Quenching of hadron spectra in cold and hot media

François Arleo

CERN

Trento – September 2005

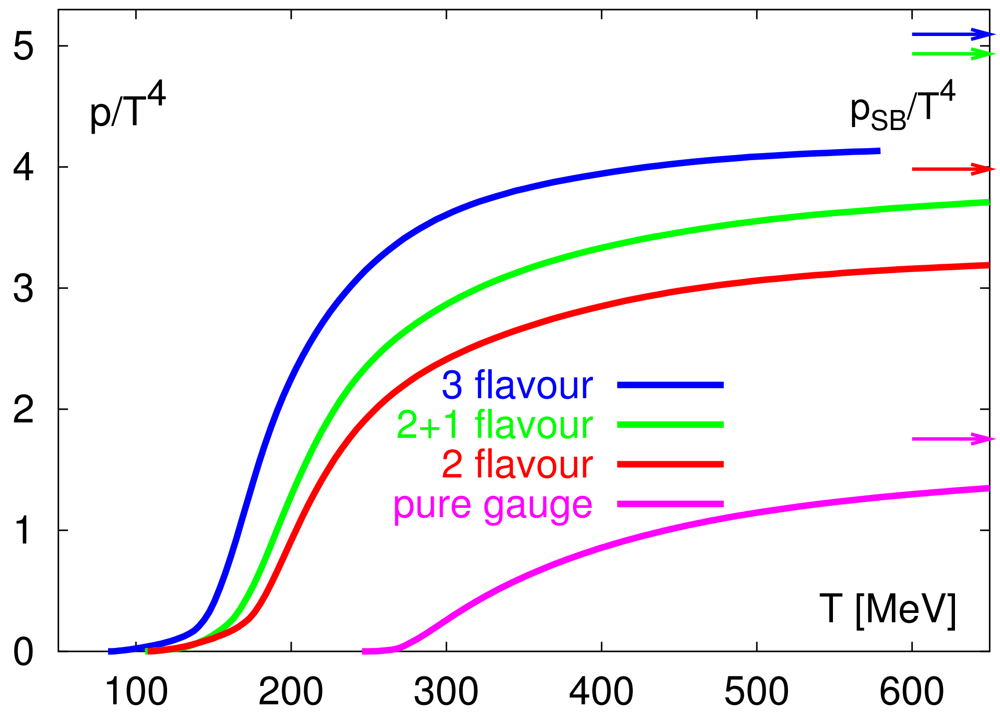
Outline

- Motivations
  - Energy loss and deconfinement
- Hadron production in DIS on nuclei
  - Model for nuclear fragmentation functions
  - Results and comparison to data
- From cold to hot matter
  - Quenching of pion and photon spectra
  - RHIC energy density
- Summary

[FA, EPJ C30 (2003) 213 + work in preparation]

Motivations

Phase transition at high temperature from hadronic matter to quark-gluon plasma



[Karsch et al. 2001]

Motivations

Phase transition at high temperature from hadronic matter to quark-gluon plasma

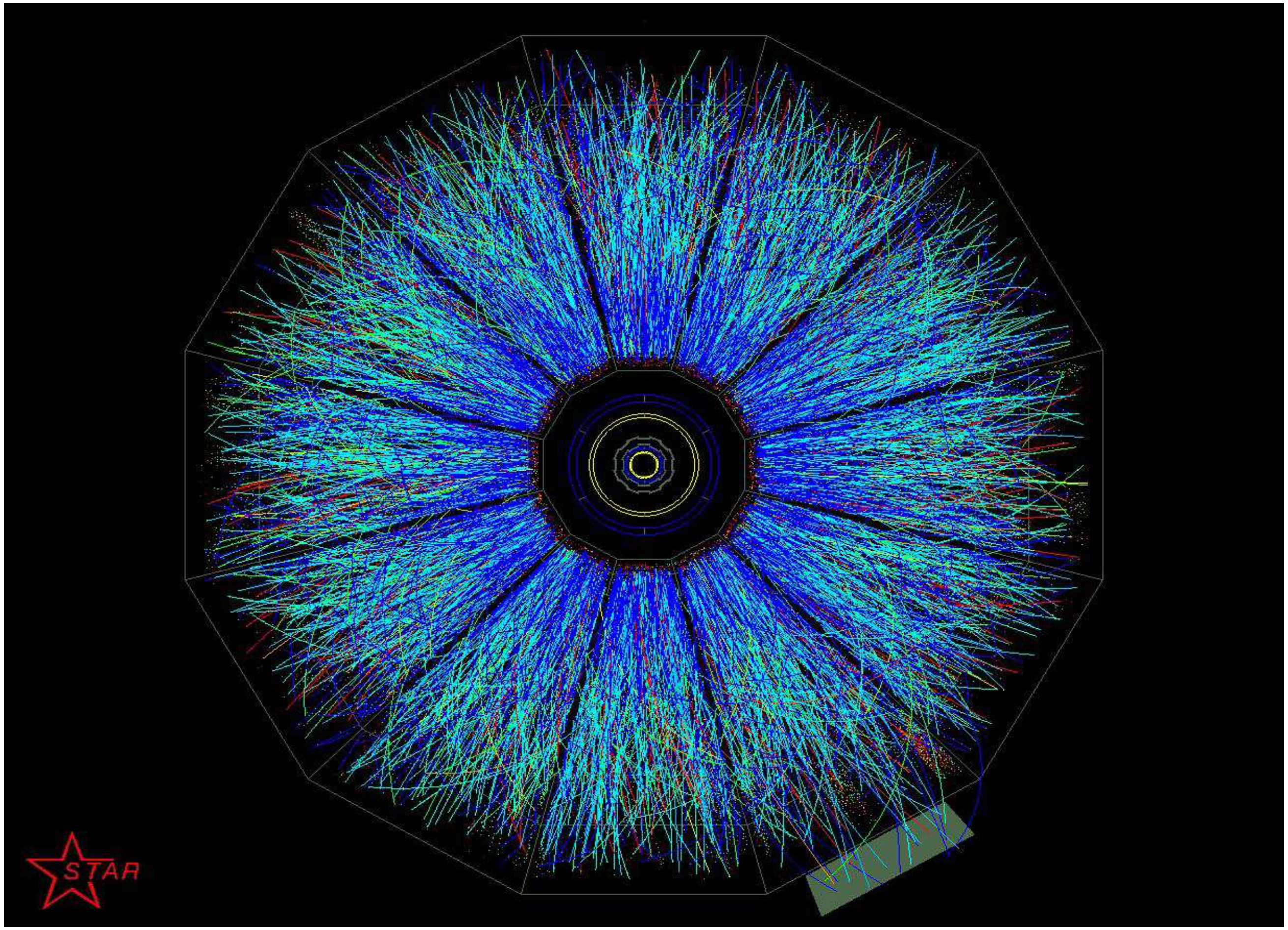
How to achieve such conditions ?

Ultra-relativistic heavy ion collisions

Motivations

- SPS (CERN), since 1994
  - Pb-Pb at $\sqrt{s} \simeq 20$ GeV
  - NA44, NA49, NA50, WA97, WA98, CERES . . .
- RHIC (Brookhaven), since 2000
  - Au-Au at $\sqrt{s} \simeq 200$ GeV
  - BRAHMS, PHENIX, PHOBOS, STAR
- LHC (CERN), starting from 2007
  - Pb-Pb at $\sqrt{s} = 5.5$ TeV
  - ALICE, CMS

Motivations

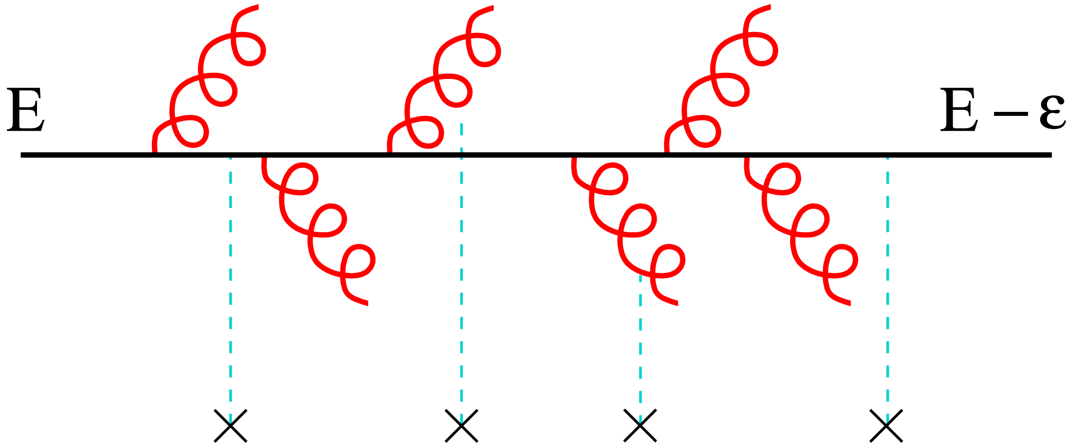


What – in that mess – could signal deconfinement ?

Parton energy loss

Multiple soft collisions incurred by hard partons

- Gluon radiation $dI/d\omega$ proportional to the medium density



[Baier, Dokshitzer, Mueller, Peigné, Schiff 1996, 1997]
[Gyulassy, Wang 1994; Gyulassy, Lévai, Vitev 2000]
[Zakharov 1996 1997 1998 ; Wiedemann 2000 2001]

Parton energy loss

Multiple soft collisions incurred by hard partons

- Gluon radiation $dI/d\omega$ proportional to the medium density
- Energy loss expected to be huge in quark-gluon plasma

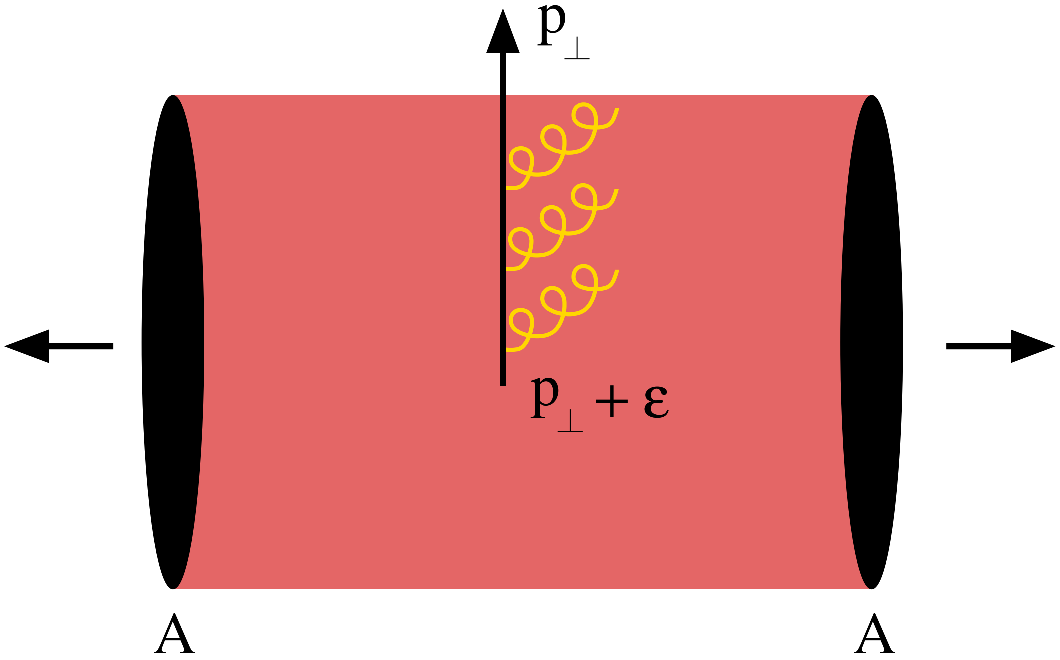
Parton energy loss

Multiple soft collisions incurred by hard partons

- Gluon radiation $dI/d\omega$ proportional to the medium density
- Energy loss expected to be huge in quark-gluon plasma

Which signal ?

Jet quenching



A clear experimental observable

Quenching of jets in heavy ion collisions

[Bjorken 1982; Gyulassy & Wang 1992]

Parton energy loss

Multiple soft collisions incurred by hard partons

- Gluon radiation $dI/d\omega$ proportional to the medium density
- Energy loss expected to be huge in quark-gluon plasma

What happens in a cold QCD medium ?

Analysis

Aim

- To explore quark energy loss in nuclei

Analysis

Aim

- To explore quark energy loss in nuclei

How ?

- Hadron production in DIS on nuclear targets
  - Sensitive to quark energy loss
  - A lot of new data

Analysis

Aim

- To explore quark energy loss in nuclei

How ?

- Hadron production in DIS on nuclear targets
  - Sensitive to quark energy loss
  - A lot of new data

Analysis of hadron production compared to HERMES and EMC measurements

Caveat

Several nuclear effects into the game

- Energy loss
  - Parton multiple scattering
- Nuclear absorption
  - Hadron inelastic interaction
- Partial deconfinement
  - Rescaling of virtuality Q^2
- ...

Caveat

Several nuclear effects into the game

- Energy loss
  - Parton multiple scattering
- Nuclear absorption
  - Hadron inelastic interaction
- Partial deconfinement
  - Rescaling of virtuality Q^2

Let's focus here only on energy loss

(for the time being)

Quenching of hadron spectra

LO hadron production in DIS on nuclei

$$\frac{1}{N_A^e}\frac{dN_A^h(\nu,z)}{d\nu\, dz} \simeq \int dx \sum_{q,\bar{q}} e_q^2\, x\, f_q^{N/A}(x,Q^2)\, D_q^h(z,Q^2,A) \Big/ \int dx \sum_{q,\bar{q}} e_q^2\, x\, f_q^{N/A}(x,Q^2)$$

- $f_q^{N/A}(x,Q^2)$: MRST 2001 LO
- $D_q^h(z,Q^2,A)$: Kretzer 2000 LO

Quenching of hadron spectra

LO hadron production in DIS on nuclei

$$\frac{1}{N_A^e}\frac{dN_A^h(\nu, z)}{d\nu\, dz} \simeq D_u^h(z, Q^2, A) \qquad (\, x \simeq 0.1 \,)$$

Quenching of hadron spectra

LO hadron production in DIS on nuclei

$$\frac{1}{N_A^e} \frac{dN_A^h(\nu, z)}{d\nu\, dz} \simeq D_u^h(z, Q^2, A) \qquad (\, x \simeq 0.1\,)$$

Nuclear production ratio

$$R_A^h(z, \nu) = \frac{1}{N_A^e} \frac{dN_A^h(\nu, z)}{d\nu\, dz} \Bigg/ \frac{1}{N_D^e} \frac{dN_D^h(\nu, z)}{d\nu\, dz}$$

Quenching of hadron spectra

LO hadron production in DIS on nuclei

$$\frac{1}{N_A^e}\frac{dN_A^h(\nu,z)}{d\nu\,dz} \simeq D_u^h(z,Q^2,A) \qquad (\,x \simeq 0.1\,)$$

Nuclear production ratio

$$R_A^h(z,\nu) \simeq D_u^h(z,Q^2,A) \Big/ D_u^h(z,Q^2,D)$$

Quenching of hadron spectra

LO hadron production in DIS on nuclei

$$\frac{1}{N_A^e}\frac{dN_A^h(\nu, z)}{d\nu\, dz} \simeq D_u^h(z, Q^2, A) \qquad (\, x \simeq 0.1 \,)$$

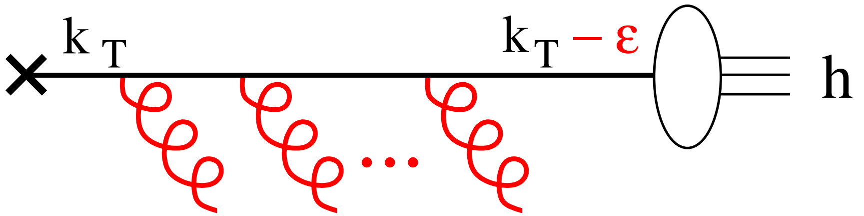
Nuclear production ratio

$$R_A^h(z, \nu) \simeq D_u^h(z, Q^2, A) \Big/ D_u^h(z, Q^2, D)$$

How does the nuclear medium affect fragmentation ?

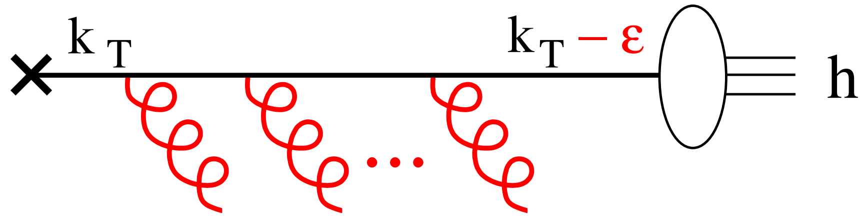
Model

Multiple scatterings shift quark energy from $k_\perp$ to $k_\perp - \epsilon$



Model

Multiple scatterings shift quark energy from $k_\perp$ to $k_\perp - \epsilon$



Model for fragmentation functions

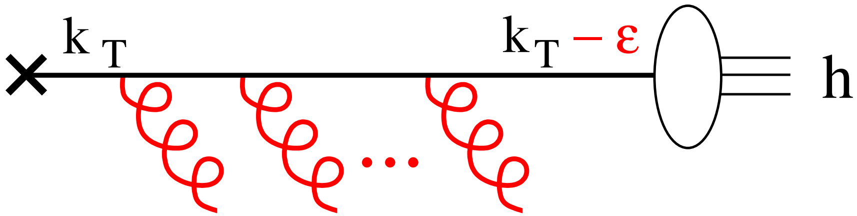
[Wang, Huang, Sarcevic 1996]

$$z D_{h/k}^{med}(z,\mu) = \int_0^{(1-z)E} d\epsilon \; \mathcal{P}(\epsilon, E) \;\; z^* \, D_{h/k}(z^*, \mu)$$

$$\text{with} \;\; z^* = \frac{E_h}{E - \epsilon} = \frac{z}{1 - \epsilon/E}$$

Model

Multiple scatterings shift quark energy from $k_\perp$ to $k_\perp - \epsilon$



Model for fragmentation functions

[Wang, Huang, Sarcevic 1996]

$$z D_{h/k}^{med}(z,\mu) = \int_0^{(1-z)E} d\epsilon \, \mathcal{P}(\epsilon, E) \, z^* \, D_{h/k}(z^*, \mu)$$

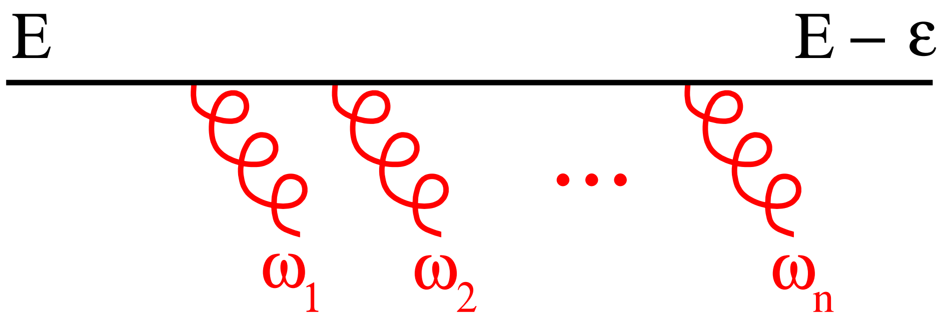
$$\text{with} \quad z^* = \frac{E_h}{E - \epsilon} = \frac{z}{1 - \epsilon/E}$$

How to compute $\mathcal{P}(\epsilon, E)$?

Quenching weight

[Baier, Dokshitzer, Mueller, Schiff 2001]

Independent gluon radiation ➛ Poisson approximation

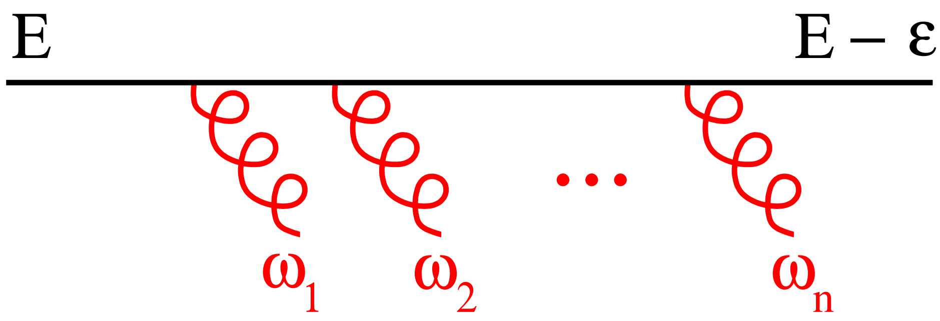


$$\mathcal{P}(\epsilon) \propto \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i \right)$$

Quenching weight

[Baier, Dokshitzer, Mueller, Schiff 2001]

Independent gluon radiation ➛ Poisson approximation



$$\mathcal{P}(\epsilon) \propto \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i\right)$$

- Unique ingredient: gluon spectrum $dI/d\omega$

Quenching weight

[Baier, Dokshitzer, Mueller, Schiff 2001]

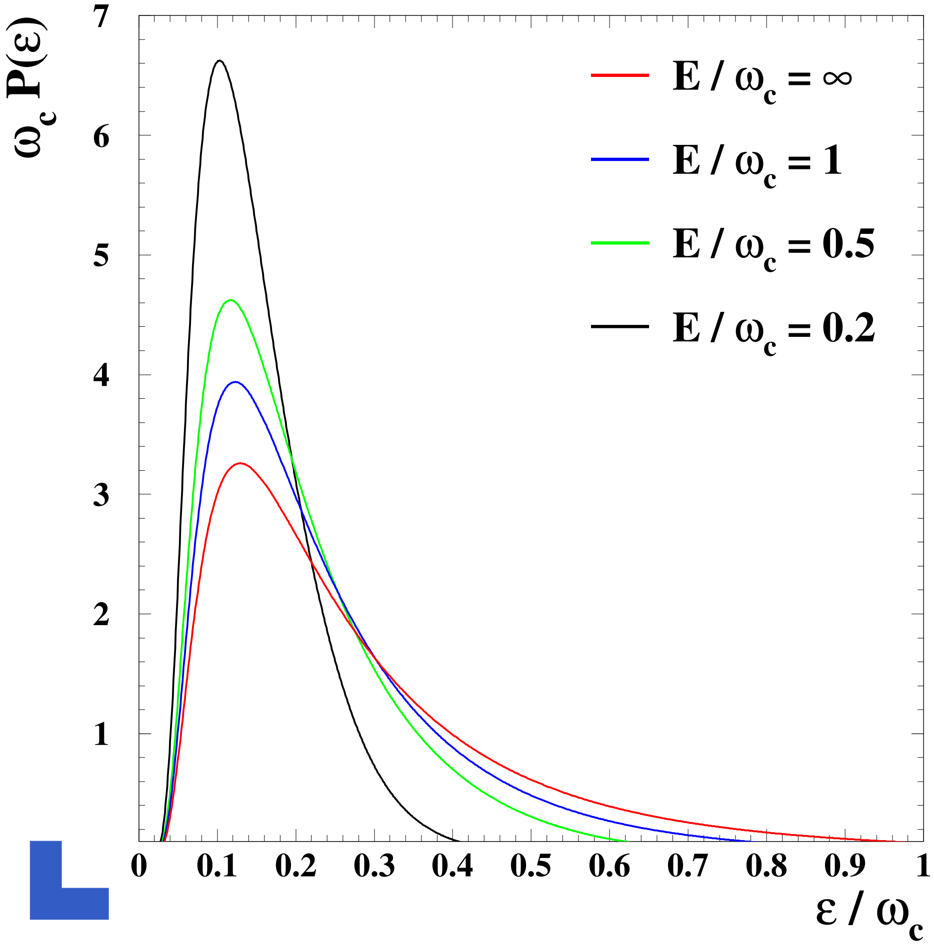
Relevant scale for the induced gluon spectrum $dI/d\omega$

$$\omega_c = \frac{1}{2}\,\hat{q}\,L^2$$

- $\hat{q}$: transport coefficient
  - scattering property of the medium (say its density)
- L : length of matter covered by the hard parton

Quenching weight

[Baier, Dokshitzer, Mueller, Schiff JHEP 2001]
[FA JHEP 2002]



Relevant scale

$$\omega_c = \frac{1}{2}\,\hat{q}\,L^2$$

Transport coefficient $\hat{q}$

Perturbative estimate

[Baier, Dokshitzer, Mueller, Peigné, Schiff NPB 1997]

$\hat{q}$ related to gluon density

$$\hat{q} = \frac{4\,\pi^2 \alpha_s\, N_c}{N_c^2 - 1}\, \rho\, x\, G(x, Q^2)$$

$$\simeq 0.25\ \mathrm{GeV/fm^2}$$

Transport coefficient $\hat{q}$

Perturbative estimate

[Baier, Dokshitzer, Mueller, Peigné, Schiff NPB 1997]

$\hat{q}$ related to gluon density

$$\hat{q} = \frac{4\,\pi^2 \alpha_s\, N_c}{N_c^2 - 1}\, \rho\, x\, G(x, Q^2)$$

$$\simeq 0.25 \text{ GeV}/\text{fm}^2$$

Constraints from Drell-Yan data

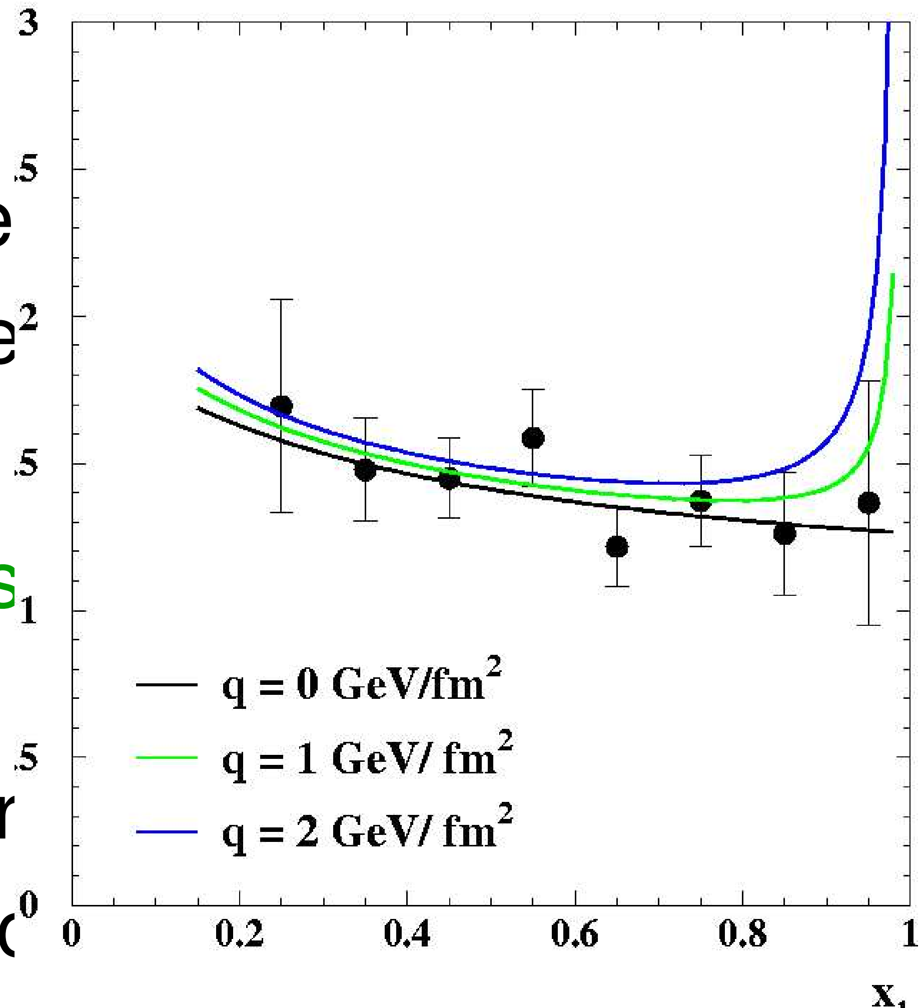
[FA PLB 2002]

Large energy loss ruled out

Transport coefficient $\hat{q}$

Perturbative estimate

[Baier, Dokshitzer, Mueller, Peigné, Schiff NPB 1997]



$\hat{q}$ relate … $\rho\, x\, G(x, Q^2)$

gluon de … $/\mathrm{fm}^2$

Constraints

FA PLB 2002]

Large ener

ruled (

Transport coefficient $\hat{q}$

Perturbative estimate

[Baier, Dokshitzer, Mueller, Peigné, Schiff NPB 1997]

$\hat{q}$ related to gluon density

$$\hat{q} = \frac{4\,\pi^2\alpha_s\,N_c}{N_c^2-1}\,\rho\,x\,G(x,Q^2)$$
$$\simeq 0.25\ \mathrm{GeV/fm^2}$$

Constraints from Drell-Yan data

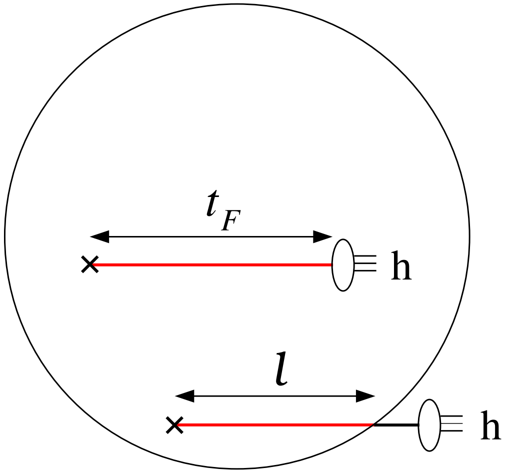
[FA PLB 2002]

Large energy loss ruled out

$$\hat{q} = 0.72 \pm 0.54\ \mathrm{GeV/fm^2}$$

Length of matter

Averaging L from a hard sphere nucleus

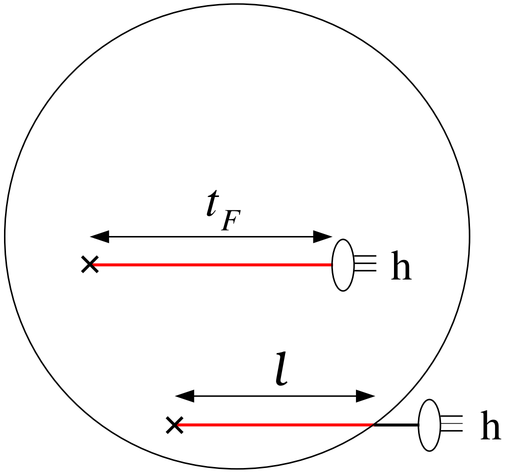


$$L = \frac{3}{4} R \qquad t_f \geq 2\,R$$

$$L = t_f \times \left[1 - \frac{3}{8}\frac{t_f}{R} + \frac{1}{64}\left(\frac{t_f}{R}\right)^3 \right]$$

Length of matter

Averaging L from a hard sphere nucleus



$$L = \frac{3}{4} R \qquad t_f \geq 2\,R$$

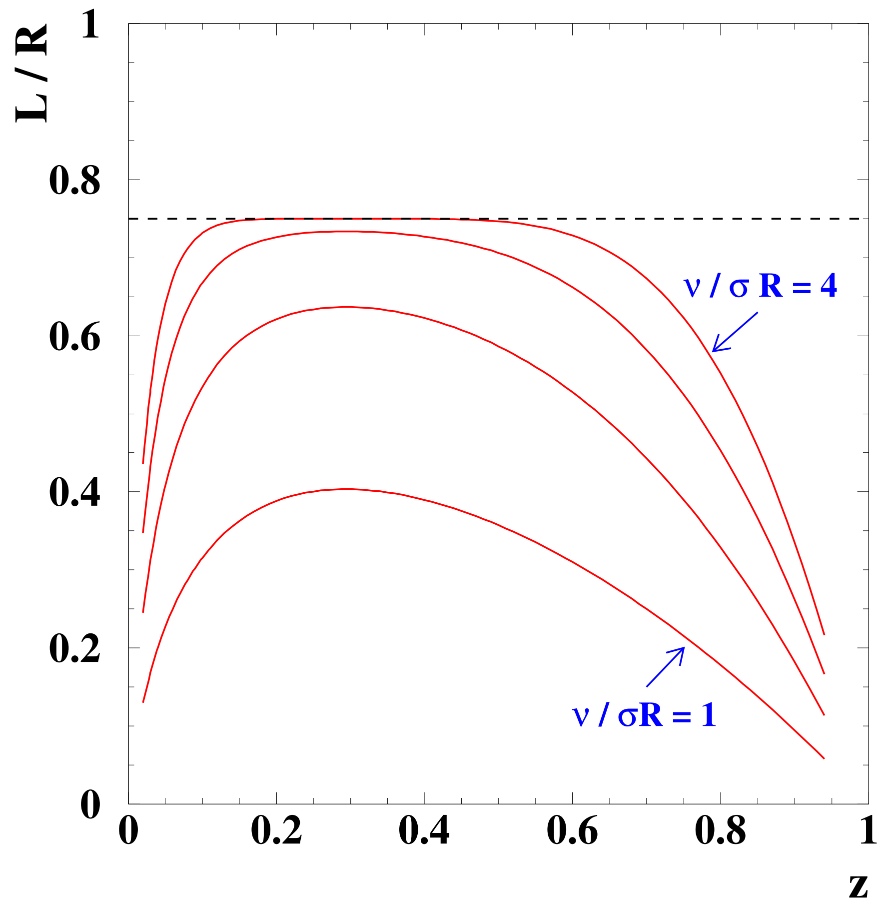
$$L = t_f \times \left[1 - \frac{3}{8} \frac{t_f}{R} + \frac{1}{64} \left(\frac{t_f}{R} \right)^3 \right]$$

Take Lund model hadron formation time t_f

$$t_f = \left(\frac{\ln(1/z^2) - 1 + z^2}{1 - z^2} \right) \times \frac{z\,\nu}{\sigma}$$

σ: string tension

Length of matter



Large formation time effects at large z and/or small ν

Hadron attenuation $R_A^h(\nu, z)$

Taking Kretzer parameterization $z\,D(z, Q^2) \sim (1-z)^\eta$

$$R_A^h(\nu, z) \simeq \frac{D(z^*, Q^2)}{D(z, Q^2)} \simeq 1 - \frac{z}{1-z}\,\frac{\epsilon}{\nu}\,\eta^h$$

Hadron attenuation $R_A^h(\nu, z)$

Taking Kretzer parameterization $z\,D(z, Q^2) \sim (1-z)^\eta$

$$R_A^h(\nu, z) \simeq \frac{D(z^*, Q^2)}{D(z, Q^2)} \simeq 1 - \frac{z}{1-z}\,\frac{\epsilon}{\nu}\,\eta^h$$

Main features

- Stronger attenuation at small ν

Hadron attenuation $R_A^h(\nu, z)$

Taking Kretzer parameterization $z\, D(z, Q^2) \sim (1-z)^\eta$

$$R_A^h(\nu, z) \simeq \frac{D(z^*, Q^2)}{D(z, Q^2)} \simeq 1 - \frac{z}{1-z}\,\frac{\epsilon}{\nu}\,\eta^h$$

Main features

- Stronger attenuation at small ν
- Competing effects at large z
  - Phase space restricted $\epsilon < \nu - E_h$

$$R_A^h(z) \sim \int_0^{(1-z)\nu} \mathcal{P}(\epsilon)$$

Hadron attenuation $R_A^h(\nu, z)$

Taking Kretzer parameterization $z\,D(z,Q^2) \sim (1-z)^\eta$

$$R_A^h(\nu,z) \simeq \frac{D(z^*,Q^2)}{D(z,Q^2)} \simeq 1 - \frac{z}{1-z}\,\frac{\epsilon}{\nu}\,\eta^h$$

Main features

- Stronger attenuation at small ν
- Competing effects at large z
  - Phase space restricted $\epsilon < \nu - E_h$

$$R_A^h(z) \sim \int_0^{(1-z)\nu} \mathcal{P}(\epsilon)$$

  - Hadronization inside the nucleus

Hadron attenuation $R_A^h(\nu, z)$

Taking Kretzer parameterization $z\, D(z, Q^2) \sim (1-z)^\eta$

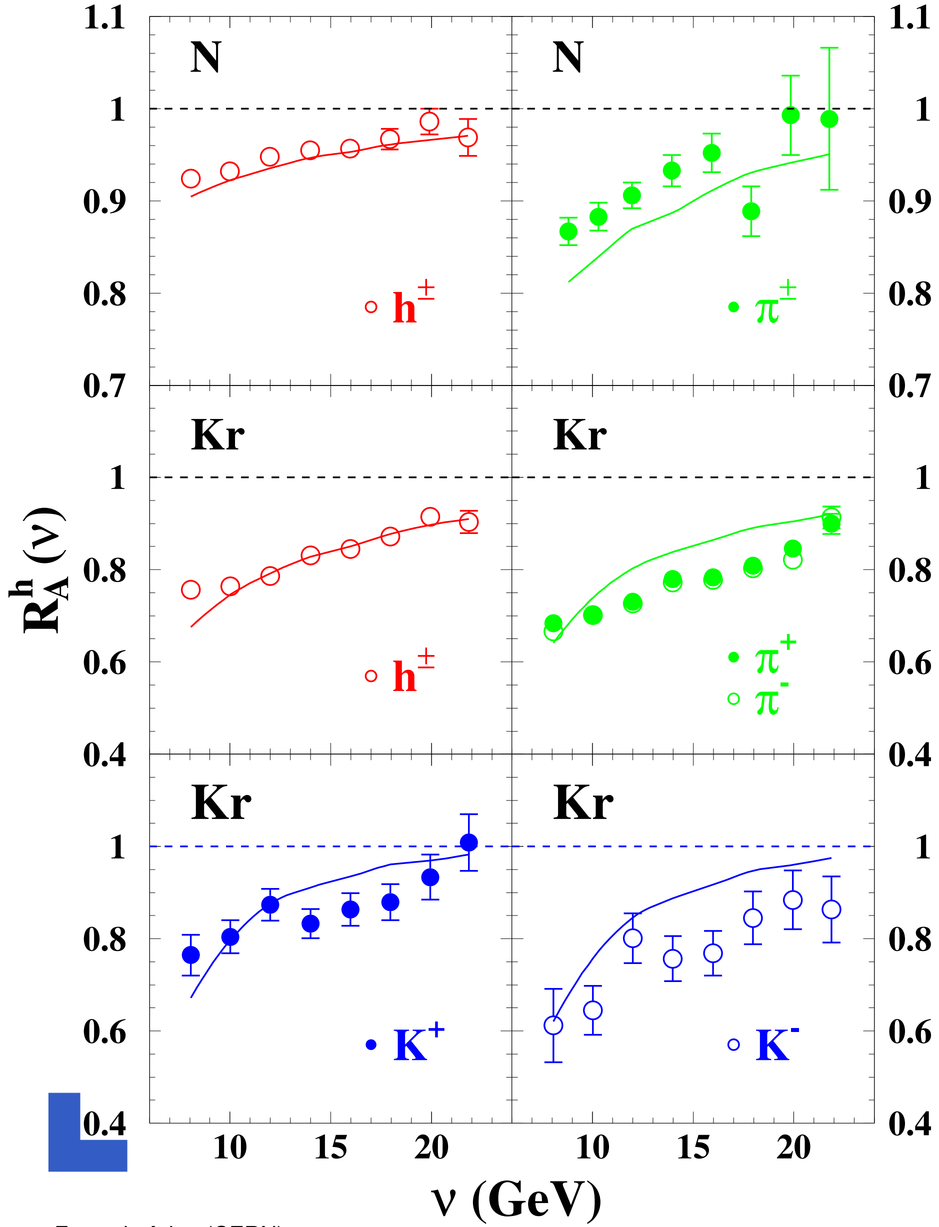
$$R_A^h(\nu, z) \simeq \frac{D(z^*, Q^2)}{D(z, Q^2)} \simeq 1 - \frac{z}{1-z}\,\frac{\epsilon}{\nu}\,\eta^h$$

Main features

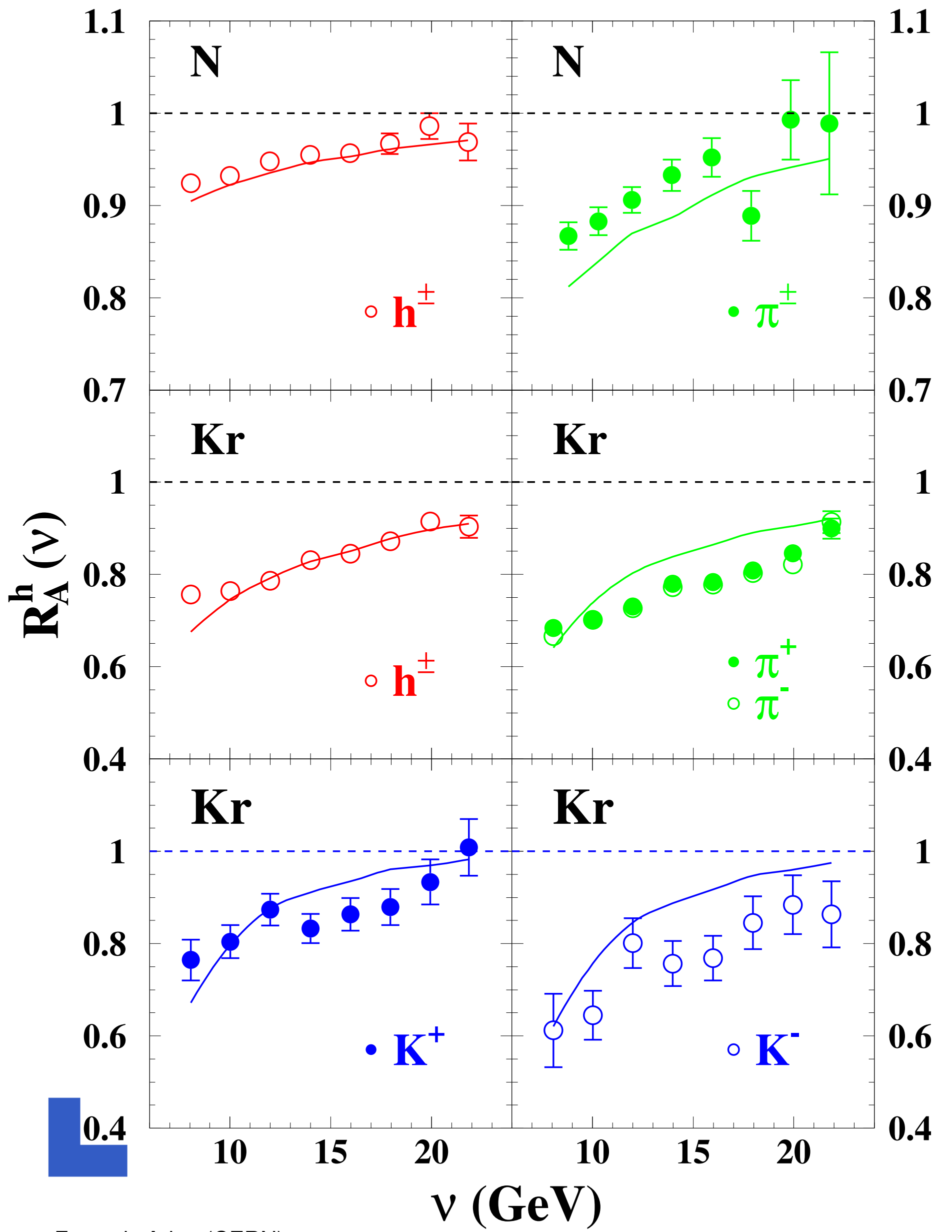
- Stronger attenuation at small ν
- Competing effects at large z
- Depletion depends on FF slopes η^h

Comparing with HERMES

[FA EPJ C 2003]



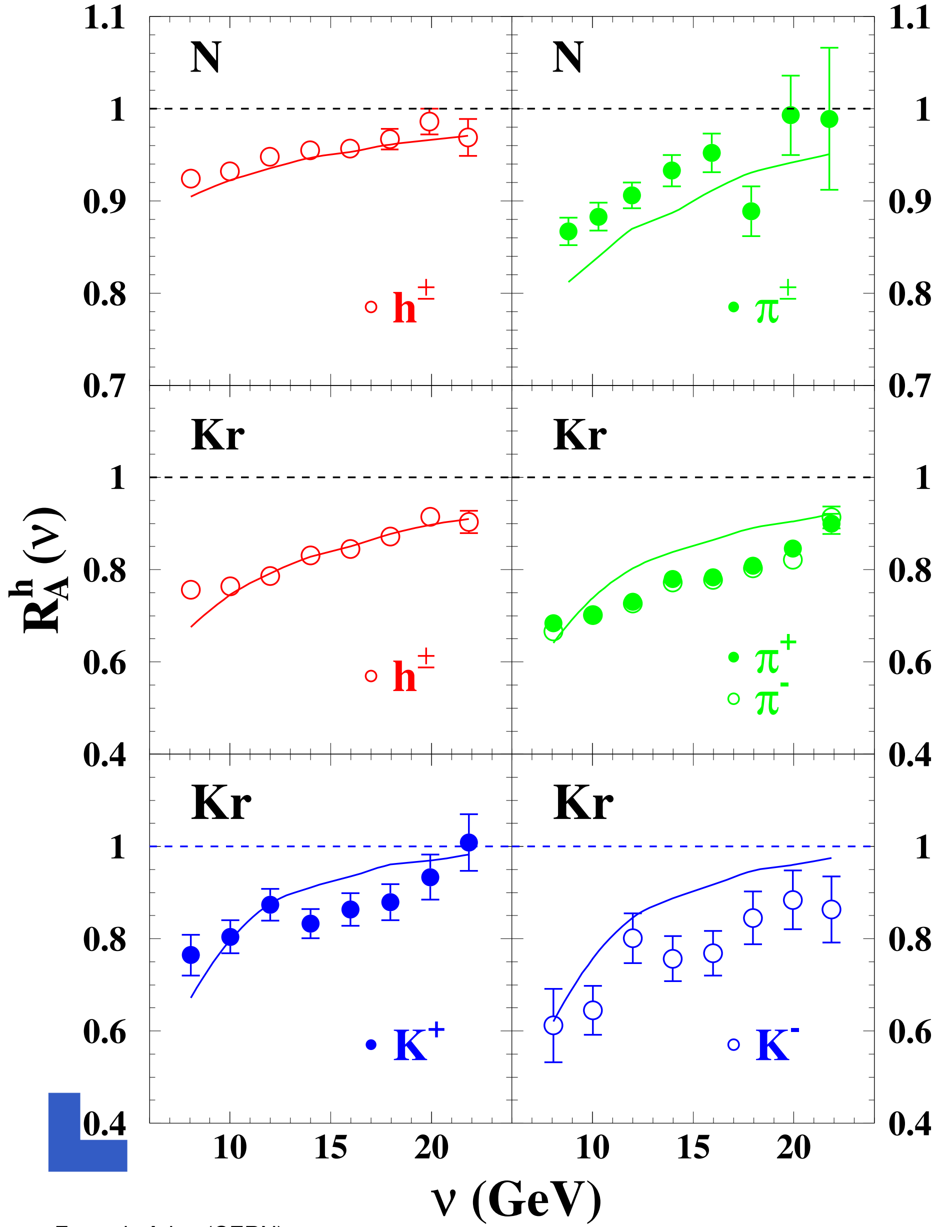
Comparing with HERMES



[FA EPJ C 2003]

- Pretty good agreement (except pions)

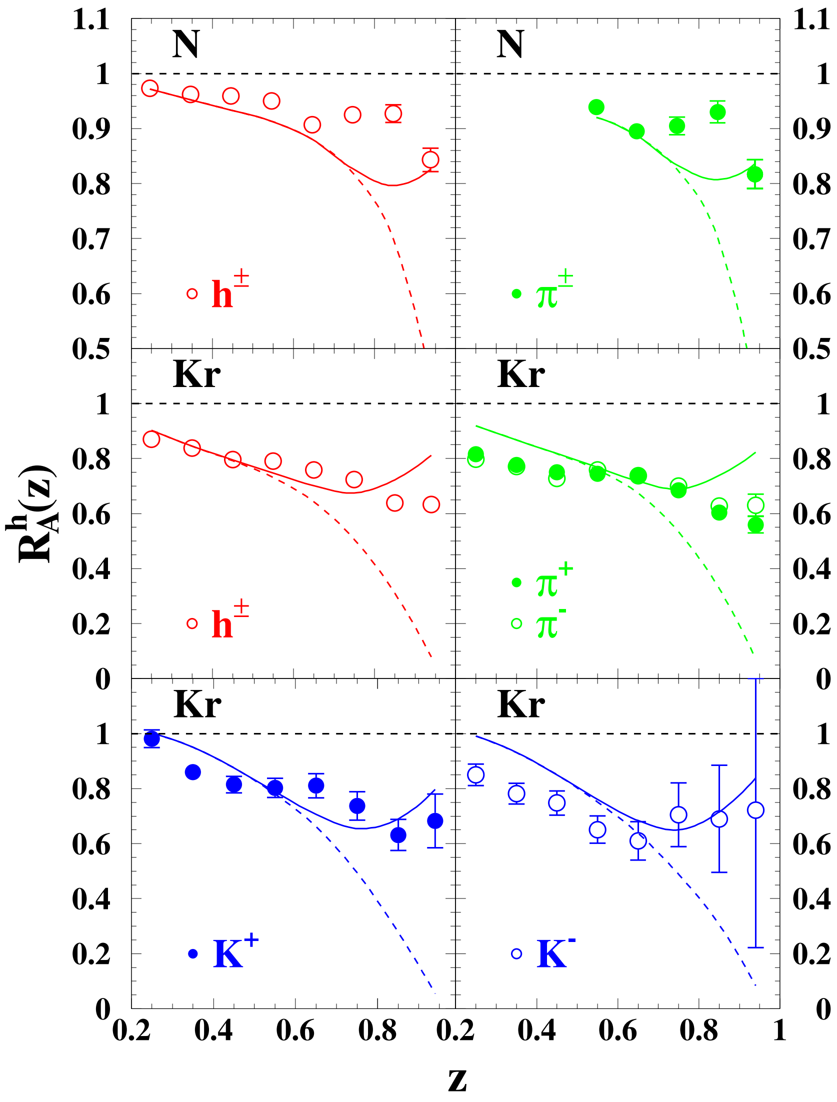
Comparing with HERMES



[FA EPJ C 2003]

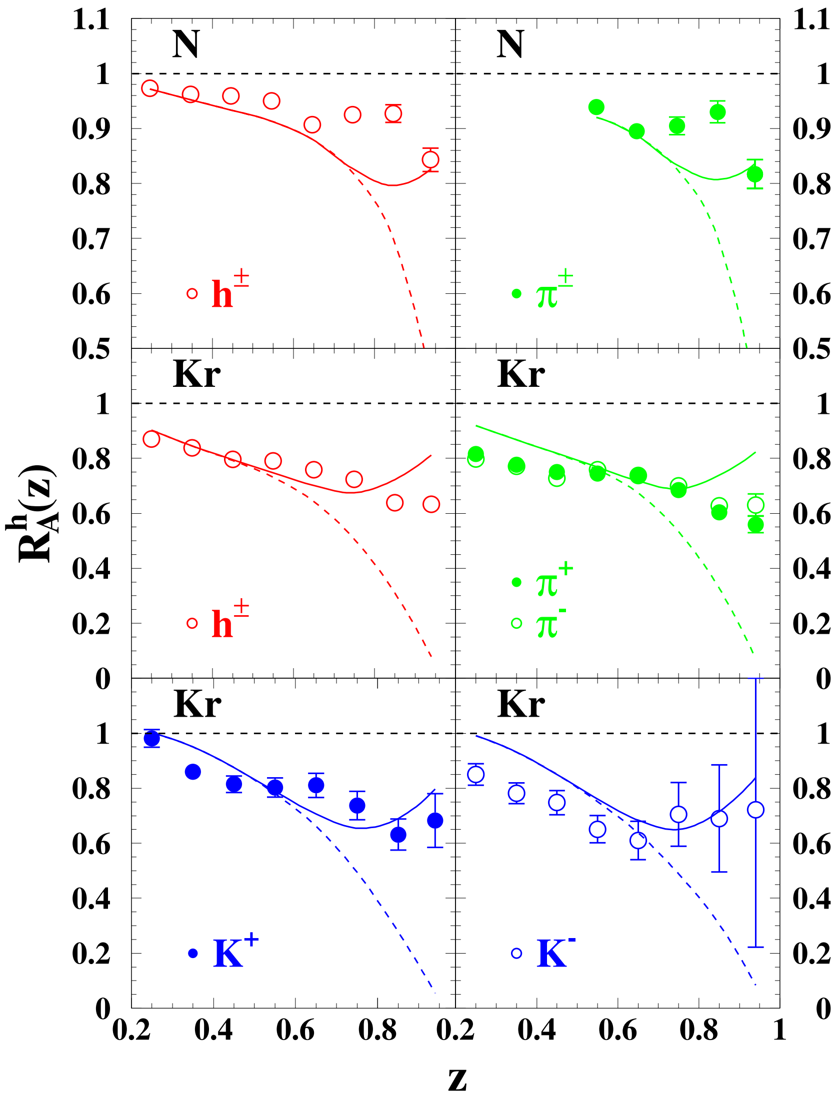
- Pretty good agreement (except pions)
- Isospin effects
  - easier to fragment $u \to K^+$ than $u \to K^-$

Comparing with HERMES



[FA EPJ C 2003]

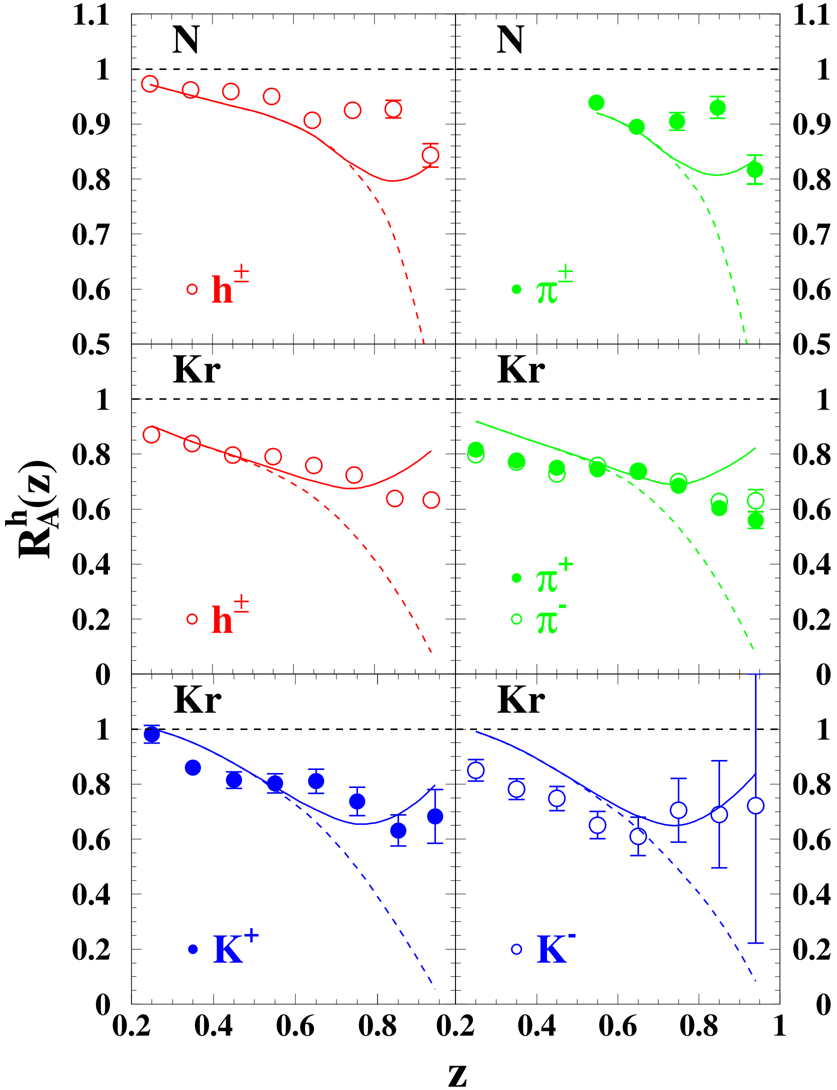
Comparing with HERMES



[FA EPJ C 2003]

- Pretty good agreement for all hadron species

Comparing with HERMES



[FA EPJ C 2003]

- Pretty good agreement for all hadron species
- Important formation time effects at large z

Disentangling nuclear effects

What about possible hadron absorption in the nucleus ?

Two predictions to (hopefully) clarify the picture

[FA DIS03 hep-ph/0309108]

Disentangling nuclear effects

What about possible hadron absorption in the nucleus ?

Two predictions to (hopefully) clarify the picture

[FA DIS03 hep-ph/0309108]

1. Energy loss saturates in large nuclei ($L \simeq t_F$)

➛ Xe / Kr $\simeq$ 1

Disentangling nuclear effects

What about possible hadron absorption in the nucleus ?

Two predictions to (hopefully) clarify the picture

[FA DIS03 hep-ph/0309108]

1. Energy loss saturates in large nuclei ($L \simeq t_F$)

➛ Xe / Kr $\simeq$ 1

2. At smaller x, u and $\bar{u}$ sea quarks contribute equally

➛ $K^+/K^- \simeq 1$

Disentangling nuclear effects

What about possible hadron absorption in the nucleus ?

Two predictions to (hopefully) clarify the picture

[FA DIS03 hep-ph/0309108]

1. Energy loss saturates in large nuclei ($L \simeq t_F$)

➛ Xe / Kr $\simeq$ 1

2. At smaller x, u and $\bar{u}$ sea quarks contribute equally

➛ $K^+/K^- \simeq 1$

➛ Need for heavy nuclei

➛ Need for Q^2 dependence

Disentangling nuclear effects

What about possible hadron absorption in the nucleus ?

Two predictions to (hopefully) clarify the picture

[FA DIS03 hep-ph/0309108]

1. Energy loss saturates in large nuclei ($L \simeq t_F$)

   ➛ Xe / Kr $\simeq$ 1

2. At smaller x, u and $\bar{u}$ sea quarks contribute equally

   ➛ $K^+/K^- \simeq 1$

➛ Need for heavy nuclei

➛ Need for Q^2 dependence

Talk by A. Accardi

From cold to hot media

(from DIS to heavy ion)

Phenomenology

- Drell-Yan in h - A collisions
  - Nuclear matter transport coefficient

[FA PLB 2002]

- Hadrons in semi-inclusive DIS
  - Modified fragmentation functions

[FA EPJ C 2003]

- Pions and photons in heavy ion collisions
  - Dense medium properties

[FA, Aurenche, Belghobsi, Guillet JHEP 2004]
[FA, in preparation]

Quenching

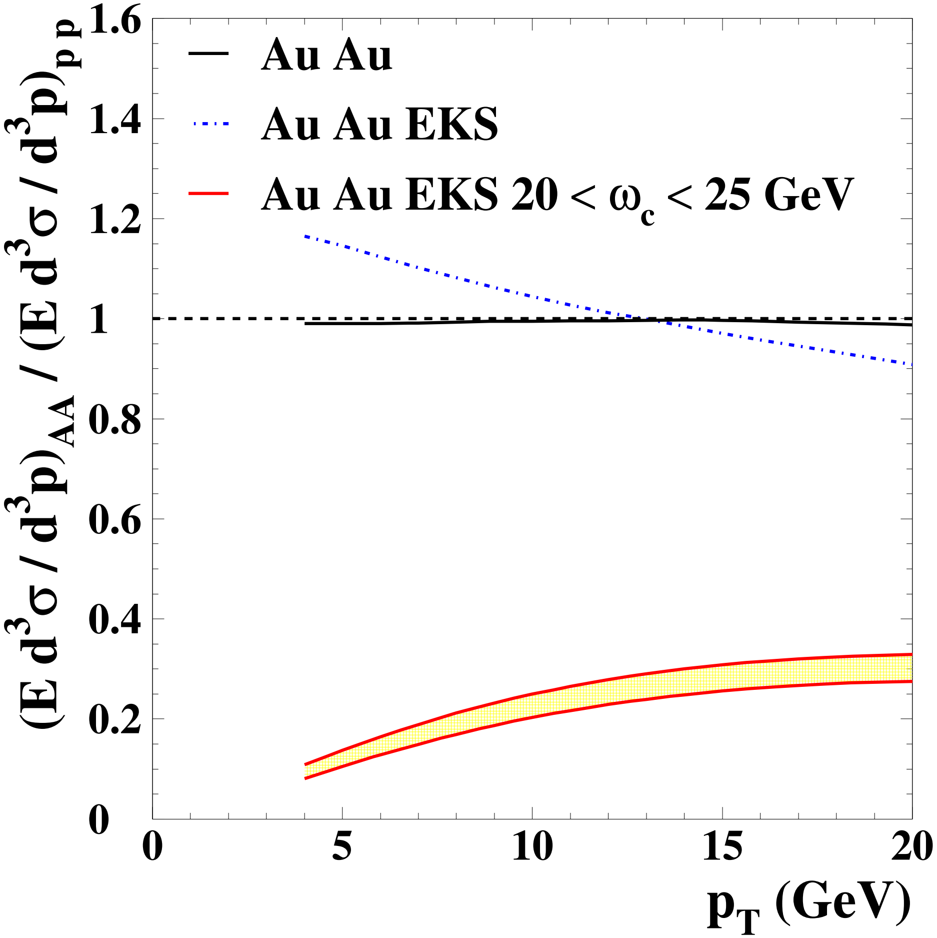
Quenching factor

$$R_{AA}(p_\perp) = \frac{d\sigma_{AA}(p_\perp)}{dp_\perp^2} \Bigg/ \frac{N_{\rm coll}\, d\sigma_{pp}(p_\perp)}{dp_\perp^2}$$

computed assuming

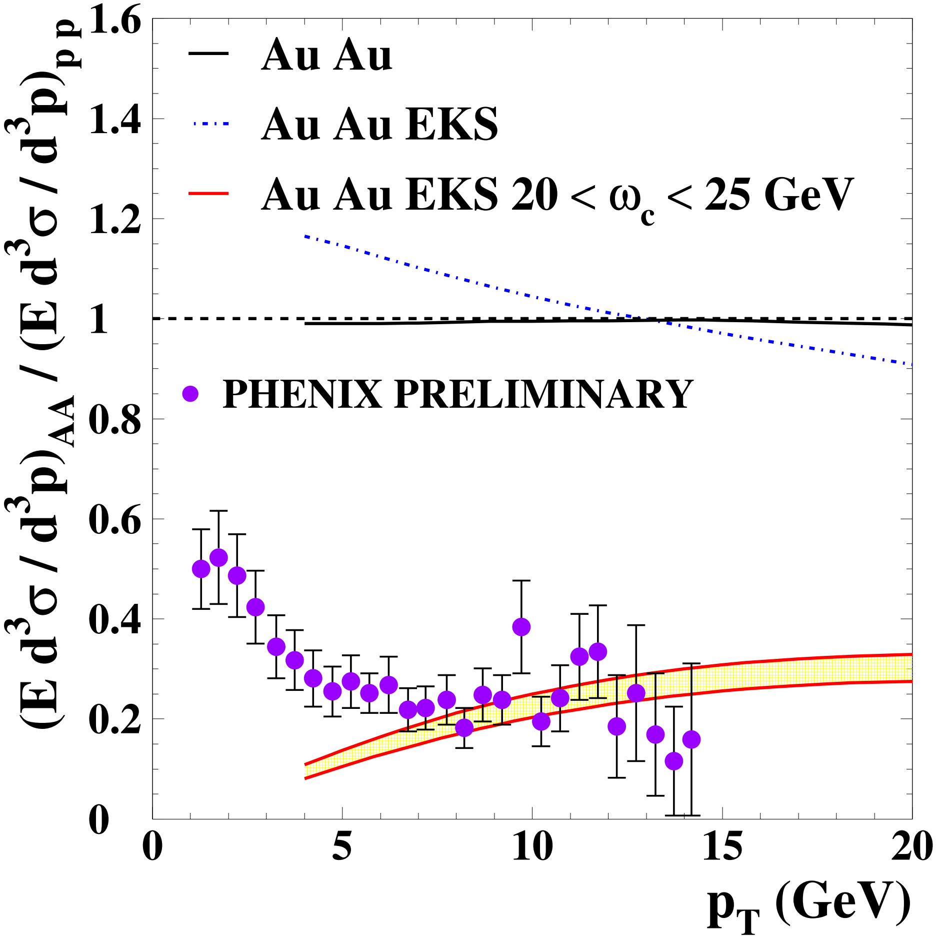
- nuclear shadowing (as given by EKS) or not
- energy loss process ($20 \leq \omega_c \leq 25$ GeV) or not

π quenching



- Strong suppression in the π^0 channel

π quenching



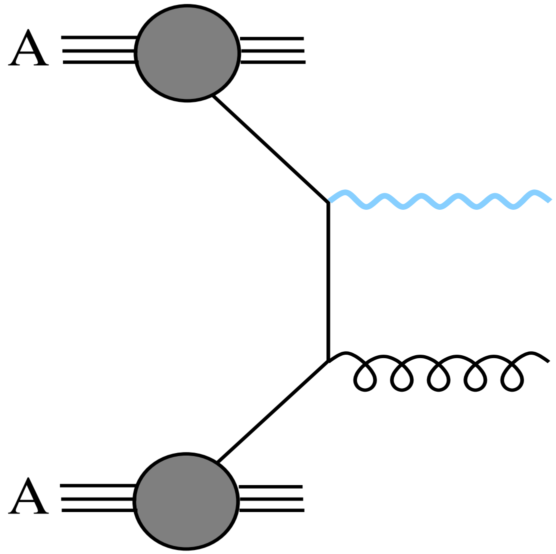
- Strong suppression in the π^0 channel
  - good agreement at high $p_\perp$ for $\omega_c \simeq 20 - 25$ GeV

Prompt photons

Terminology

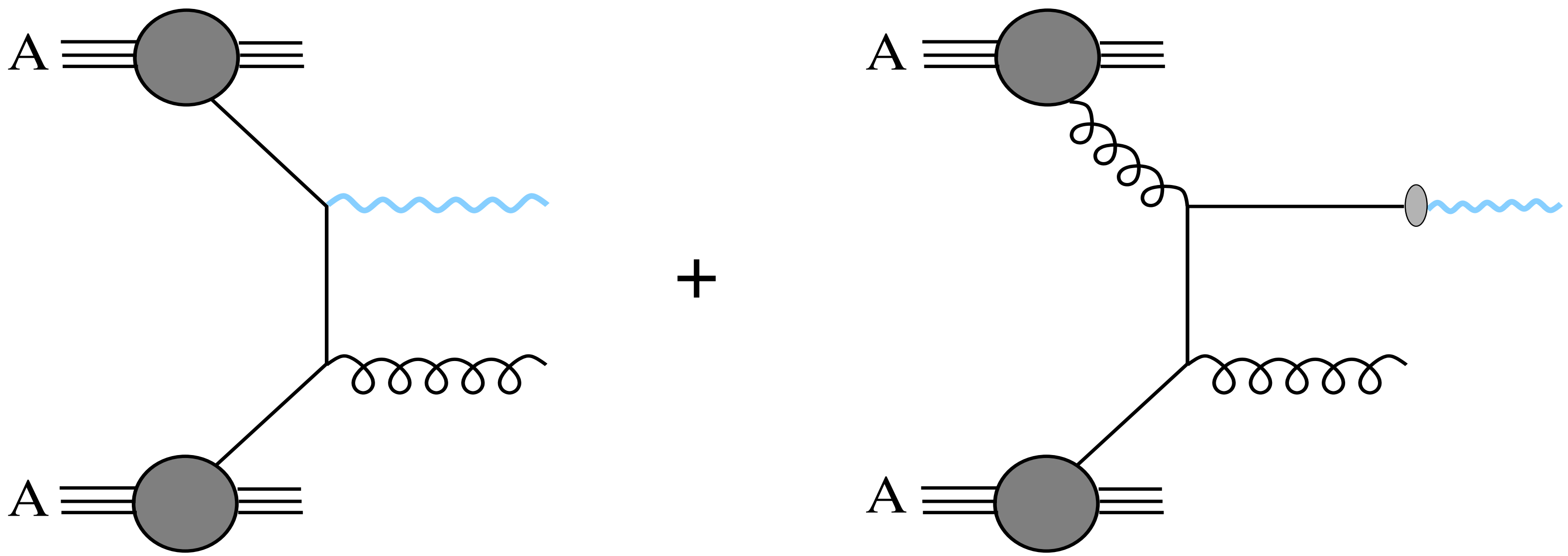
- Prompt photons $p_\perp \gg \Lambda_{QCD}$
  - produced in NN collisions
- Thermal photons $p_\perp = \mathcal{O}\left(T\right)$
  - quark-gluon plasma radiation
- Decay photons $\pi^0 \rightarrow \gamma\,\gamma$
  - radiative decays

Prompt photons



$$\frac{d\sigma}{d\vec{p}_{_T} d\eta} \simeq \sum_{i,j=q,g} \int dx_1 dx_2 \; F^A_{i/h_1}(x_1) \; F^A_{j/h_2}(x_2) \frac{d\widehat{\sigma}_{ij}}{d\vec{p}_{_T} d\eta}$$

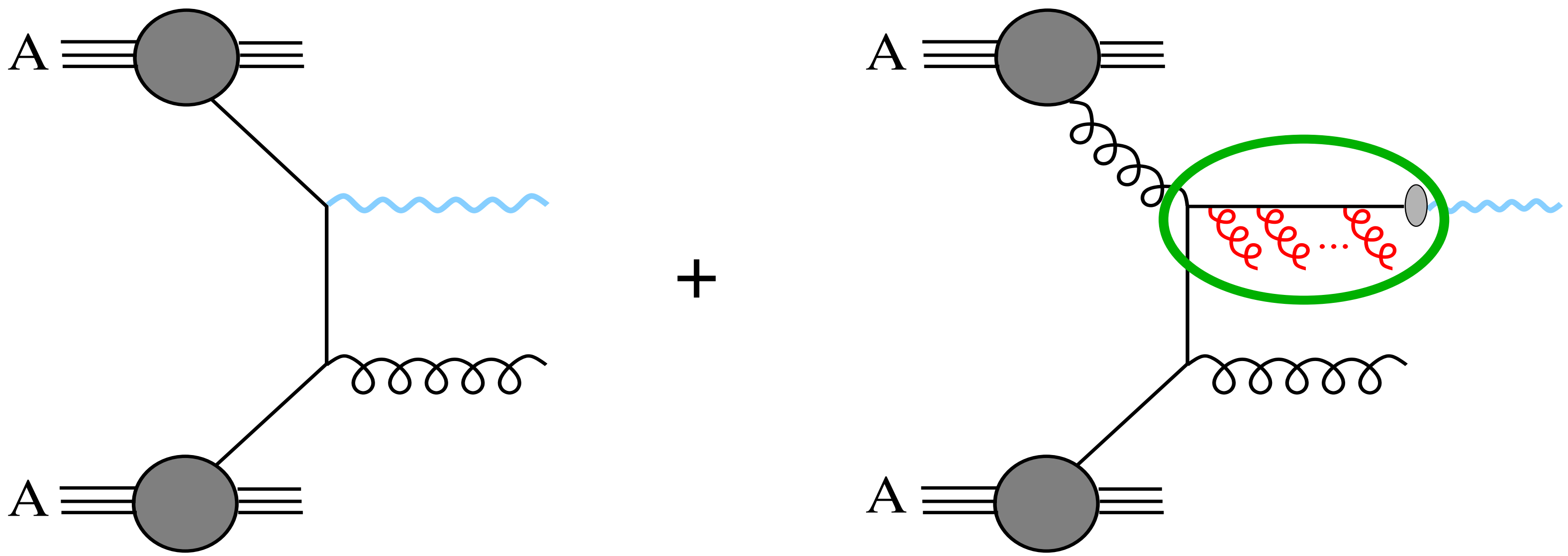
Prompt photons



$$\frac{d\sigma}{d\vec{p}_T d\eta} \simeq \sum_{i,j=q,g} \int dx_1 dx_2 \; F^A_{i/h_1}(x_1) \; F^A_{j/h_2}(x_2) \frac{d\widehat{\sigma}_{ij}}{d\vec{p}_T d\eta}$$

$$+ \sum_{i,j,k=q,g} \int dx_1 dx_2 \; F^A_{i/h_1}(x_1) F^A_{j/h_2}(x_2) \; \frac{dz}{z^2} \; D_{\gamma/k}(z,\mu) \; \frac{d\widehat{\sigma}^k_{ij}}{d\vec{p}_T d\eta}$$

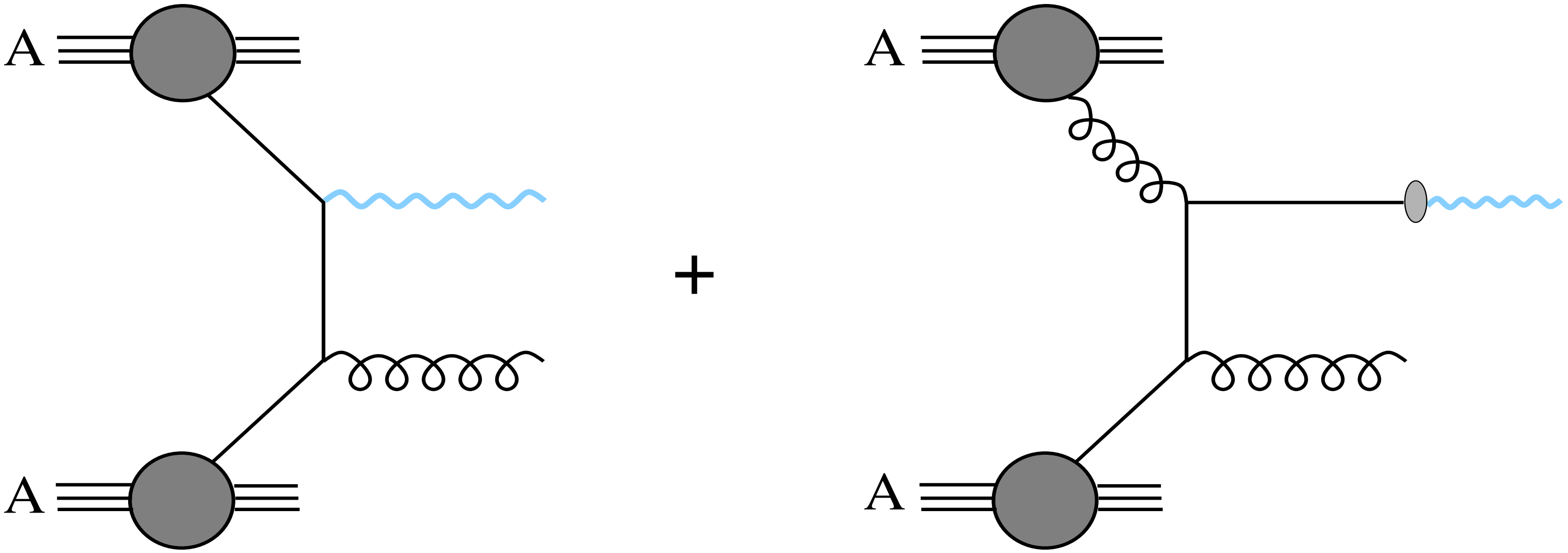
Prompt photons



$$\frac{d\sigma}{d\vec{p}_T d\eta} \simeq \sum_{i,j=q,g} \int dx_1 dx_2 \; F^A_{i/h_1}(x_1)\; F^A_{j/h_2}(x_2) \frac{d\widehat{\sigma}_{ij}}{d\vec{p}_T d\eta}$$

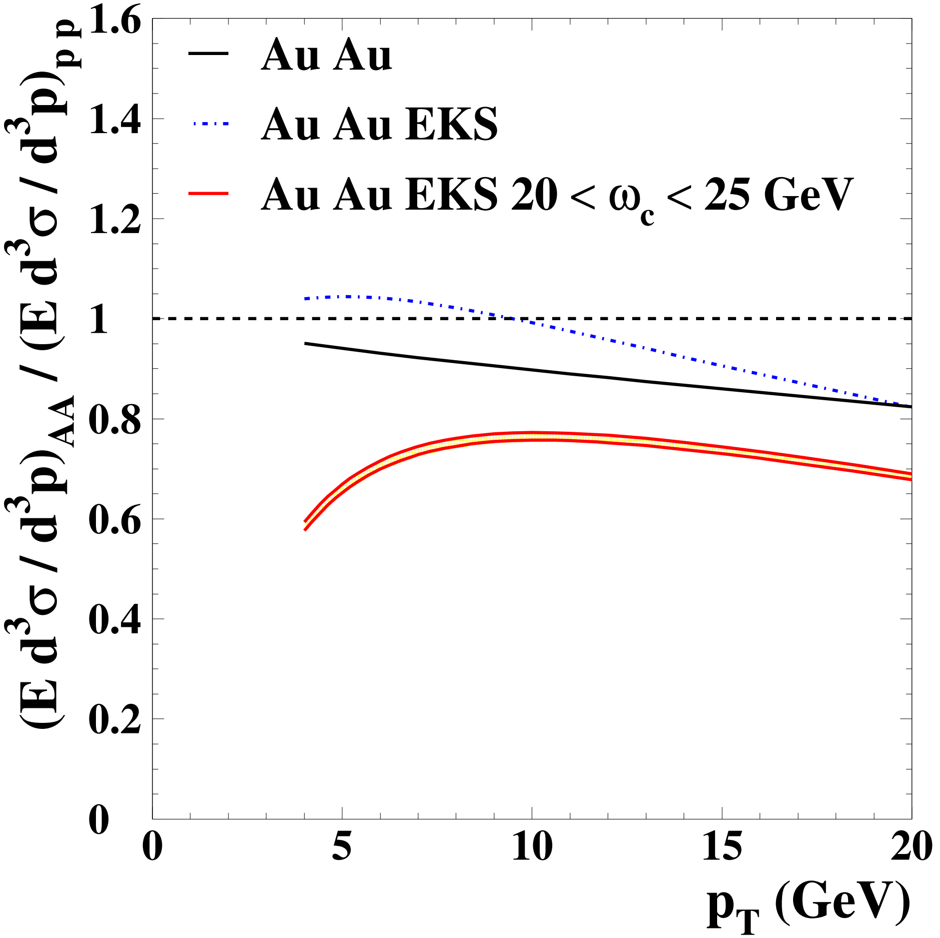
$$+ \sum_{i,j,k=q,g} \int dx_1 dx_2 \; F^A_{i/h_1}(x_1) F^A_{j/h_2}(x_2) \; \frac{dz}{z^2} \; D^{\mathrm{med}}_{\gamma/k}(z,\mu) \; \frac{d\widehat{\sigma}^k_{ij}}{d\vec{p}_T d\eta}$$

Prompt photons



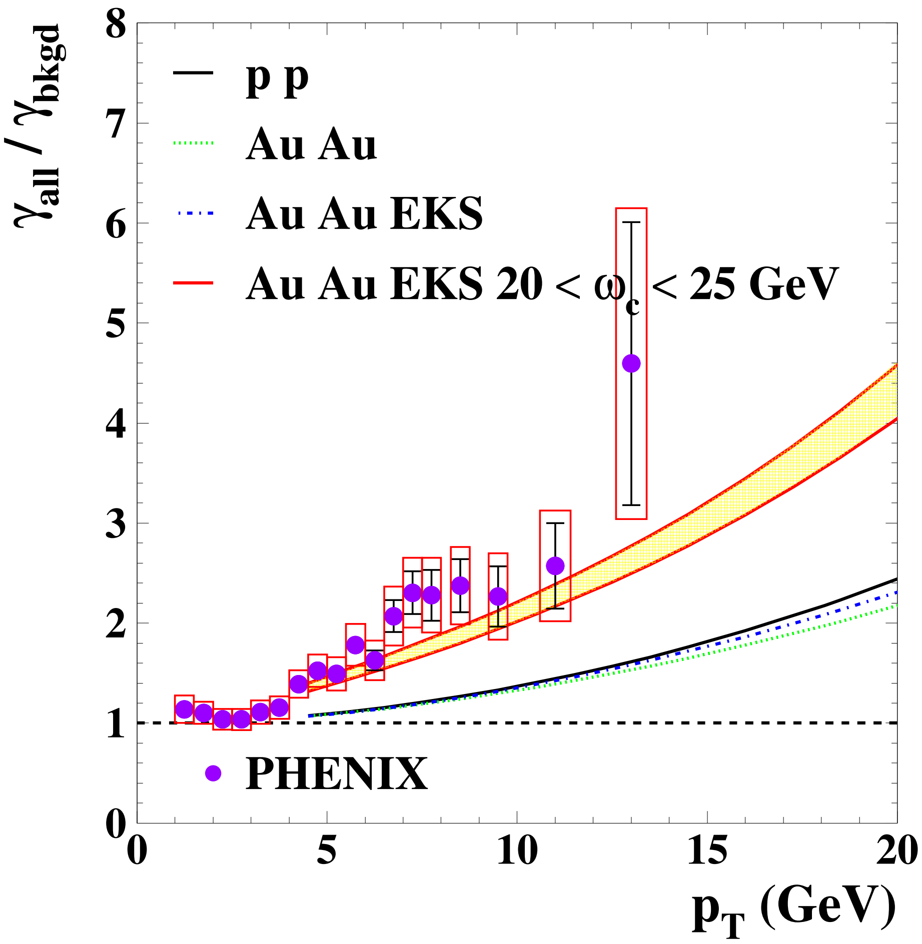
- Direct photons
    - Drell-Yan like
- Bremmstrahlung photons
    - jet like

γ quenching



- Much weaker suppression than for the π^0
- Isospin effect not negligible

γ/π^0



- Underestimate at high $p_\perp$

Discussion

RHIC data

$$\omega_c \simeq 20 - 25 \text{ GeV}$$

Discussion

RHIC data

$$\omega_c \simeq 20 \ - \ 25 \text{ GeV}$$

Mean transport coefficient

(with $\langle L \rangle = 5$ fm)

$$\langle \hat{q} \rangle_{\text{RHIC}} = \frac{2\,\omega_c}{\langle L \rangle^2} \simeq 0.3 \ - \ 0.4 \text{ GeV}^2/\text{fm}$$

Discussion

RHIC data

$$\omega_c \simeq 20 \ - \ 25 \text{ GeV}$$

Mean transport coefficient

(with $\langle L \rangle = 5$ fm)

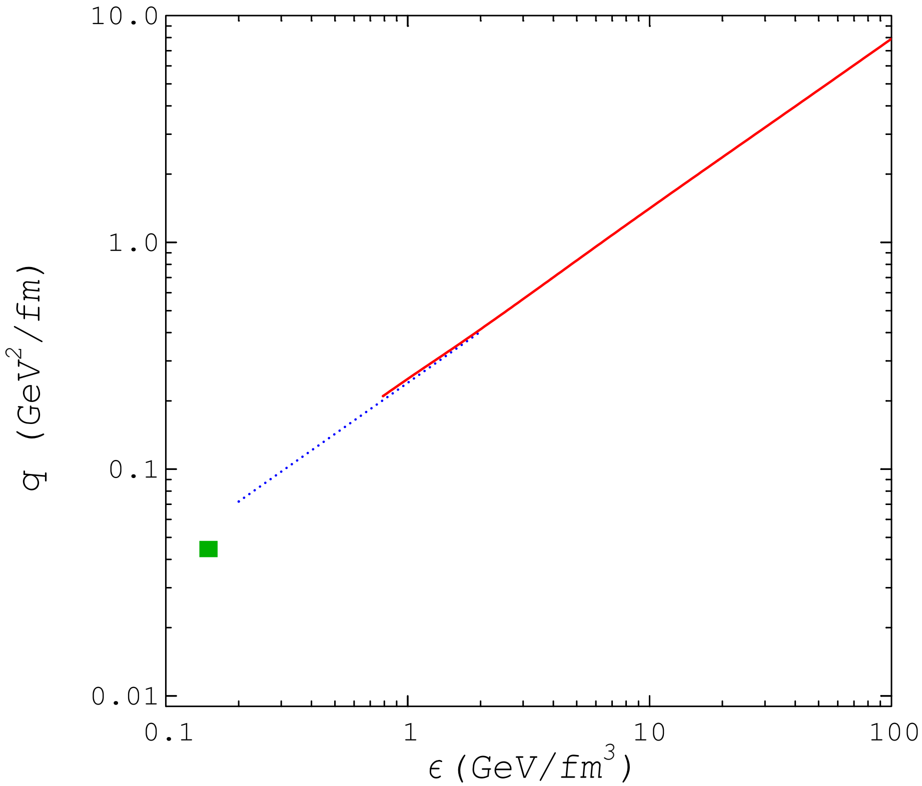
$$\langle \hat{q} \rangle_{\text{RHIC}} = \frac{2\,\omega_c}{\langle L \rangle^2} \simeq 0.3 \ - \ 0.4 \text{ GeV}^2/\text{fm}$$

Initial transport coefficient

(with Bjorken and $t_0 = 0.5$ fm)

$$\hat{q}_{\text{RHIC}}(t_0) \simeq \frac{\omega_c}{t_0\,\langle L \rangle} \simeq 1.6 \ - \ 2 \text{ GeV}^2/\text{fm}$$

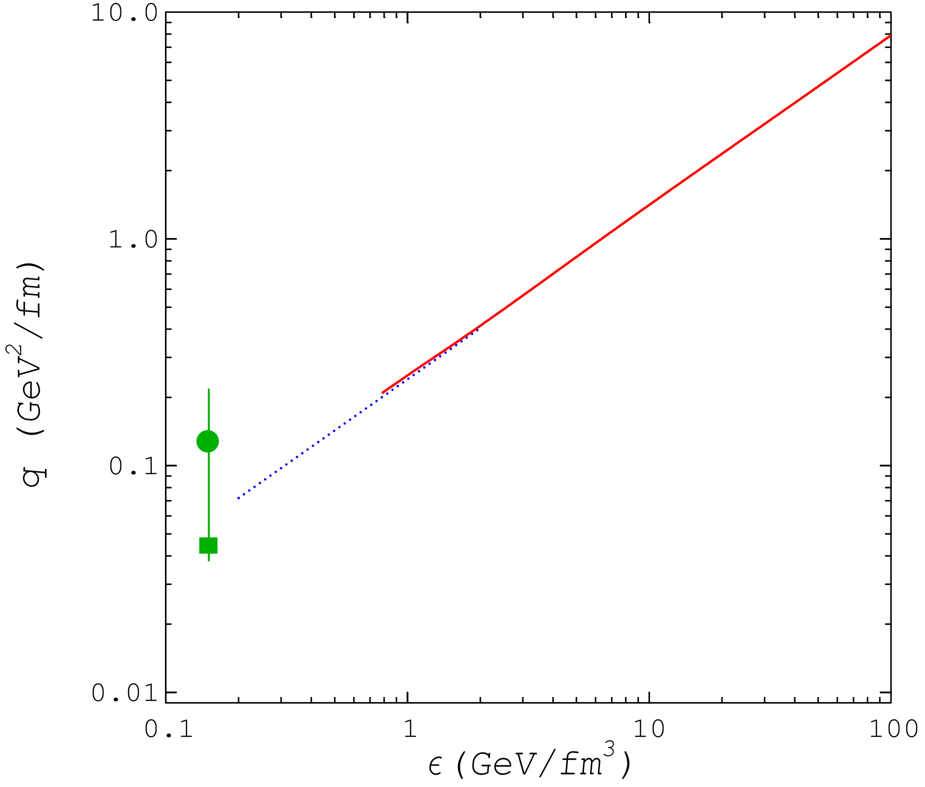
Transport coefficient



[Baier NPA 2002]

- Cold medium
  - pQCD

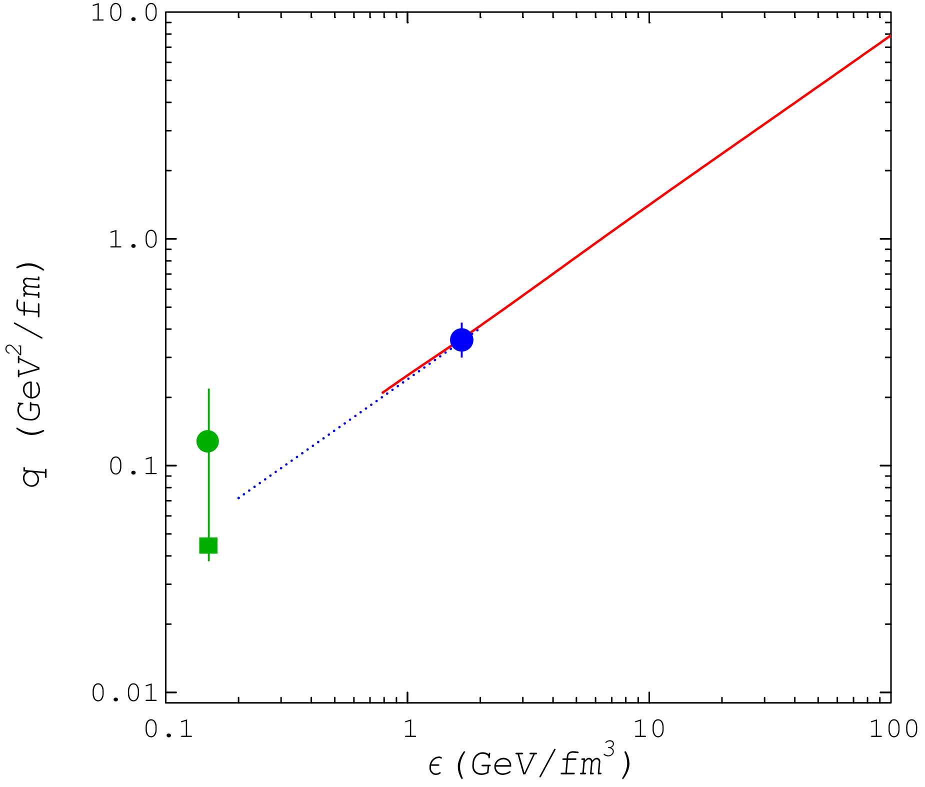
Transport coefficient



[Baier NPA 2002]

- Cold medium
  - pQCD
  - Drell-Yan and DIS

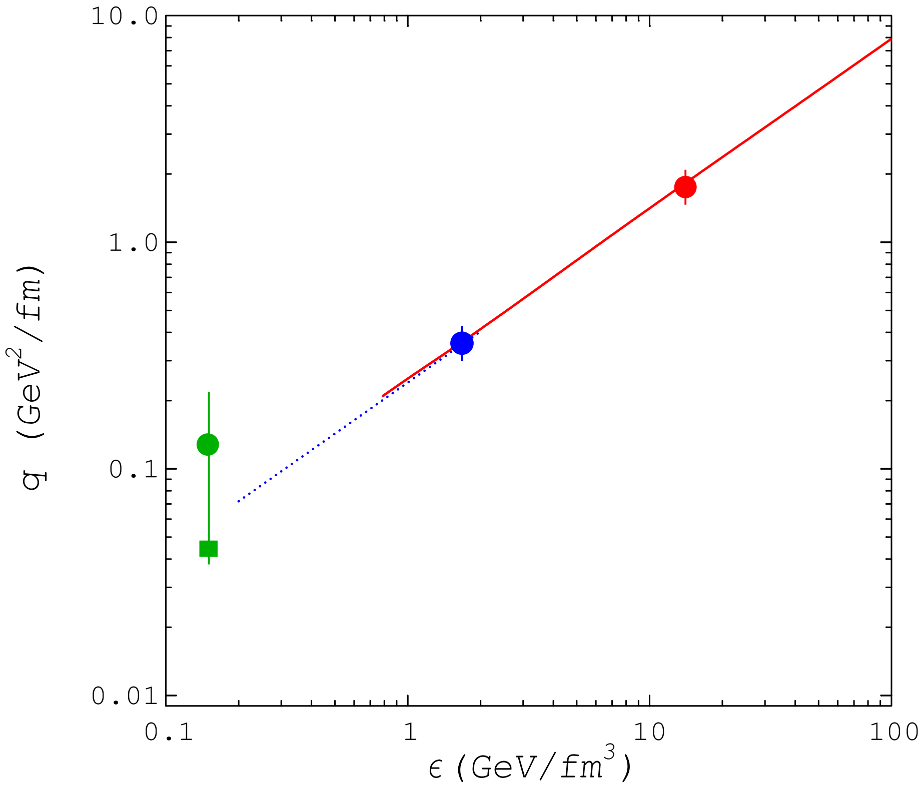
Transport coefficient



[Baier NPA 2002]

- Cold medium
- $\langle \hat{q} \rangle_{\rm RHIC}$

Transport coefficient



[Baier NPA 2002]

- Cold medium
- $\langle \hat{q} \rangle_{\rm RHIC}$
- $\hat{q}_{\rm RHIC}(t_0)$

Discussion

Naively . . .

$$\epsilon\,(t_0\;\simeq\;0.5\,\mathrm{fm})\gtrsim\;10\,\mathrm{GeV}/\mathrm{fm}^3\;\;\text{at RHIC}$$

Discussion

Naively . . .

$$\epsilon\,(t_0 \simeq 0.5\,\mathrm{fm}) \gtrsim 10\,\mathrm{GeV/fm}^3 \ \text{ at RHIC}$$

. . . but many theoretical uncertainties

- assume a thermalized medium (and at $t_0 = 0.5$ fm !)
- $\hat{q}$ depends on
  - geometry modelling
  - which longitudinal and transverse expansion
- correspondence $\hat{q} - \epsilon$ indicative only

Summary

- Energy loss probes dense media
  - Proportional to the medium scattering power
- Energy loss in DIS
  - good description of HERMES and EMC data
  - possible formation time effects probed by CLAS
- Energy loss in heavy ion collisions
  - γ and π^0 at RHIC
  - $\epsilon_{\rm RHIC} \gtrsim 50\, \epsilon_{\rm cold}$