Jet quenching on hadron yields and ratios at RHIC and LHC

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Budapest - Kent - Columbia

1. Energy loss of jets in hot, dense non-Abelian plasma:
- — energy loss in a THICK plasma - BDMS, LCPI
- — energy loss in a THIN plasma - GLV method
  - $\Longrightarrow$ OPACITY expansion ($N = 1, 2, 3, ..$)

2. Jet quenching on hadron yields (RHIC,LHC)
- — E-indep. vs. E-dependent energy loss
- — latest results fom RHIC (π^0 in PHENIX)

3. Baseline: pQCD calculation in $p+p$, $p+A$, $A+A$:
- — intrinsic k_T in $p+p$ $(p+\overline{p})$
- — p_T broadening in $p+A$ (saturated Cronin)
- — A+A collision by pQCD (high p_T)
  - $\Longrightarrow$ G. Papp's QM'01 talk

4. Hadron ratios as probes of jet quenching (RHIC)
- — K^+/π^+, K^-/π^- ratios at $L/\lambda = 1, 2, 3, ..$

QM'2001, Brookhaven — Stony Brook
19 January 2001

Bibliography:

- Jet quenching - GLV (opacity expansion, tagged target)
  M. Gyulassy, P. Lévai, I. Vitev
  Nucl. Phys. **B594** (2001) 371. (nucl-th/0006010)
  Phys. Rev. Lett. **85** (2000) 5535. (nucl-th/0005032)
  Nucl. Phys. **B571** (2000) 197. (hep-ph/9907461)
  Nucl. Phys. **A661** (1999) 637. (hep-ph/9904501)

- Jet quenching vs. Cronin effect at SPS/RHIC
  M. Gyulassy, P. Lévai
  Phys. Lett. **B442** (1998) 1. (hep-ph/9807247)

- pQCD description of $p+p$ and $p+A$ collision
  G. Papp, P. Lévai, G. Fai, G.G. Barnaföldi and Y. Zhang
  Phys. Rev. **C61** (2000) 021902. (hep-ph/9903012)
  Proc. UDQCD Trento Wshop (hep-ph/9904503)
  Proc. XXVIII. Hirschegg Wshop (nucl-th/0001053)
  J. of Physics G. (nucl-th/0004066)

- Hadron ratios as probes of jet quenching at RHIC
  P. Lévai, G. Papp, G. Fai, M. Gyulassy
  nucl-th/0012017

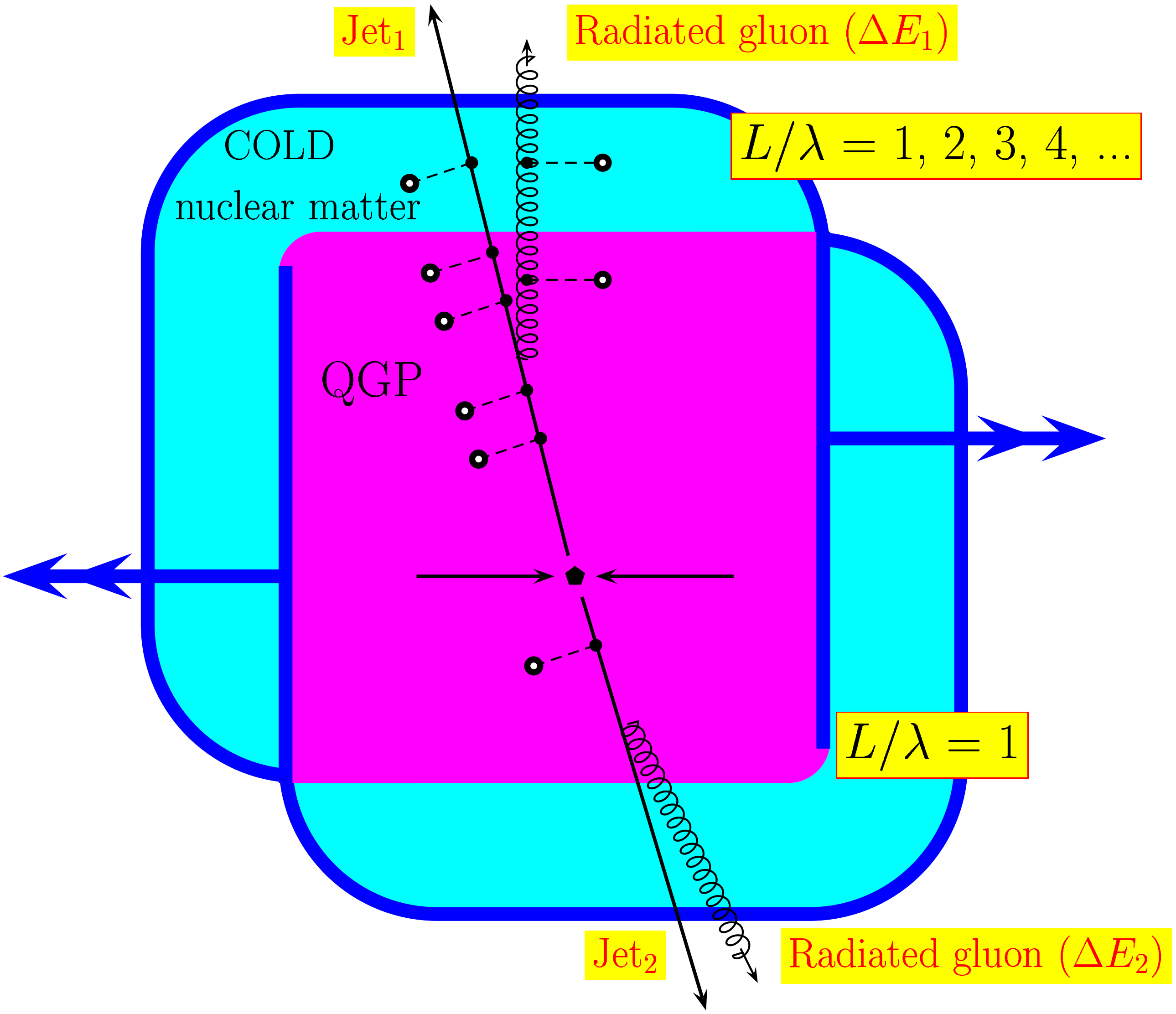
1. Energy loss of jets in non-Abelian plasma

A+A Collisions $\Longrightarrow$ QGP (non-pert. matter)

$\Longrightarrow$ High p_T jets (perturb. QCD)

Radiative energy loss (jet-quenching): $E_{jet} \longrightarrow E_{jet} - \Delta E$

pQCD probe of the non-pert. QGP phase



Medium induced radiative energy loss - 1

THICK plasma: $L \gg \lambda_g$ [LLA]

GW: QED - analogy $\Longrightarrow$ $\Delta E_{GW}/dx$ = 1-2 GeV/fm

M. Gyulassy, X.N. Wang '94

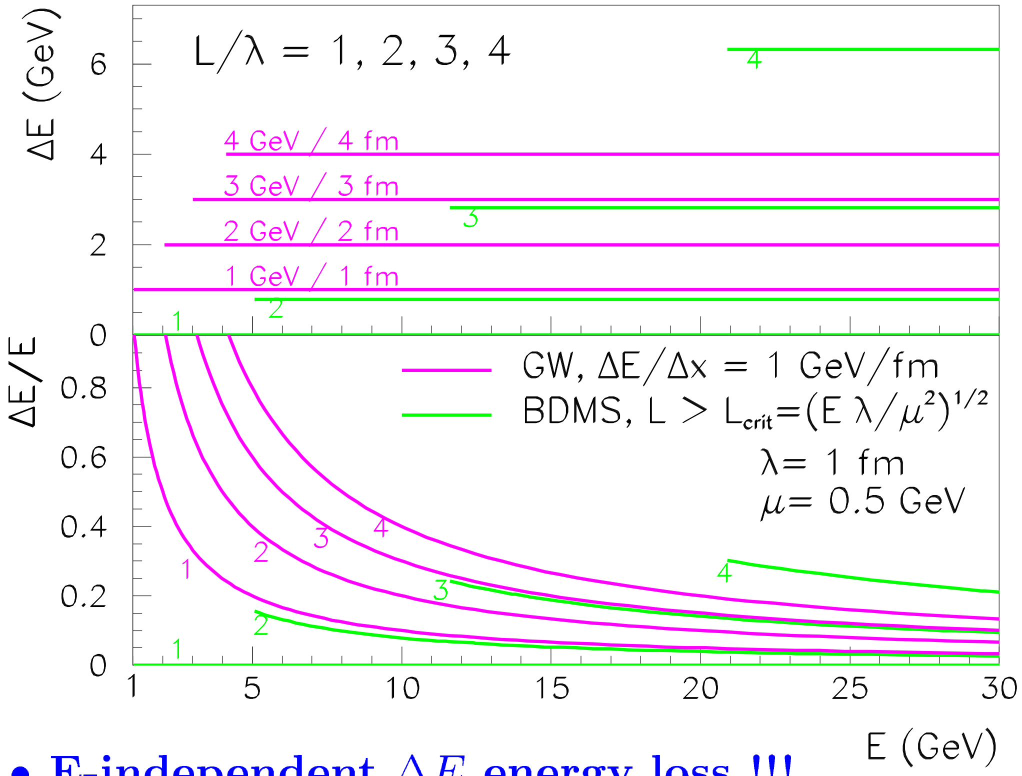
BDMS: time-ordered pQCD (Feynman diagram.) $\Longrightarrow$

$$\Delta E_{BDMS} = \frac{C_R \alpha_s}{4} \frac{L^2 \mu^2}{\lambda_g} \log \frac{L}{\lambda_g}$$

Baier-Dokshitzer-Mueller-Schiff '97,'98

LCPI: light-cone path integral formalism $\Longrightarrow$ $\equiv$ BDMS

B.G. Zakharov '96,'98



- **E-independent ΔE energy loss !!!**

Medium induced radiative energy loss - 2

THIN plasma: $L \sim \lambda_g$

GLV: time-ordered pQCD (Feynman diagrammatic)

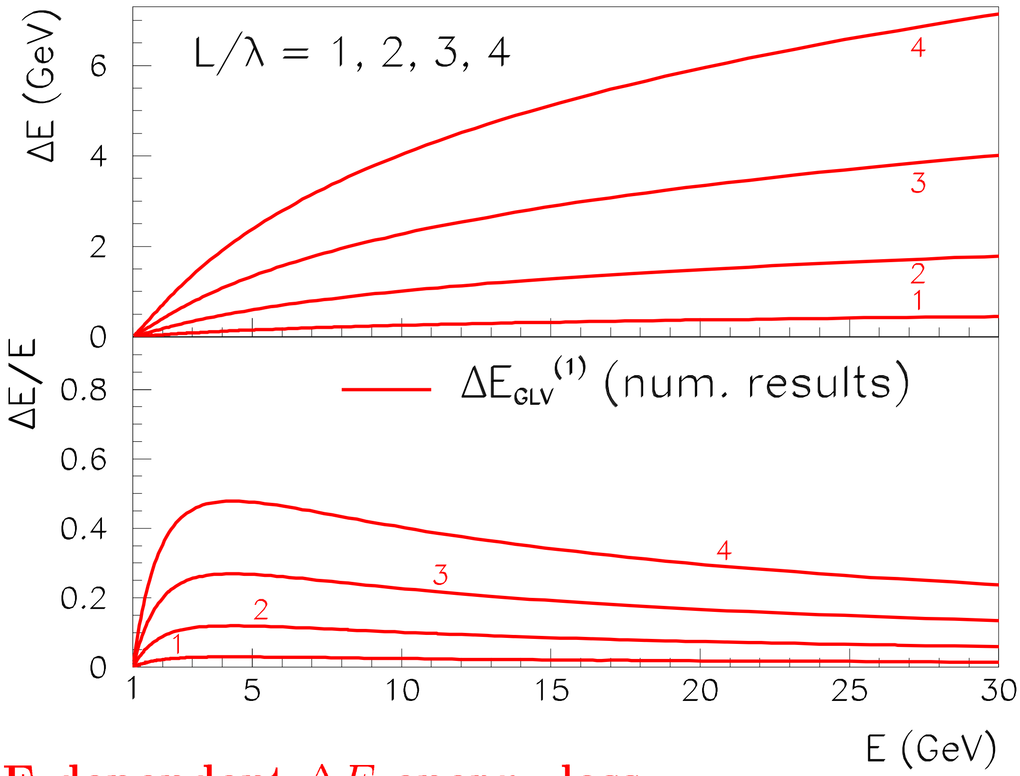
$+$ OPACITY expansion ($N = 1, 2, 3, ...$)

$+$ kinematical cuts $\Rightarrow$ U. Wiedemann, QM'01 talk

$$\Longrightarrow \Delta E_{GLV} \approx \Delta E^{(1)}_{GLV} \approx \frac{C_R \alpha_s}{N(E)} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu}$$

N(E) is a numerical function, $N(E) \longrightarrow 4$ at $E \longrightarrow \infty$.

Gyulassy-Levai-Vitev, PRL85,5535; NPB594,371



- **E-dependent ΔE energy loss**
- **$\approx$ E-independent $\Delta E/E$** in $3 < E < 10$ GeV

Medium induced radiative energy loss - 3

THIN plasma: $L \sim \lambda_g$

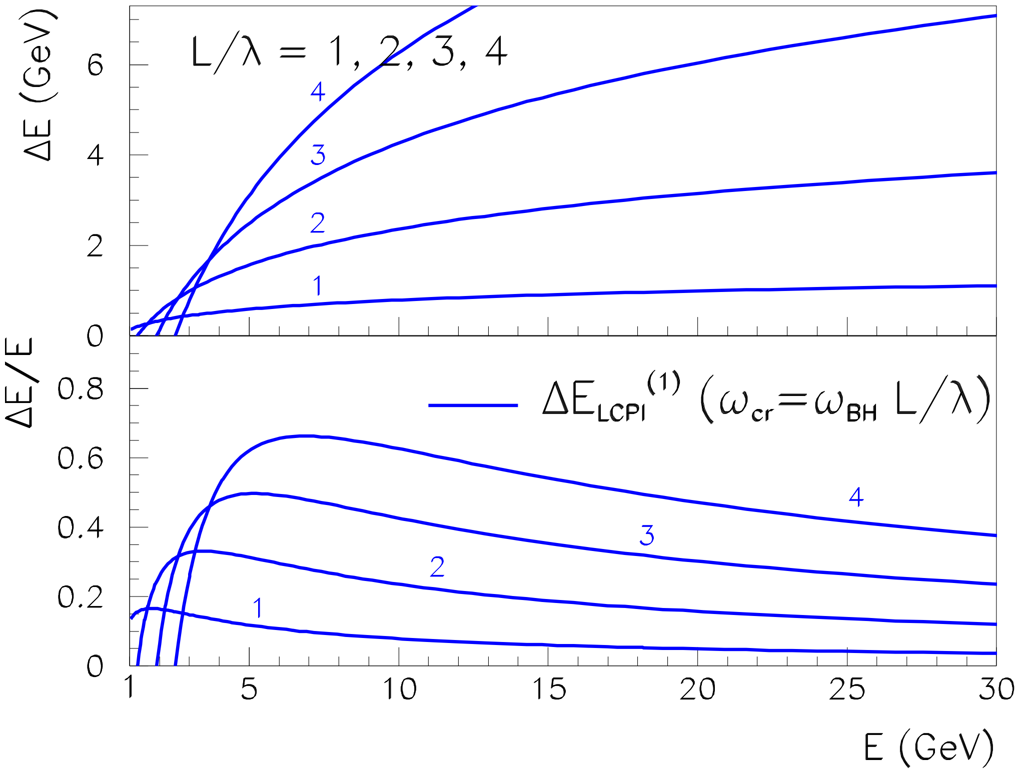
LCPI: light-cone path integral formalism at $N = 1$

(no kinematical cuts) $\Longrightarrow$

$$\Delta E^{(1)}_{LCPI} = \frac{C_R \alpha_s}{4} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\omega_{cr}}$$

$$\omega_{cr} = \max\left(nC_3 L^2/4;\ L\mu^2/2 = \omega_{BH} \cdot L/\lambda\right)$$

B.G. Zakharov, (hep-ph/0012360)

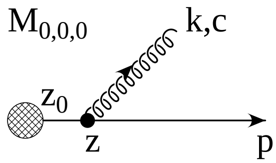


$$\Longleftrightarrow \quad \Delta E^{(1)}_{GLV} \approx \frac{C_R \alpha_s}{N'(E)} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\omega_{BH}}$$

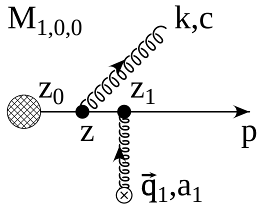
Opacity expansion in the GLV method - 1

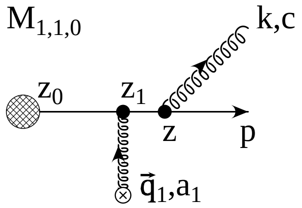
Time-ordered perturbative calculation of gluon radiation
pQCD Feynman diagrams with n_s scattering centers:

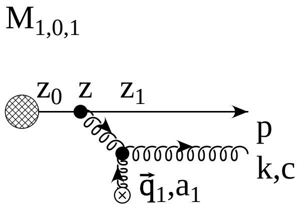
$n_s = 0$



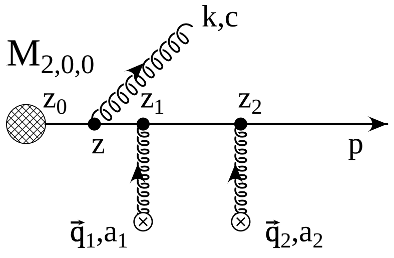
$n_s = 1$

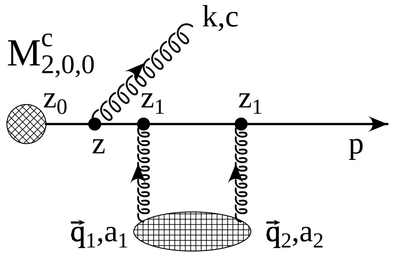




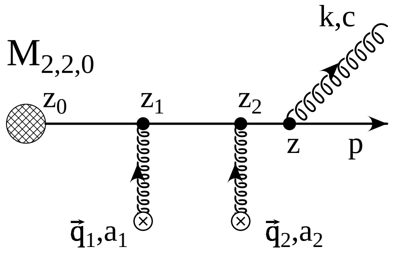


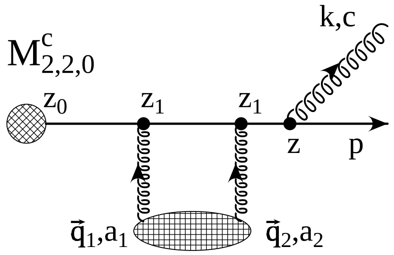
$n_s = 2$





[More terms ...] + Unitarity correction





$n_s = 2$: 7 tree + 4 unitarity correction diagrams
$n_s = 3$: 15 tree + 19 unitarity correction diagrams!!
$n_s = 4$: 31 tree + ...

Opacity expansion in the GLV method - 2

Average number of jet scatterings, $\overline{n} = L/\lambda$

Gluon radiation amplitudes $I^{(N)} \Longleftrightarrow (\sigma_{el}/A_\perp)^N \propto (L/\lambda)^N$

OPACITY EXPANSION: $I = I^{(1)} + I^{(2)} + I^{(3)} + \ldots$

$I^{(0)}$: $(L/\lambda)^0 \propto (\sigma_{el}/A_\perp)^0$ contributions

- $1 \ (n_s = 0) \times (n_s = 0)^\dagger$

$I^{(1)}$: $(L/\lambda)^1 \propto (\sigma_{el}/A_\perp)^1$ contributions

- $4 \ (n_s = 2) \times (n_s = 0)^\dagger$
- $9 \ (n_s = 1) \times (n_s = 1)^\dagger$

$I^{(2)}$: $(L/\lambda)^2 \propto (\sigma_{el}/A_\perp)^2$ contributions

- $13 \ (n_s = 4) \times (n_s = 0)^\dagger$
- $57 \ (n_s = 3) \times (n_s = 1)^\dagger$
- $65 \ (n_s = 2) \times (n_s = 2)^\dagger$

After evaluating these amplitudes [see NPB594(2001)371]

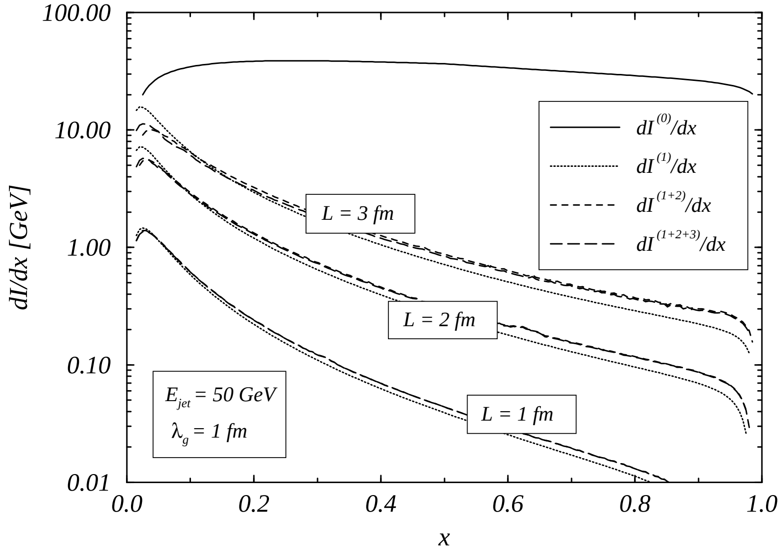
e.g. $xdI^{(1)}/dxdk_\perp^2 \Longrightarrow \Delta E^{(1)}$:

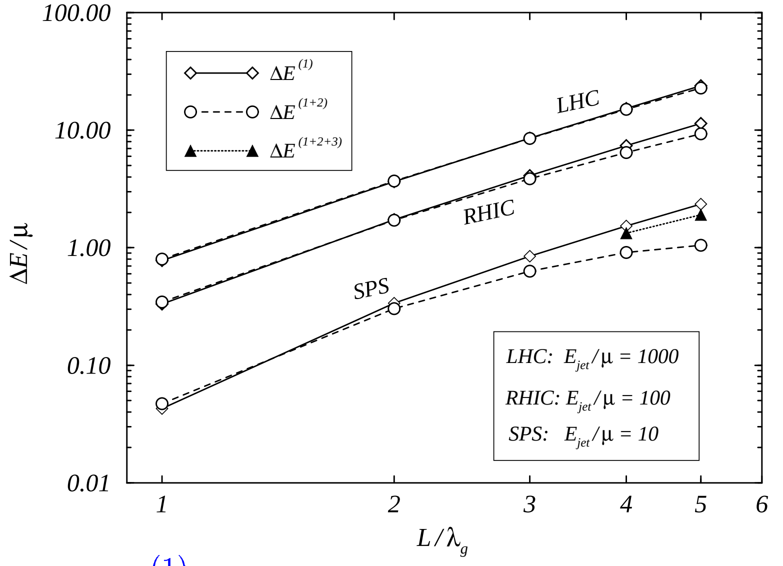
$$\Delta E^{(1)}_{GLV} = \frac{2C_R\alpha_s}{\pi}\frac{EL}{\lambda_g}\int_0^1 dx \int_0^{k^2_{max}} \frac{d\mathbf{k}_\perp^2}{\mathbf{k}_\perp^2}$$

$$\int_0^{q^2_{\max}} \frac{d^2\mathbf{q}_\perp\,\mu^2_{eff}}{\pi(\mathbf{q}_\perp^2+\mu^2)^2}\cdot\frac{2\,\mathbf{k}_\perp\cdot\mathbf{q}_\perp(\mathbf{k}-\mathbf{q})^2_\perp L^2}{16x^2E^2 \ + \ (\mathbf{k}-\mathbf{q})^4_\perp L^2}$$

Opacity expansion in the GLV method - 3

OPACITY EXPANSION:
FAST CONVERGENCE !!



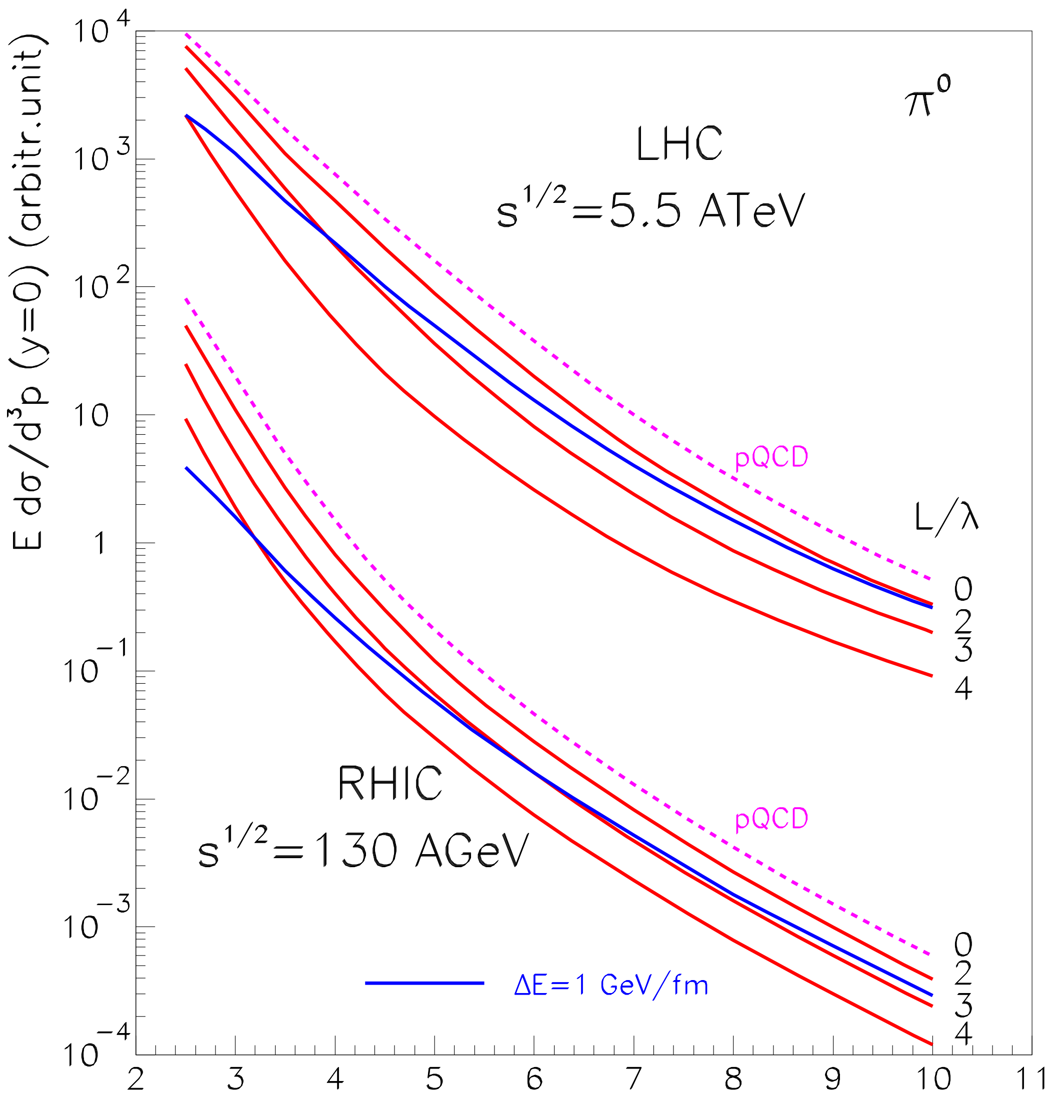


⟹ $\Delta E^{(1)}_{GLV}$ is a good approximation;

⟹ Jet energy loss is small at CERN SPS;

Jet quenching on hadron yields - 1

- Au+Au collision at RHIC, $\sqrt{s} = 130$ AGeV.
- Pb+Pb collision at LHC, $\sqrt{s} = 5500$ AGeV.

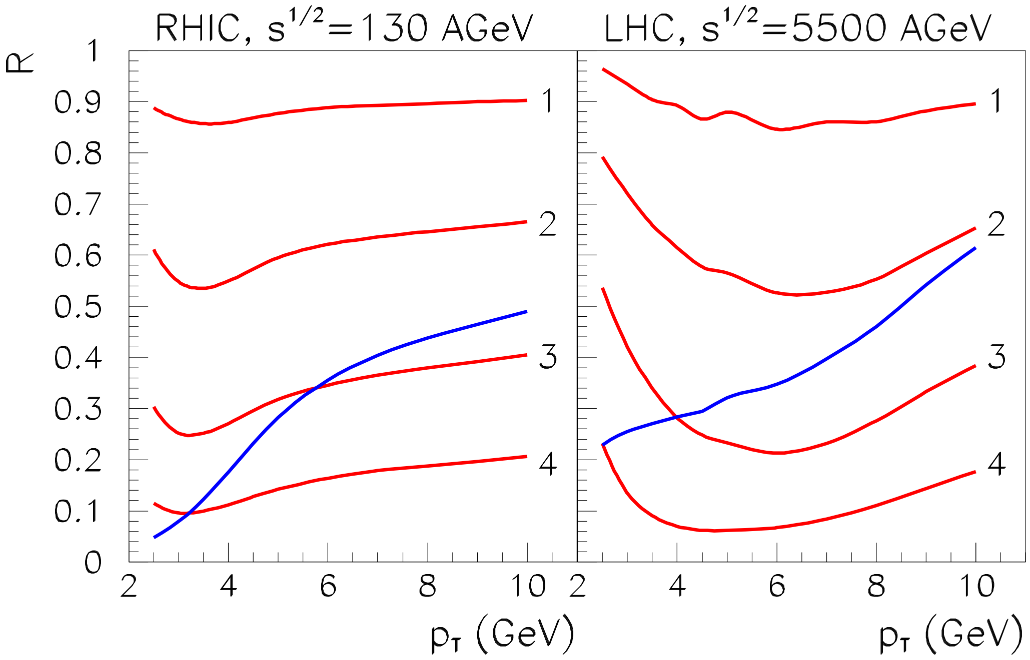


$L/\lambda = 0, 1, 2, 3, 4$ at $\mu = 0.5$ GeV, $\lambda = 1$ fm

Jet quenching on hadron yields - 2

- Au+Au collision at RHIC, $\sqrt{s} = 130$ AGeV.
- Pb+Pb collision at LHC, $\sqrt{s} = 5500$ AGeV.

"QUENCHED / NO QUENCH" ratios



Constant $\Delta E \Longrightarrow$ Varying slope

Constant $\Delta E/E \Longrightarrow$ Parallel shift

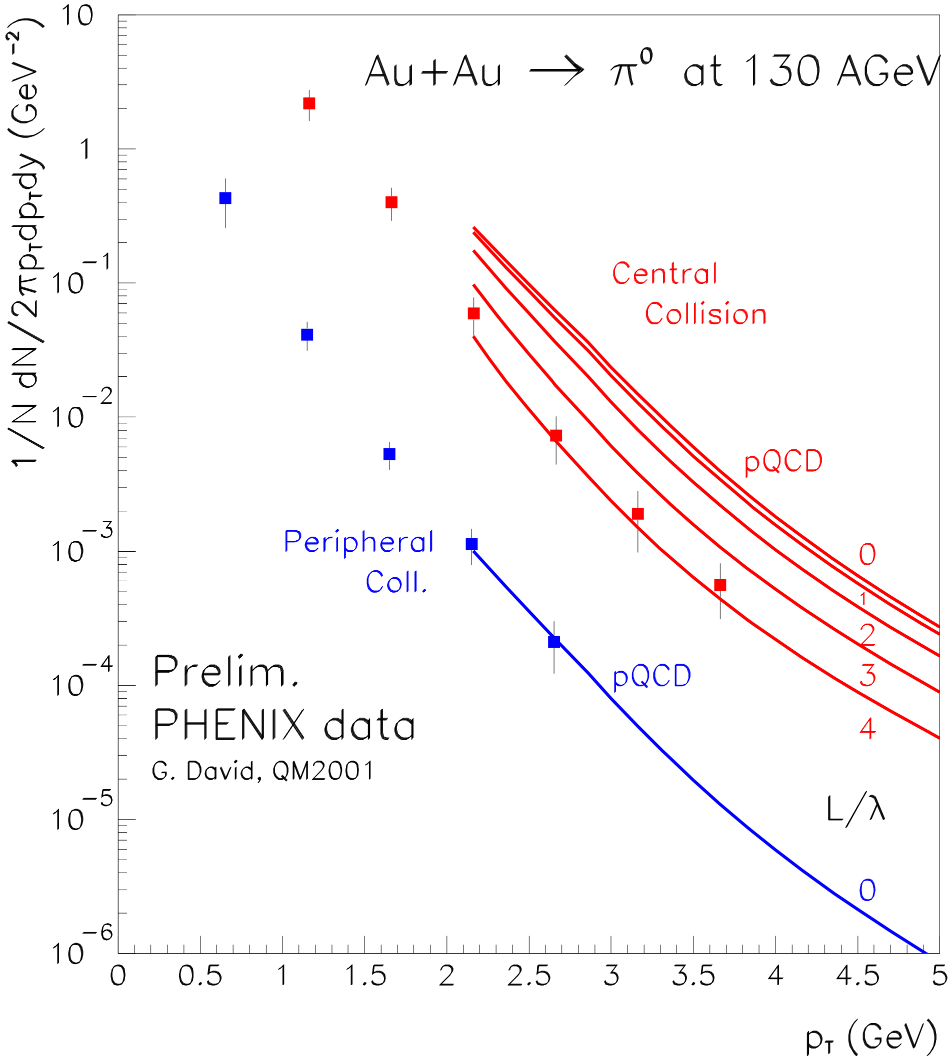
Slope analysis does not help

Compare to RHIC data:

1. Total yields (π^0 in central and perif. collision)
2. Hadron ratios (K^+/π^+, K^-/π^- ...)

Jet quenching on hadron yields - 3

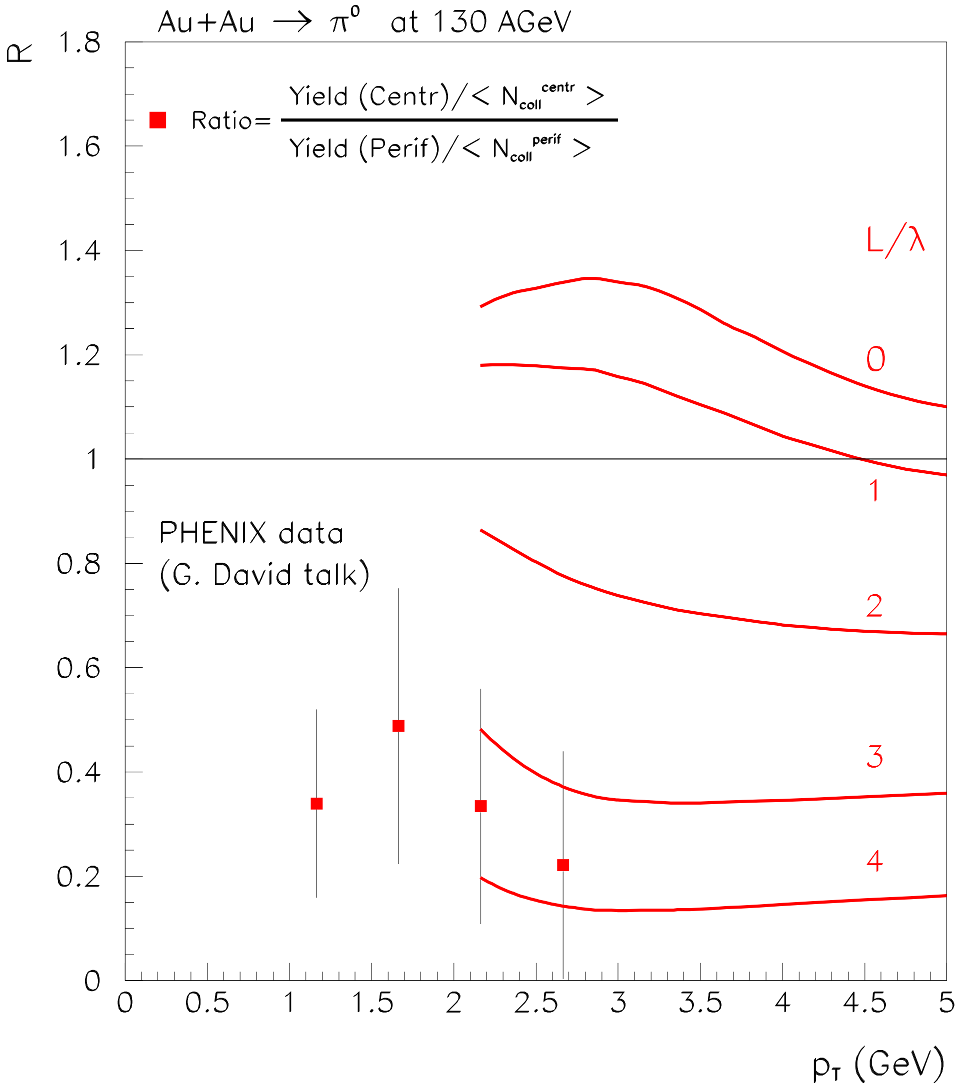
PHENIX prel. results at $\sqrt{s} = 130$ GeV G. David's talk
Periferial collisions (75-92 %; $< N_{coll} >= 5.5$)
Central collisions (10 %; $< N_{coll} >= 857$)



Factor 8-10 shift in central coll. ⟺ jet-quenching !!!!

Jet quenching on hadron yields - 4

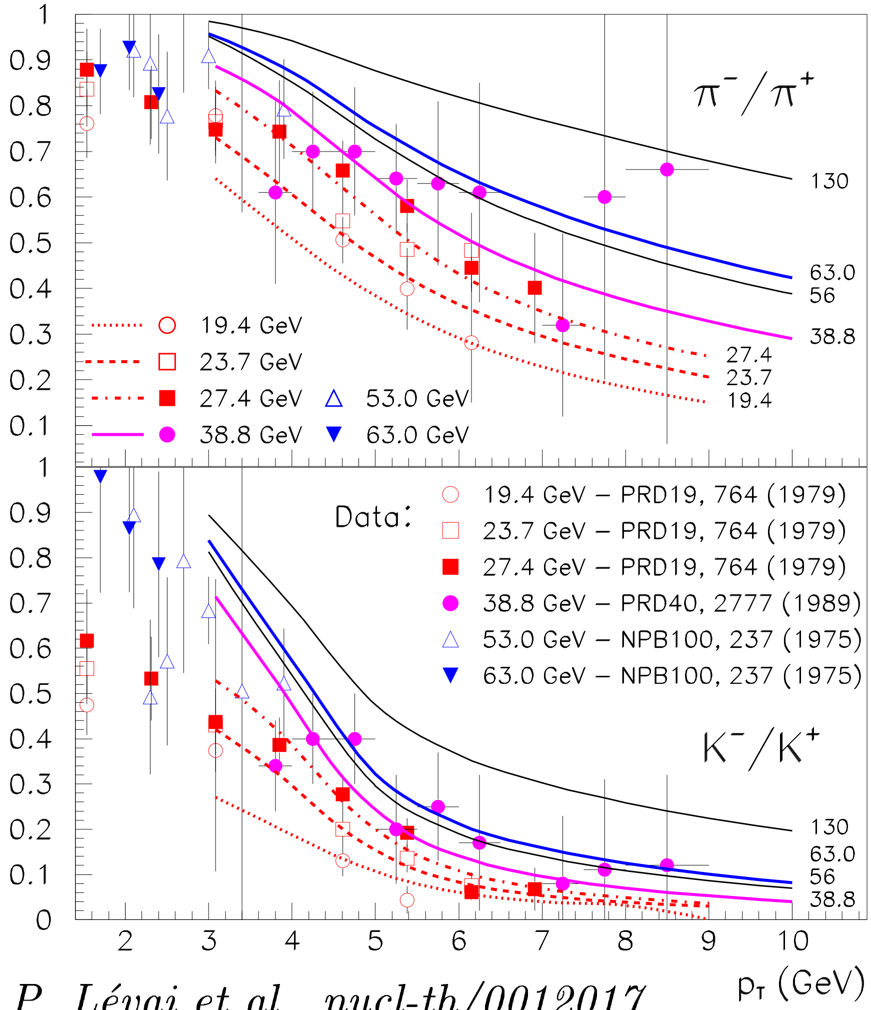
Central/periferial ratios:



Hadron production at high p_T by pQCD - 1

Pion and Kaon production in pp collisions:
$\longrightarrow$ intrinsic k_T

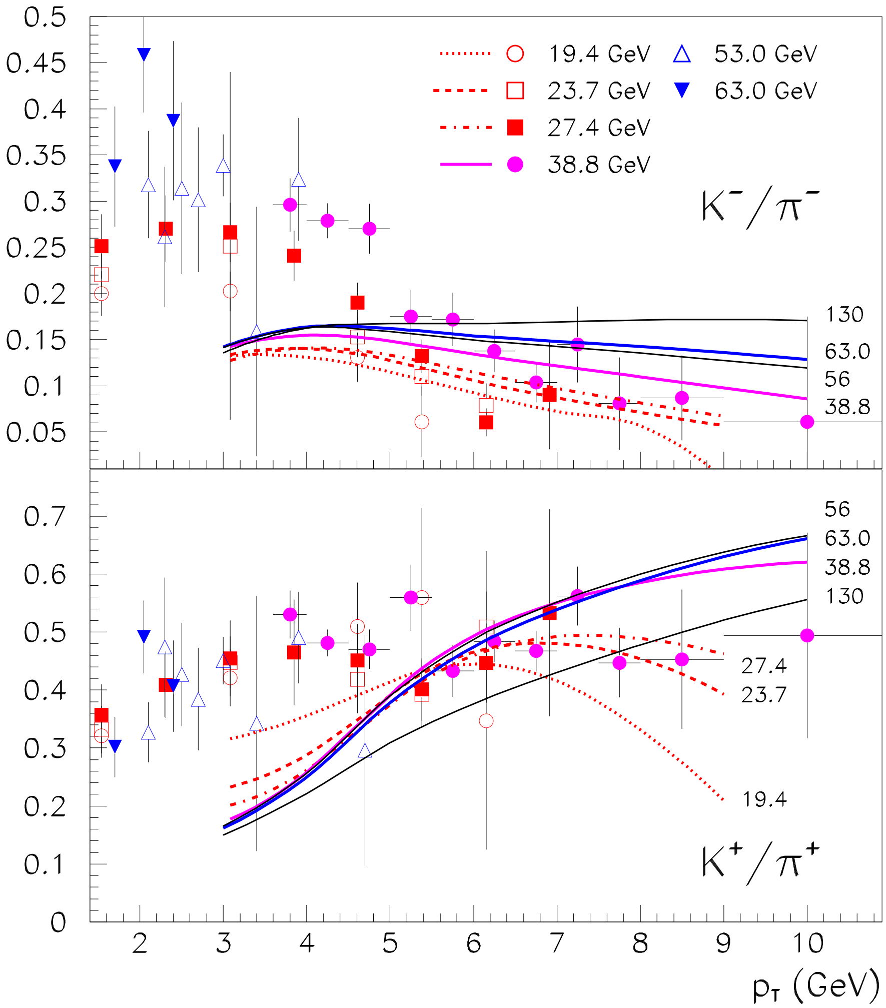
$$E_h \frac{d\sigma_h^{pp}}{d^3p} = \sum_{abcd} \int dx_1 dx_2 d^2k_{T,a} d^2k_{T,b}\, g(\vec{k}_{T,a})\, g(\vec{k}_{T,b}) \times f_{a/p}(x_1,Q^2)\, f_{b/p}(x_2,Q^2)\, \frac{d\sigma}{d\hat{t}} \frac{D_{h/c}(z_c,\widehat{Q}^2)}{\pi z_c} .$$



P. Lévai et al., nucl-th/0012017

Hadron production at high p_T by pQCD - 2

Pion and Kaon ratios in *pp* collisions:



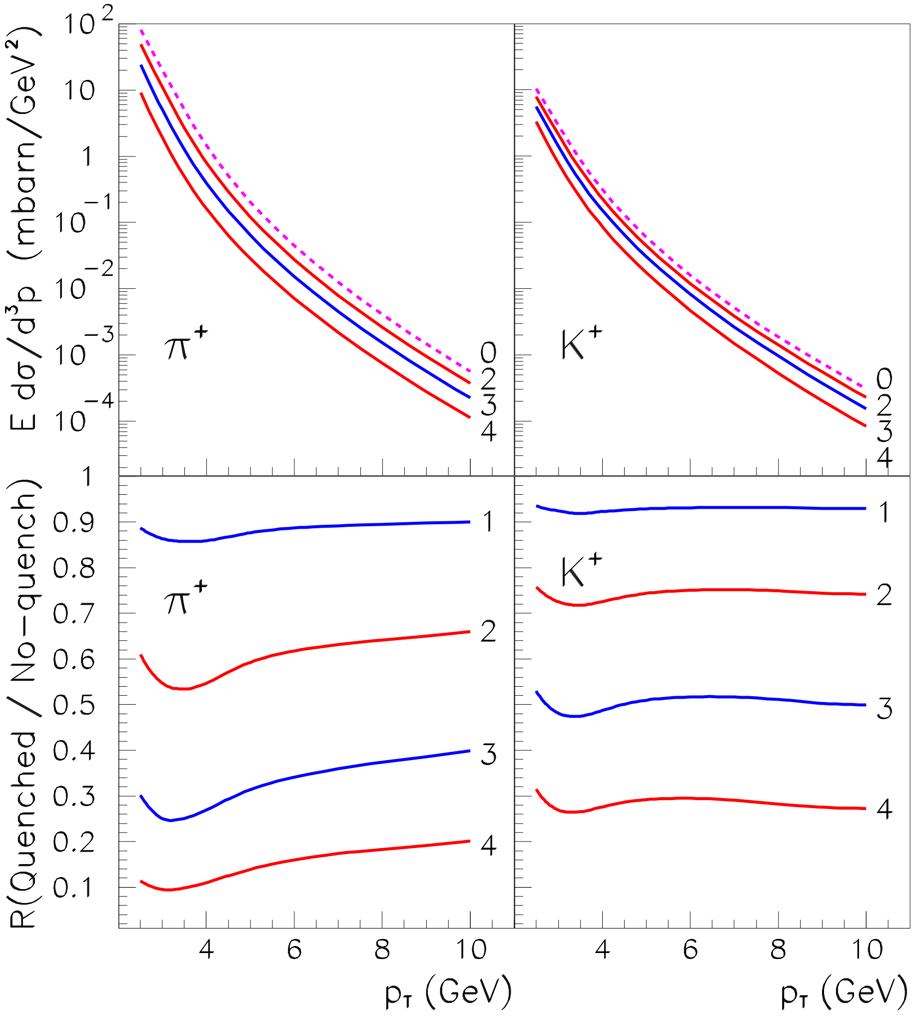
Hadron ratios as probe of jet quenching - 1

Hadron production in A+A collision (LO):

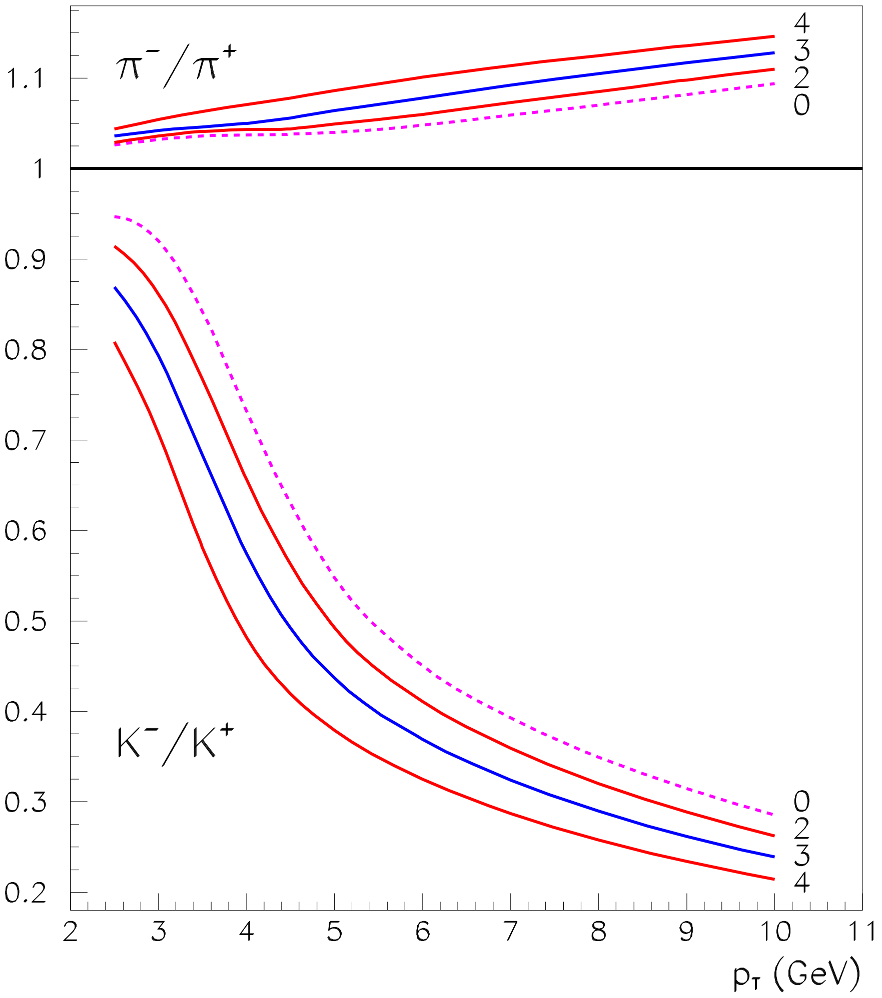
$$E_h \frac{d\sigma_h^{AA}}{d^3p} = B_{AA}^{(0)} \sum_{abcd} \int dx_1 dx_2 d^2k_{T,a} d^2k_{T,b}\; g(\vec{k}_{T,a}) g(\vec{k}_{T,b})$$
$$f_{a/A}(x_1, Q^2) f_{b/A}(x_2, Q^2)\; \frac{d\sigma}{d\hat{t}} \frac{z_c^*}{z_c} \frac{D_{h/c}(z_c^*, \widehat{Q}^2)}{\pi z_c}$$

- $f_{a/A}(x_1, Q^2)$ in-medium PDF (shadowing).
- $B_{AA}^{(0)} = 2\pi \int_0^{b_{max}} b\; db\; T_{AA}(b)$
- $T_{AA}(b)$ is the thickness function
- $z_c^*/z_c \iff$ in-medium fragmentation fuction (renorm.)

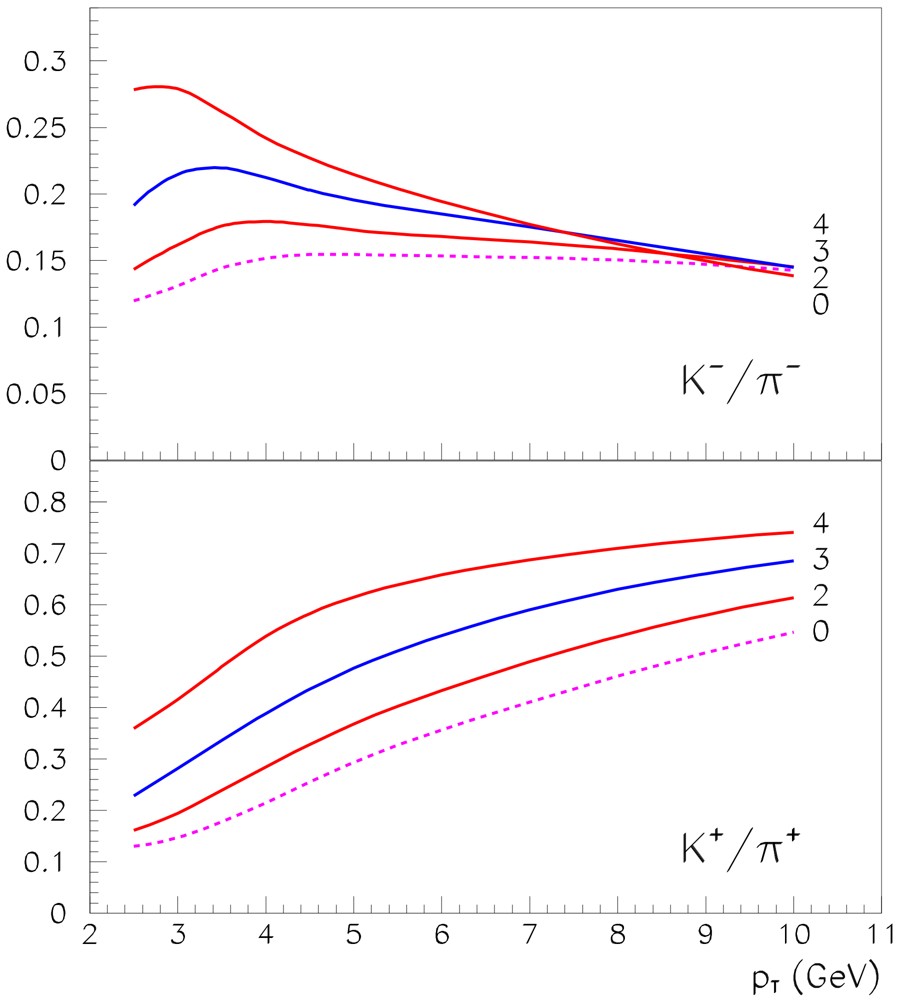
Hadron ratios as probe of jet quenching - 2



Hadron ratios as probe of jet quenching - 3



Hadron ratios as probe of jet quenching - 4



Summary

0. PHENIX result indicates strong jet-quenching:
$\sim 6-8$ fold suppression in the π^0 p_T-spectra
in central Au+Au collisions

1. Suppression pattern understood:

- appropriate description of jet energy loss
  GLV: thin matter, non-abelian case
- baseline pQCD predictions for AA collision
  precise pQCD description in pp
  multiscattering & shadowing in pA.

$\Longrightarrow$ $L/\lambda \approx 3-4$ **in an effective static medium**
expansion implies very high initial density

$$dN_g/dy \approx 1000$$

2. Flavour dependence of jet-quenching
$K^+/\pi^+, K^-/\pi^-$ ratios are sensitive to energy loss.

3. Energy loss in expanding matter
Gyulassy-Wang-Vitev (nucl-th/0012092)
$\Longrightarrow$ **Poster P113 — I. Vitev**