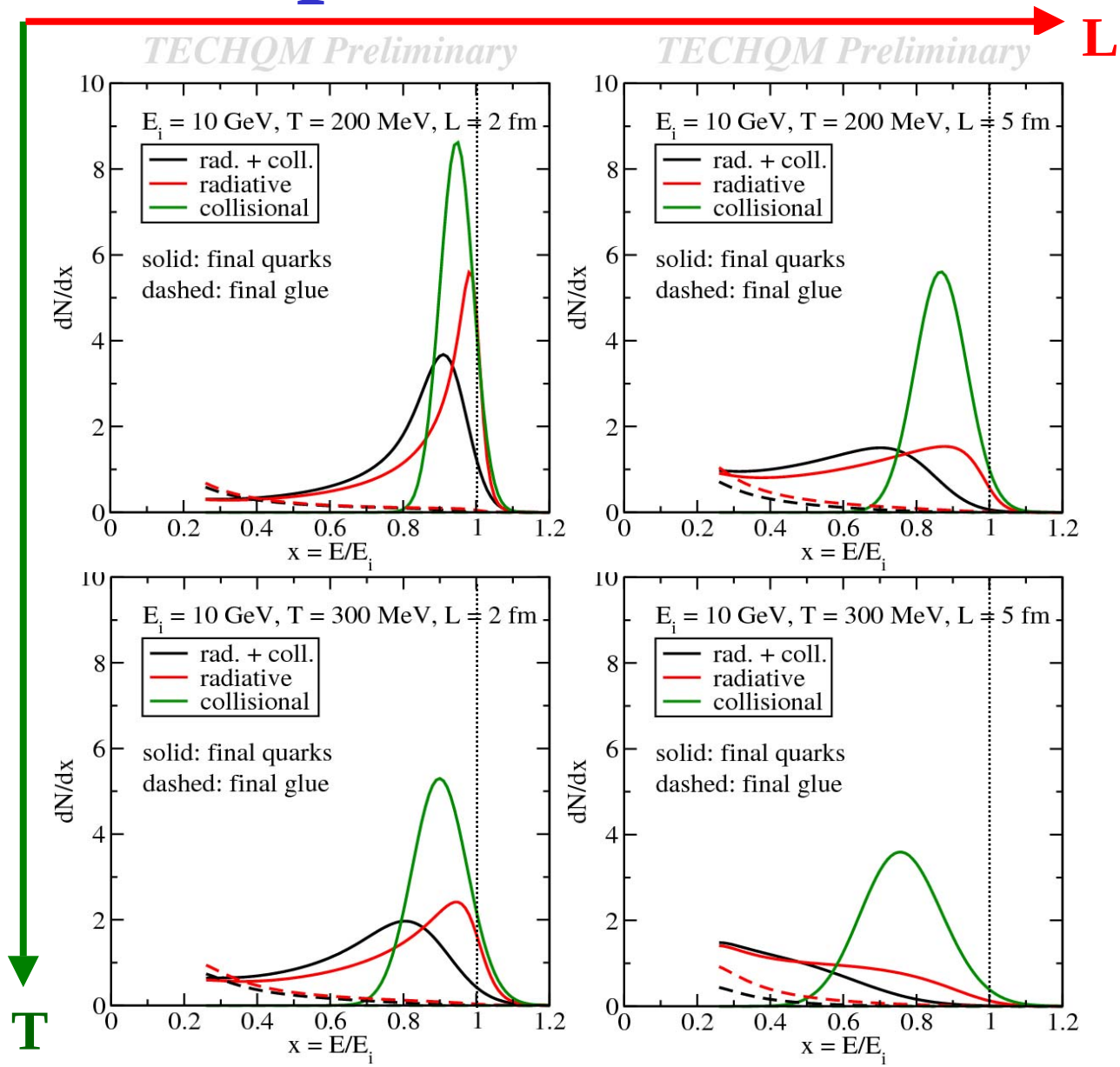
L & T dependence

- E_i=10GeV
- E_{min}=2.5GeV

- L=2fm
⇒ L=5fm

- T=200MeV
⇒ T=300MeV

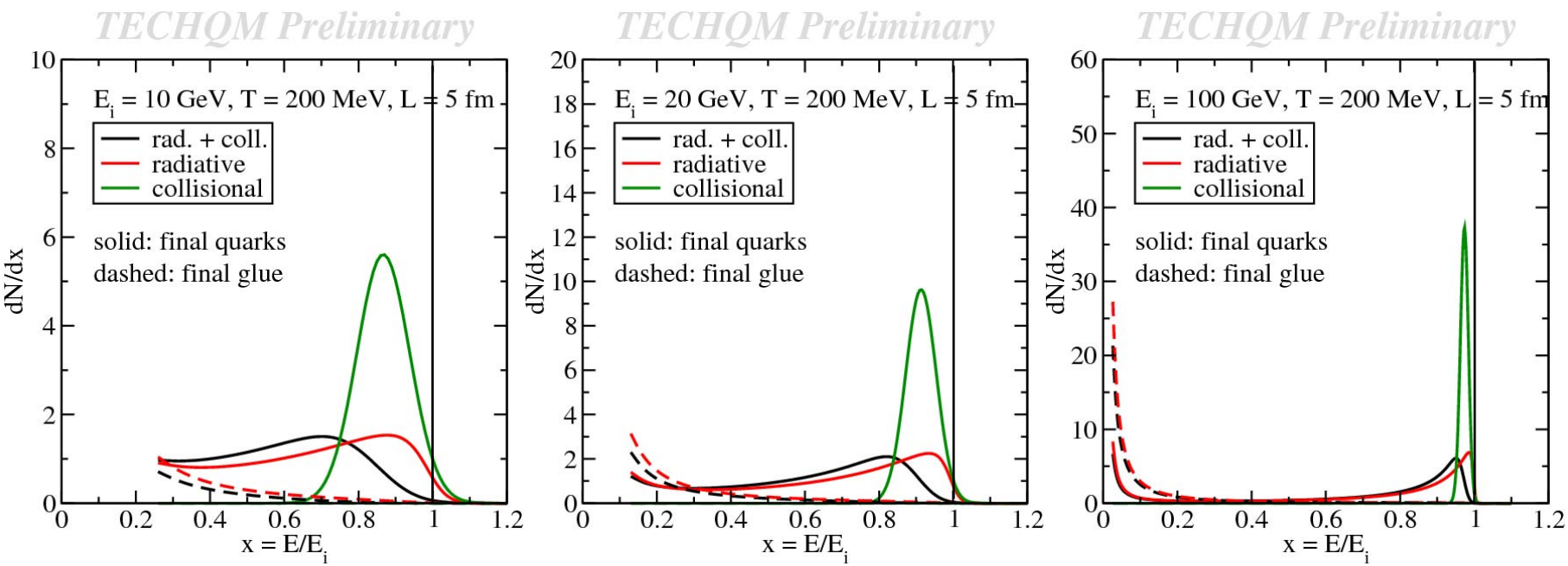
- Increasing T/L makes larger shift and broadening



E dependence

- **T=200MeV, L=5fm, E_{min}=2.5GeV**

- **E_i=10GeV ⇒ E_i=20GeV ⇒ E_i=100GeV**

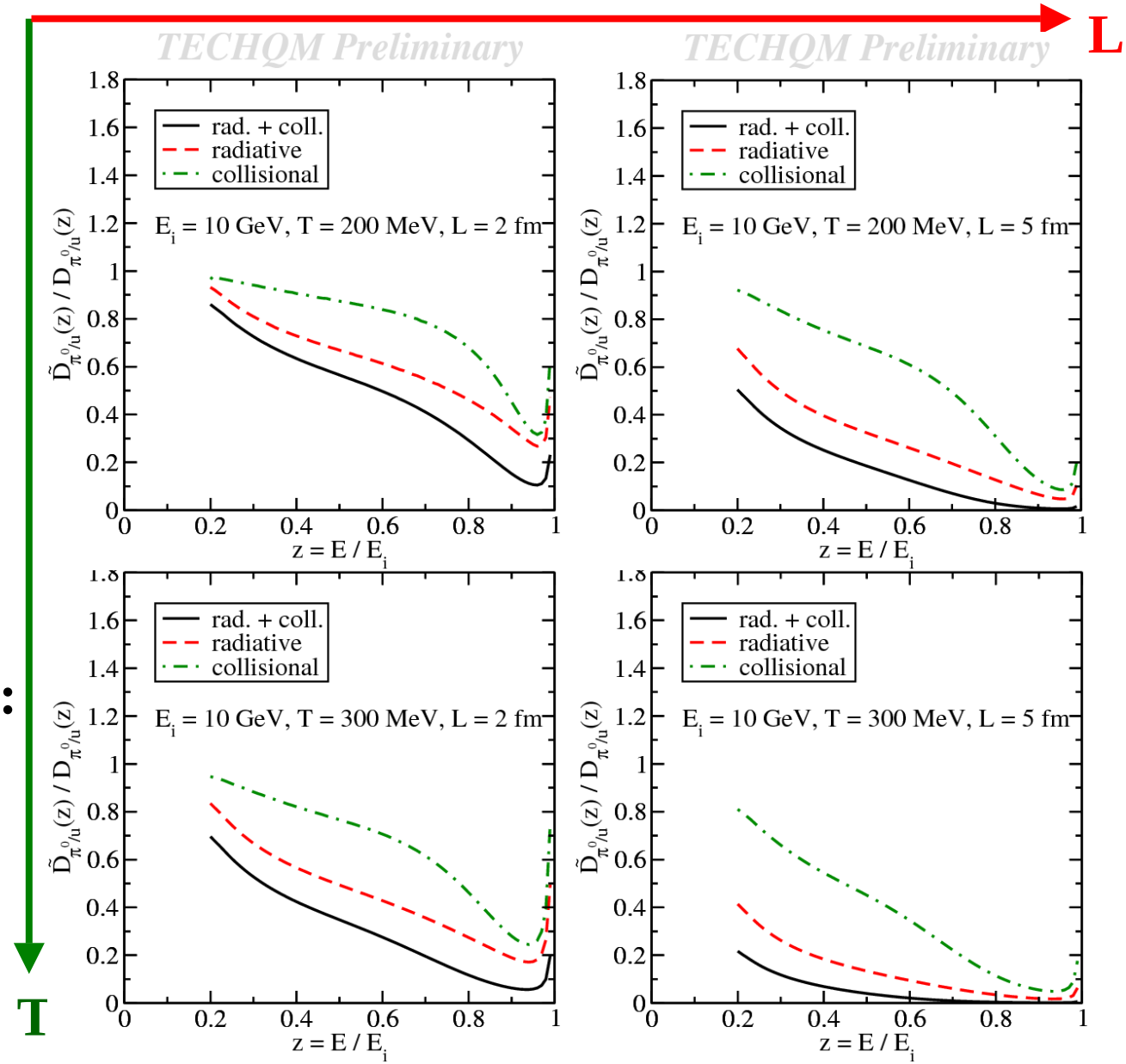


- **Higher energy jet loses smaller fraction of energy**
- **Lots of low-energy partons produced by high energy jet**

Brick results on hadronic level

Medium-modified FF

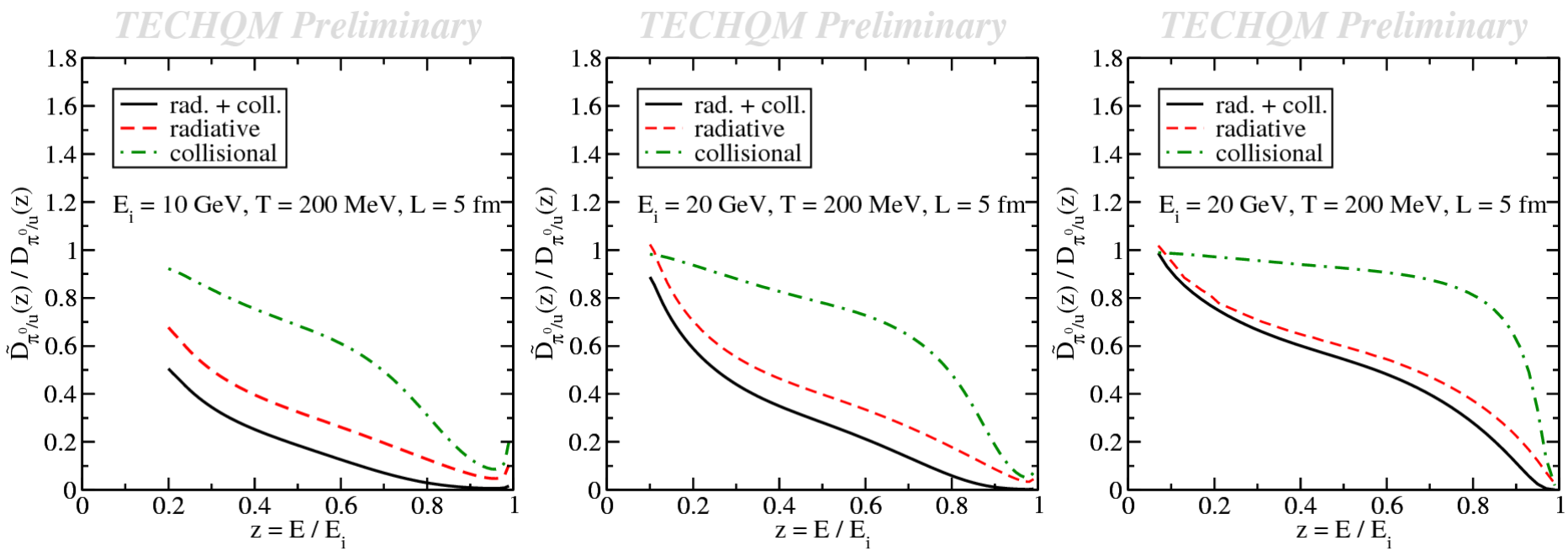
- E_i=10GeV
- L=2fm
- ⇒ L=5fm
- T=200MeV
- ⇒ T=300MeV
- Vacuum KKP : frag. scale as hadron momentum



Medium-modified FF

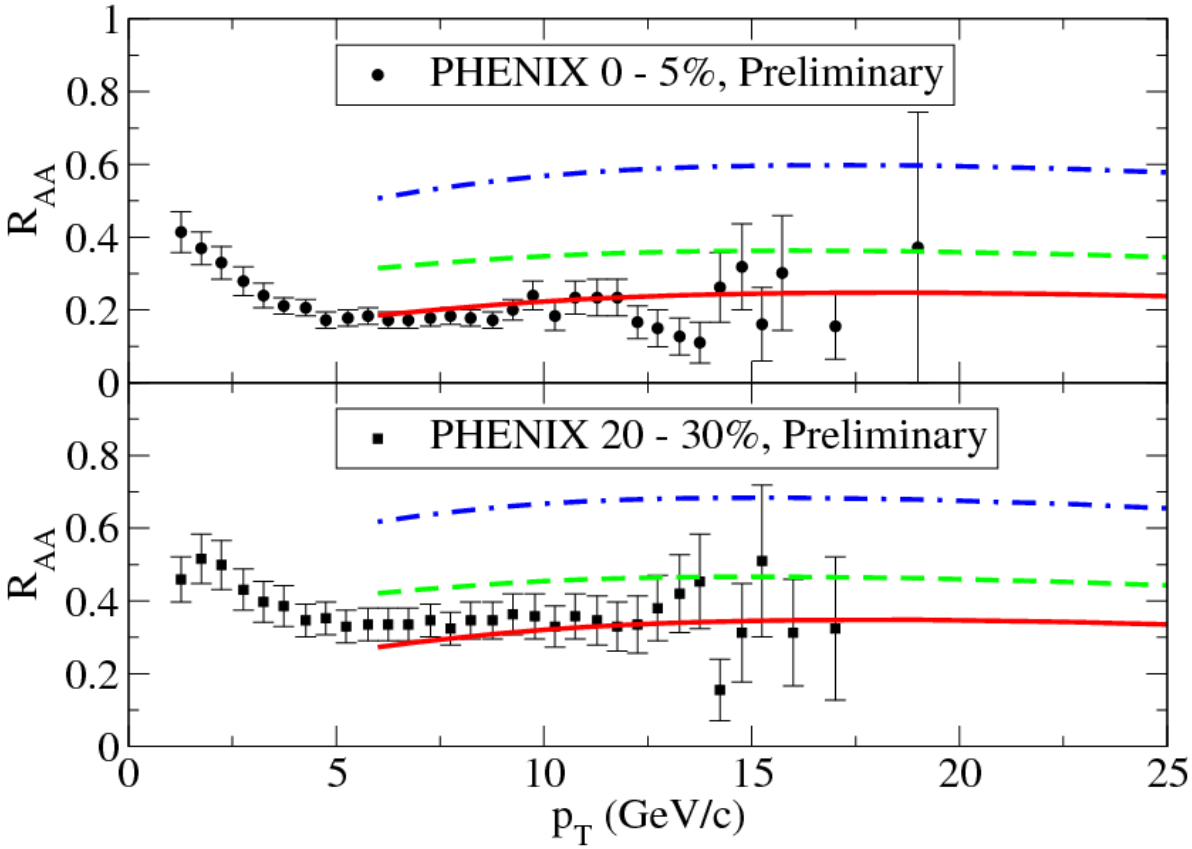
- **T=200MeV, L=5fm**

- **E_i=10GeV ⇒ E_i=20GeV ⇒ E_i=100GeV**



- **Vacuum KKP : frag. scale as hadron momentum**

R_{AA} @ RHIC



Red: tot. Green: rad. Blue: coll.

- **Medium evolution: 3D hydrodynamics** (Nonaka and Bass, 2007)
- **Initial jet spectra: pQCD**
- **Initial collision Geometry: Glauber model**
- **Jet-medium interaction: AMY**

- Qin, Ruppert, Gale, Jeon, Moore and Mustafa, PRL 100, 072301 (2008)

Summary

- **AMY includes both inelastic and elastic jet energy loss (and gain)**

- **Numerical results for brick problem: Energy loss manifests itself differently on partonic and hadronic levels (need both)**

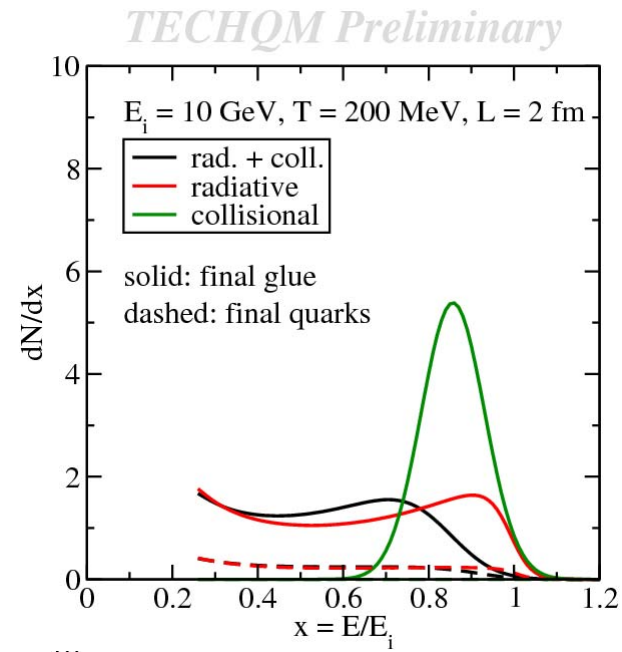
- **Separation of different energy loss mechanisms requires comparison of more observables (photons, correlations …)**

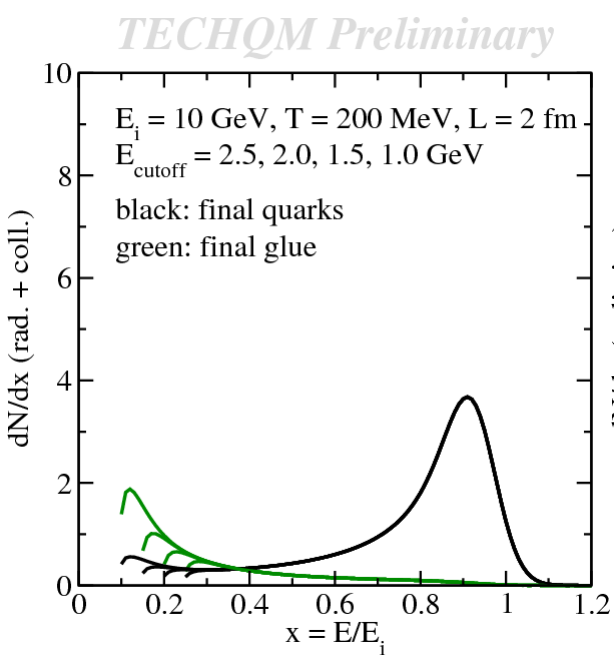
THANK YOU!

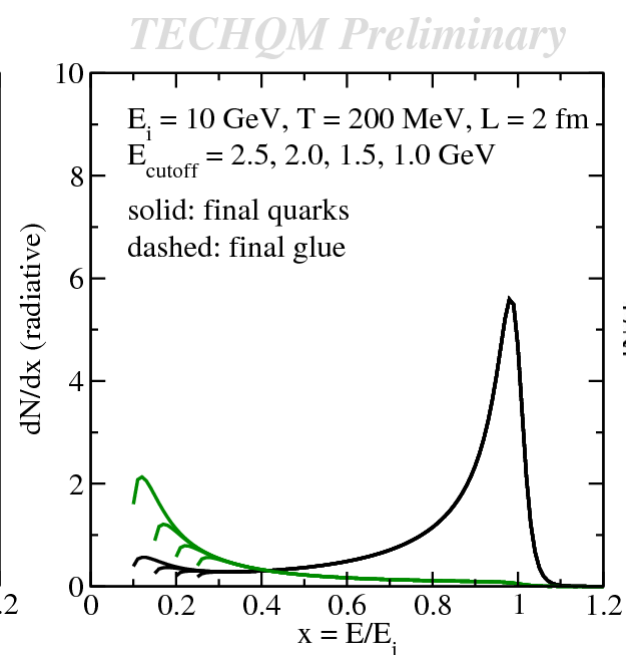
Flavour & E_{min} dependence

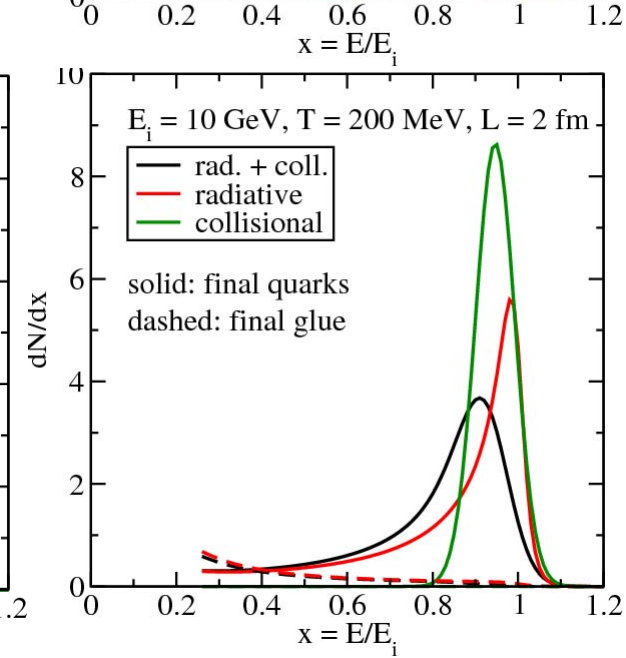
- E_i=10GeV, T=200MeV, L=2fm

- **Flavor dependence:**
  - quark v.s. gluon
- **Energy cutoff:**
  - E_{min}=2.5 ⇒ 2.0 ⇒ 1.5 ⇒ 1.0GeV









Wiedemann brick

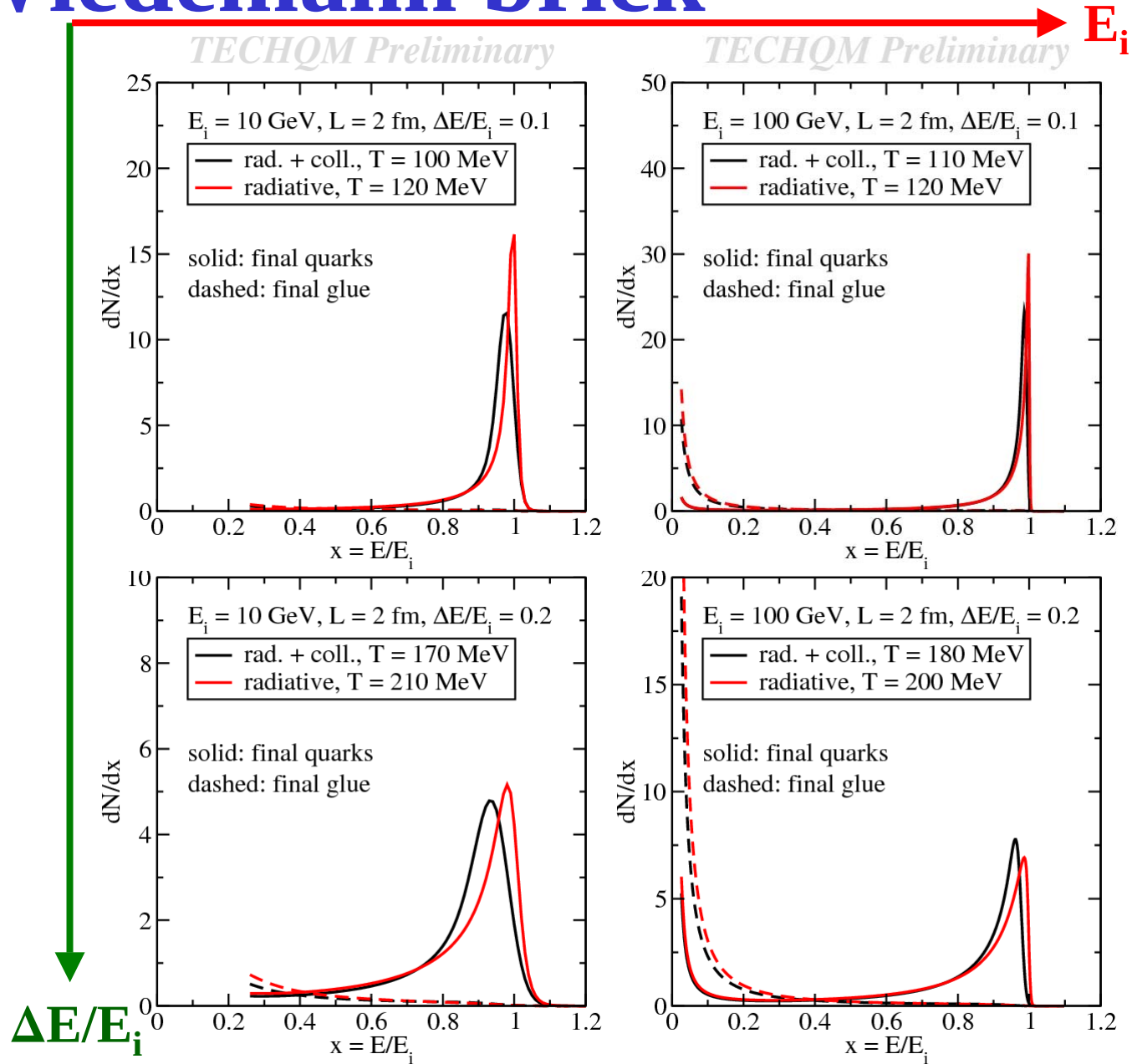
- L=2fm

- E_i=10GeV

⇒ E_i=100GeV

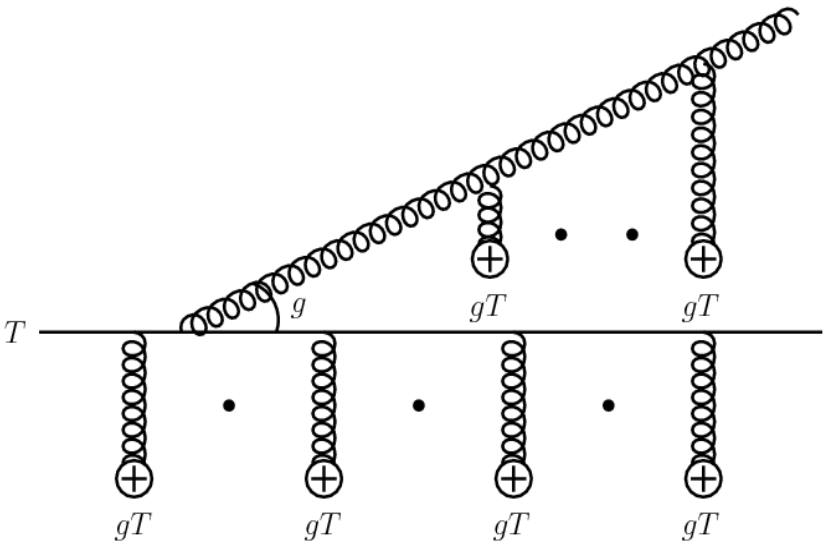
- $\Delta E/E_i$=0.1

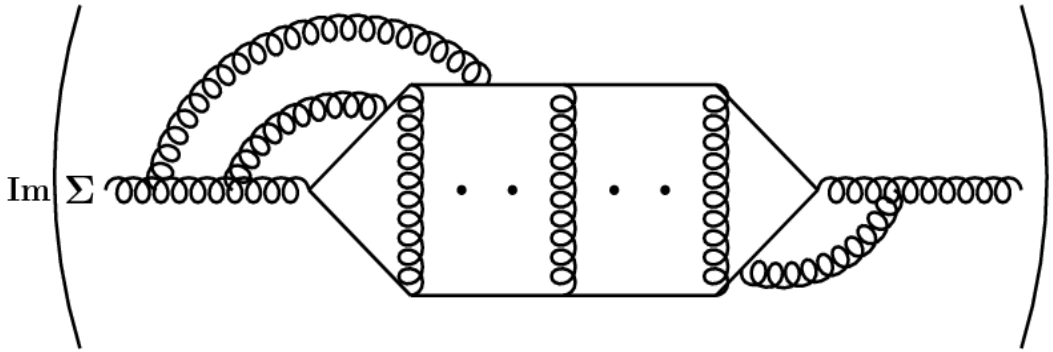
⇒ $\Delta E/E_i$=0.2



Induced gluon emission

- **High temperature medium $T \to \infty$, implying $g \ll 1$**
- **Hard parton comes in on-shell $E \sim T$, and pick up multiple soft scatterings $\mu \sim gT$**
- **LPM effect: formation time of collinear emission $t_{form} \sim 1/g^2T$, sensitive to soft scatterings**
- **Need to sum over all possible interaction points**

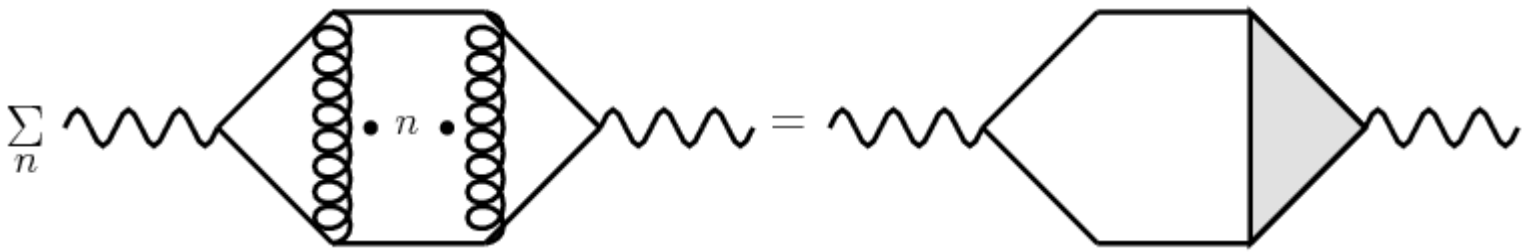




- AMY (Arnold, Moore and Yaffe), JHEP 0111, 057 (2001); JHEP 0112, 009 (2001); JHEP 0206, 030 (2002).

Resum of diagrams

- **Diagrams resummed by defining a dressed vertex**



- **The dressed vertex determined by an integral equation**

- AMY (Arnold, Moore and Yaffe), JHEP 0111, 057 (2001); JHEP 0112, 009 (2001); JHEP 0206, 030 (2002).

Evolution of parton distributions

$$\frac{dP_q(p)}{dt} = \int_k P_q(p+k)\frac{d\Gamma^q_{qg}(p+k,k)}{dkdt} - P_q(p)\frac{d\Gamma^q_{qg}(p,k)}{dkdt} + 2P_g(p+k)\frac{d\Gamma^g_{q\bar{q}}(p+k,k)}{dkdt}$$

$$\frac{dP_g(p)}{dt} = \int_k P_q(p+k)\frac{d\Gamma^q_{qg}(p+k,p)}{dkdt} + P_g(p+k)\frac{d\Gamma^g_{gg}(p+k,k)}{dkdt} - P_g(p)\left(\frac{d\Gamma^g_{q\bar{q}}(p,k)}{dkdt} + \frac{d\Gamma^g_{gg}(p,k)}{dkdt}\Theta(2k-p)\right)$$

- **k integrals range (-∞,∞)**
- **k<0: absorption of thermal partons**
- **k>p quark-anti-quark annihilation**
- ***θ*(k-p/2): prevent double counting of final states**

- Qin, Ruppert, Gale, Jeon, Moore and Mustafa, PRL 100, 072301 (2008)
- Qin, Ruppert, Turbide, Gale, Nonaka and Bass, PRC 76, 064907 (2007)
- Turbide, Gale, Jeon and Moore, PRC 72, 014906 (2005)

Collisional energy loss

- **Include collisional E-loss by calculating the drag and diffusion terms in Fokker-Planck equations**

$$\frac{dP(E)}{dt} = \frac{d}{dE}[A \times P(E)] + \frac{d^2}{dE^2}[B \times P(E)] + \cdots.,$$

- **The coefficients A & B determined by detailed balance**

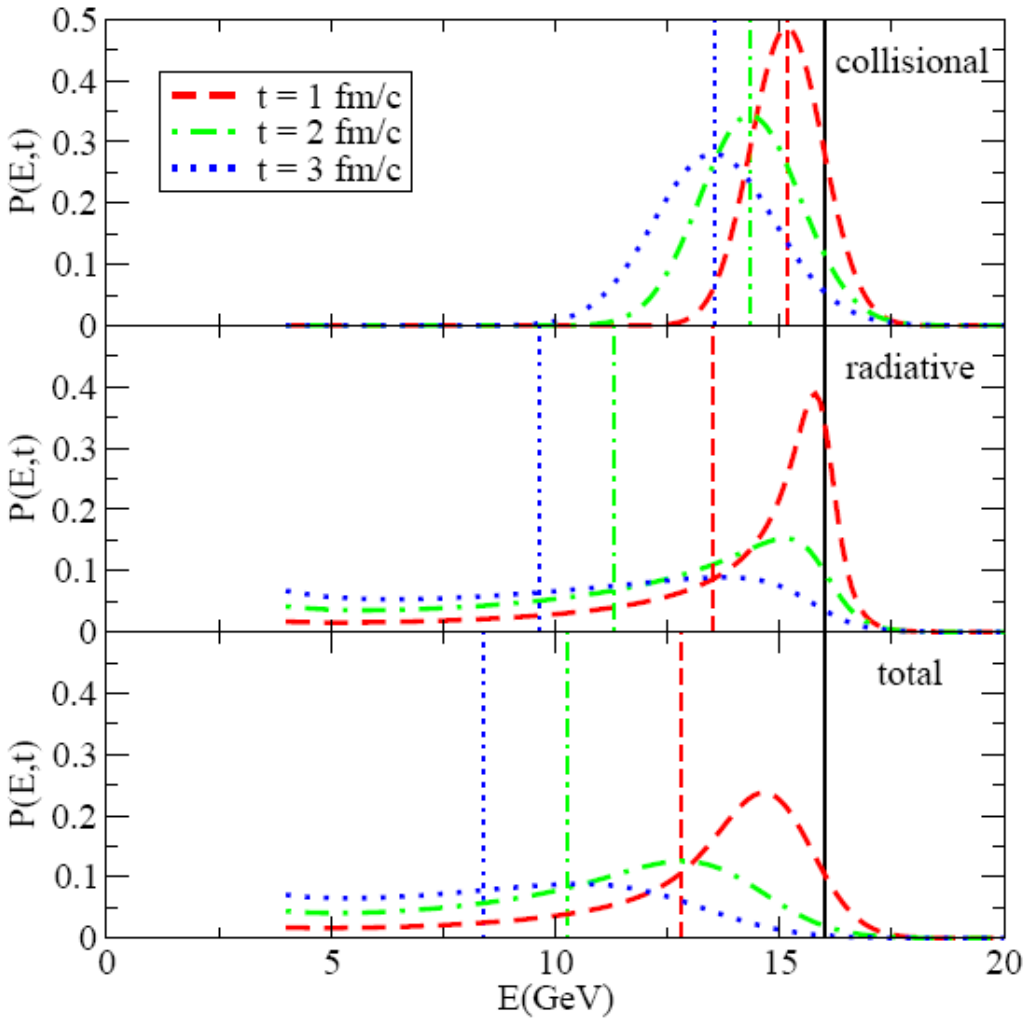
$$A = \int d\omega\omega \frac{d\Gamma(E,\omega)}{d\omega dt} = \frac{dE}{dt}, \quad B = \frac{1}{2}\int d\omega\omega^2 \frac{d\Gamma(E,\omega)}{d\omega dt} = T\frac{dE}{dt}$$

- **We calculate energy loss rate from kinetic theory**

$$\begin{aligned}\frac{dE}{dt} &= \frac{d_k}{2E}\int_{k,p',k'} (2\pi)^4\delta^4(P+K-P'-K')|\bar{M}|^2 f(k)[1 \pm f(k')] \\ &= C_{\rm coll}\pi\alpha_s^2 T^2\left[\ln\frac{ET}{m_g^2} + D_{\rm coll}\right]\end{aligned}$$

- Qin, Ruppert, Gale, Jeon, Moore and Mustafa, PRL 100, 072301 (2008)

Putting together: rad. vs coll.



- **Thermal medium: T=400MeV**
- **Evolve the entire jet distributions in the FP equations**
- **Both emission and absorption included**
- **Radiated particles tracked**

- Qin, Ruppert, Gale, Jeon, Moore and Mustafa, PRL 100, 072301 (2008)