Energy conservation in high-p_T reactions

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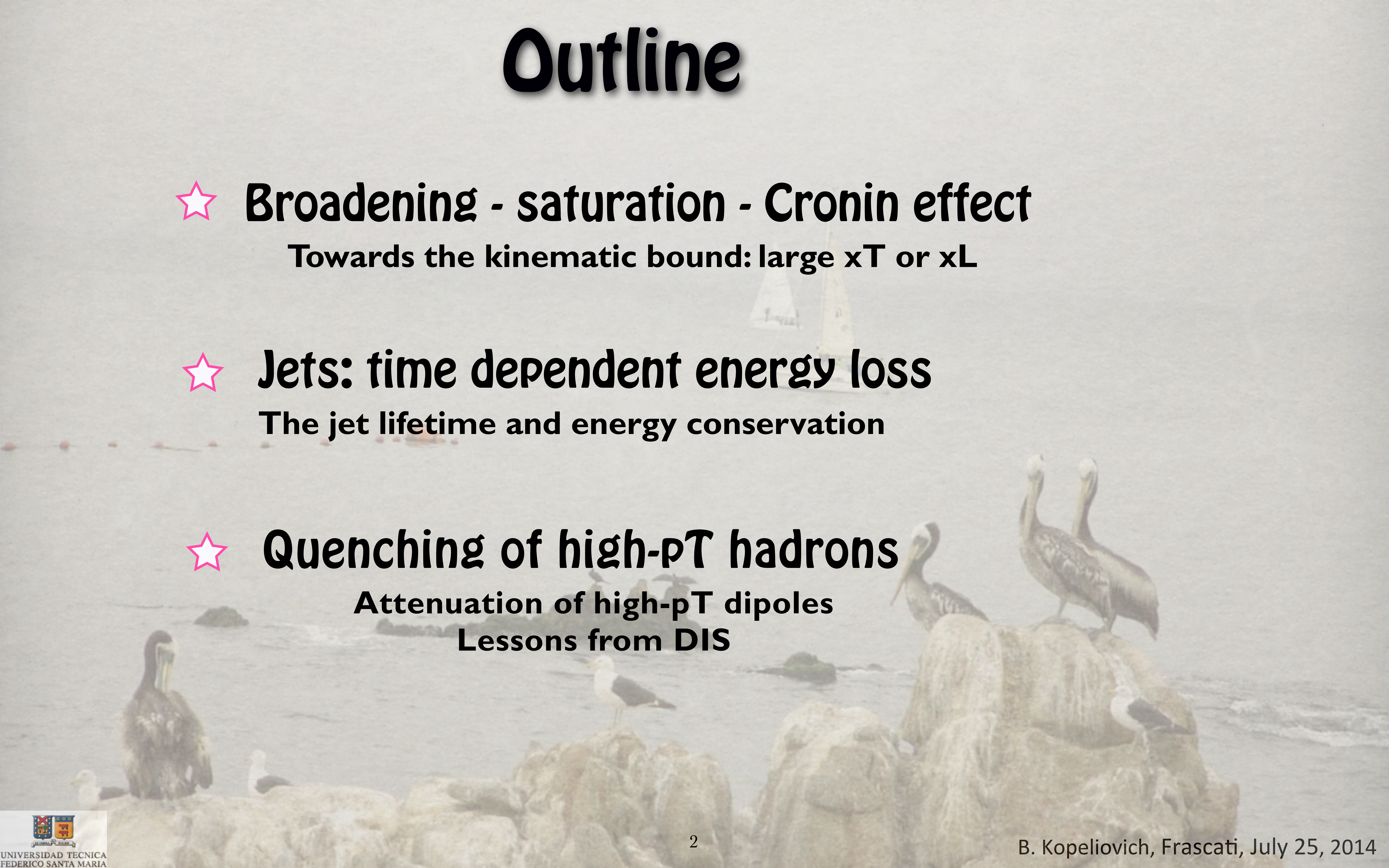
Valparaiso

Frascati, July 25, 2014

Outline



- ☆ **Broadening - saturation - Cronin effect**

  Towards the kinematic bound: large xT or xL

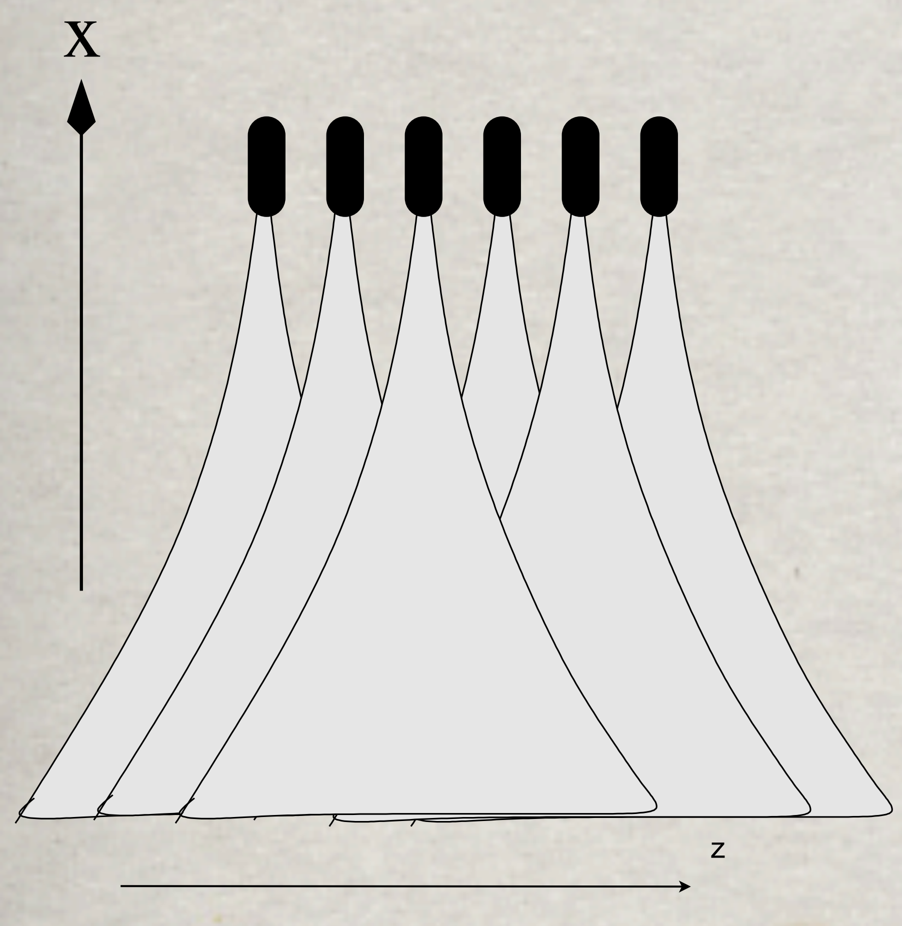
- ☆ **Jets: time dependent energy loss**

  The jet lifetime and energy conservation

- ☆ **Quenching of high-pT hadrons**

  Attenuation of high-pT dipoles
  Lessons from DIS

Saturation scale and broadening



The mean gluon transverse momentum rises with 1/x because the momenta of fusing gluons add up. Thus, non only the nuclear gluon density is reduced at small x (shadowing), but the mean gluon momentum rises. Such a modification of the gluon transverse momentum distribution is called color glass condensate (CGC), and the mean gluon momentum squared $\langle k_T^2 \rangle \equiv Q_s^2(x)$ is called saturation scale.

How does this look like in the nuclear rest frame?

A parton propagating through a medium experiences pT-broadening:

$$\Delta p_T^2 = \langle p_T^2 \rangle_{final} - \langle p_T^2 \rangle_{initial} \propto T_A(b) = \int\limits_{-\infty}^{\infty} dz \rho_A(b,z)$$

$$\boxed{Q_s^2 = \Delta p_T^2}$$

Broadening is related to the universal dipole cross section:

$$\Delta p_T^2(b,x) = \nabla_r^2 \sigma(r,x)\Big|_{r=0} T_A(b)$$

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Measuring the saturation scale

Broadening has been measured in:

- pA (Drell-Yan; E772&E866)

$$\Delta(p_T^{\bar{l}l})^2 = z_{\bar{l}l}^2 \Delta p_T^2$$

(quark broadening)

$$\langle z_{\bar{l}l} \rangle \approx 0.9$$

- J/Ψ and Υ in pA (E772)

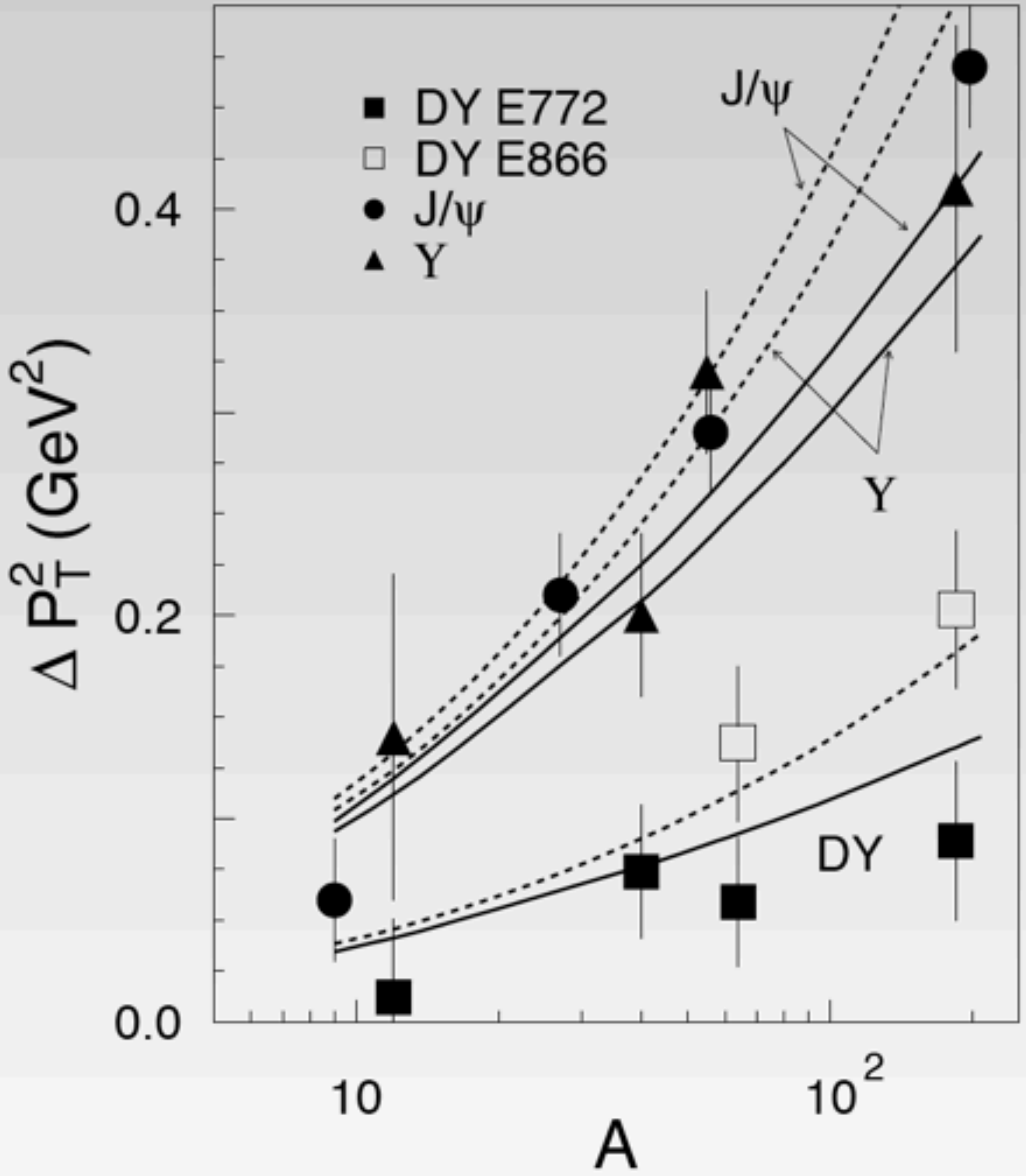
$$\Delta(p^{\bar{l}l})^2 \approx \Delta p_T^2 \times 9/4$$

(gluon broadening)

- eA (SIDIS; HERMES&CLAS)

$$\Delta(p_T^h)^2 = z_h^2 \Delta p_T^2$$

(quark broadening)

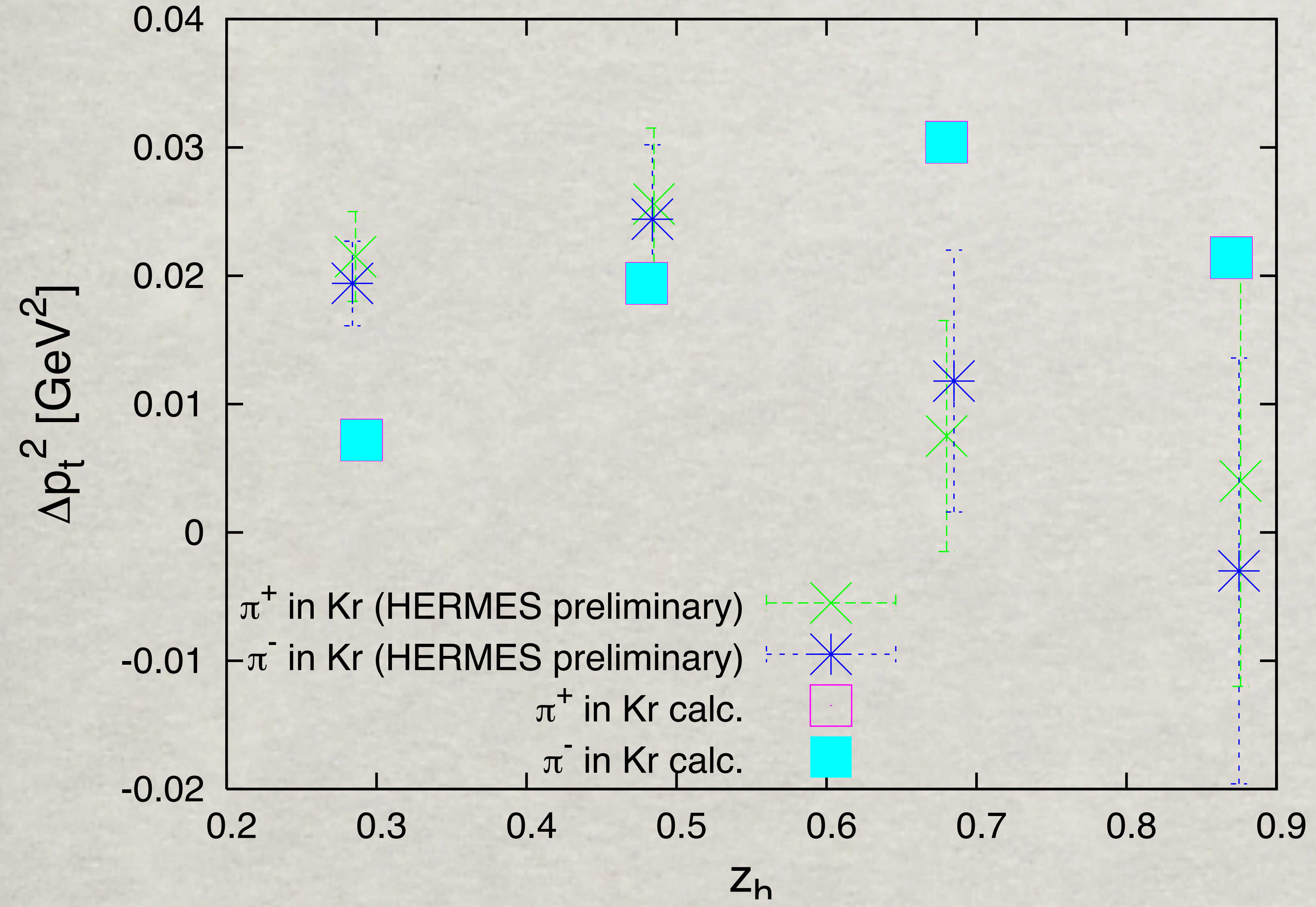


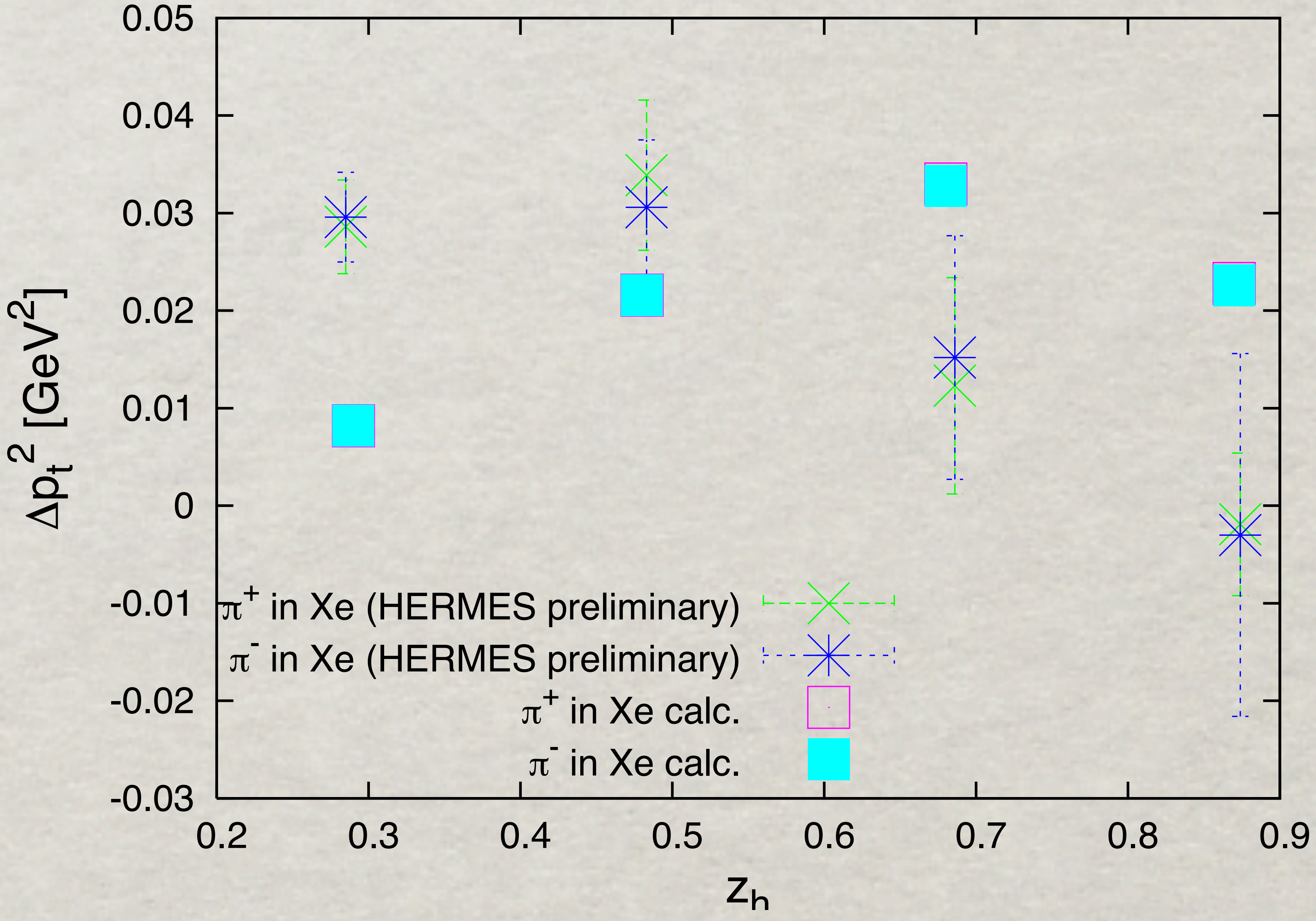
Broadening in SIDIS

Broadening originates mainly from the first stage of hadronization. Broadening of the pre-hadron proceeds with a very small elastic cross section and can be disregarded.

- Thus, broadening is a sensitive probe for the production length, $\Delta p_T^2 \propto l_p$, which was predicted to shrink for leading hadrons, $l_p \propto 1 - z_h$ [B.K., F.Niedermayer, 1984].

This is confirmed by HERMES data.





S.Domdey, D.Grünewald, B.K., H.J.Pirner, 2009

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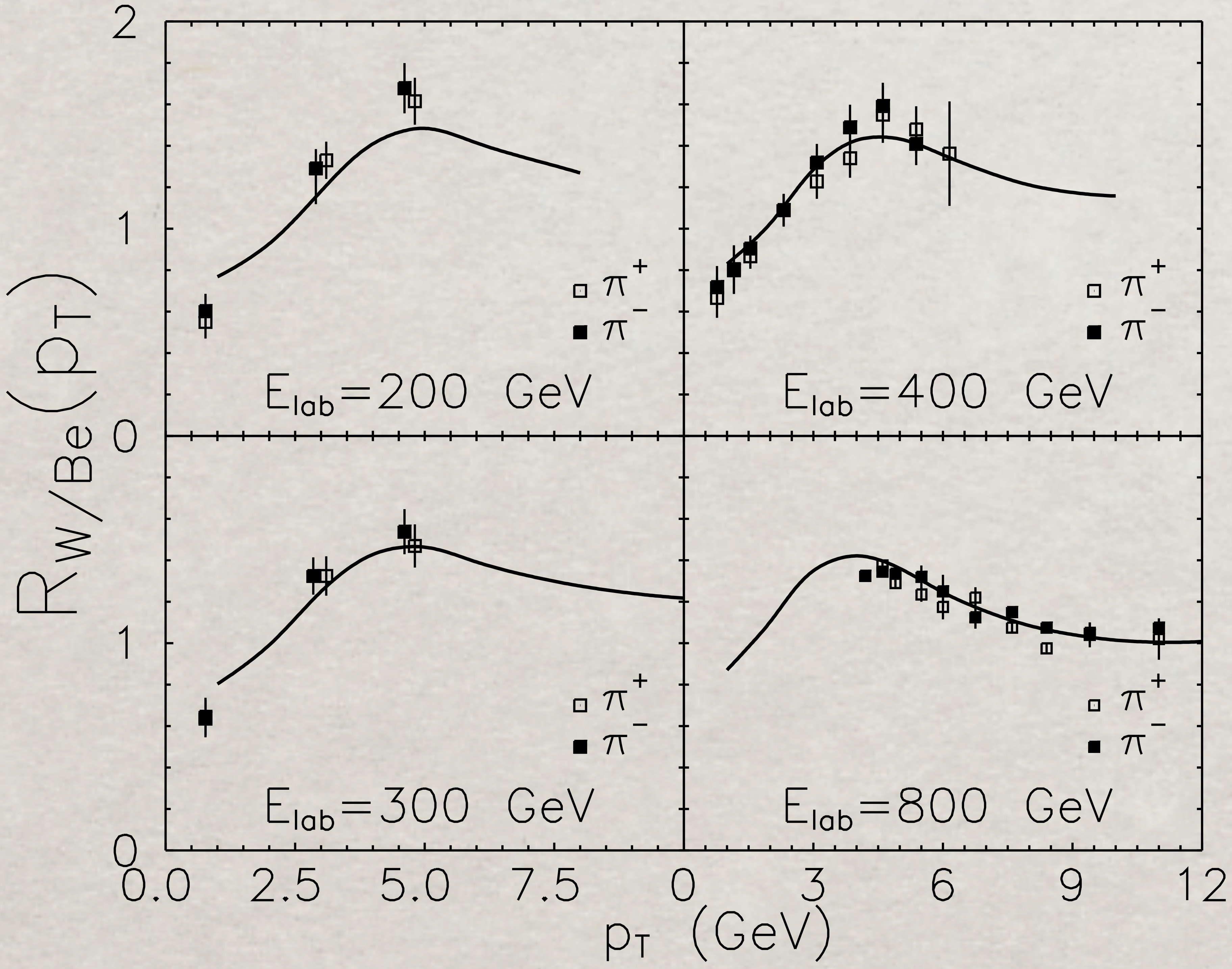
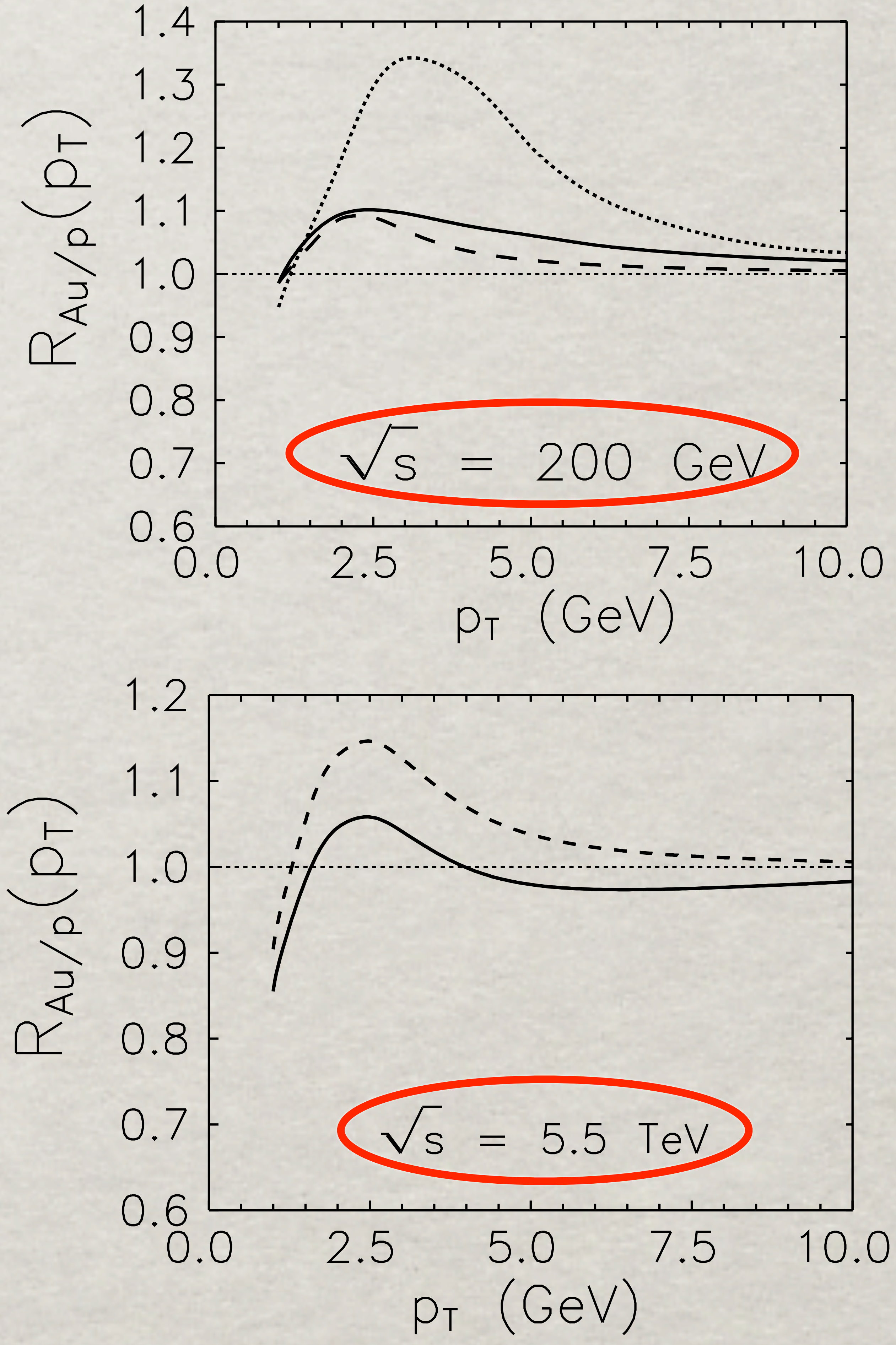
Cronin effect

Broadening leads to a nuclear enhancement, called Cronin effect.

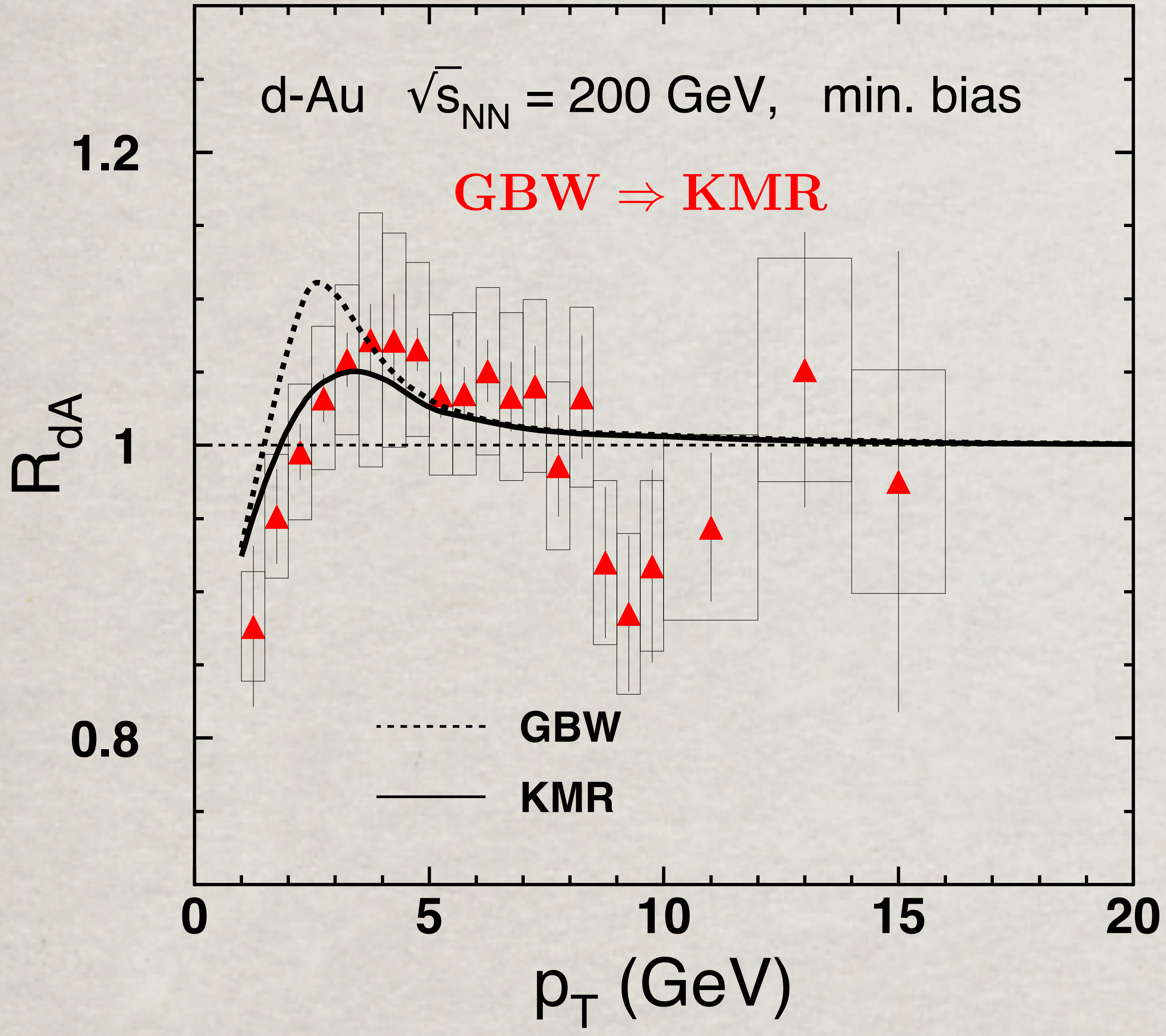
High-pT hadrons can be produced coherently from multiple interactions in nuclei at very high energies (LHC), but not at low energies of fixed target experiments. Correspondingly, the mechanisms for the Cronin enhancement are different.



B.K., J.Nemchik, A.Schafer, A.Tarasov,
PRL 88(2002)232303`



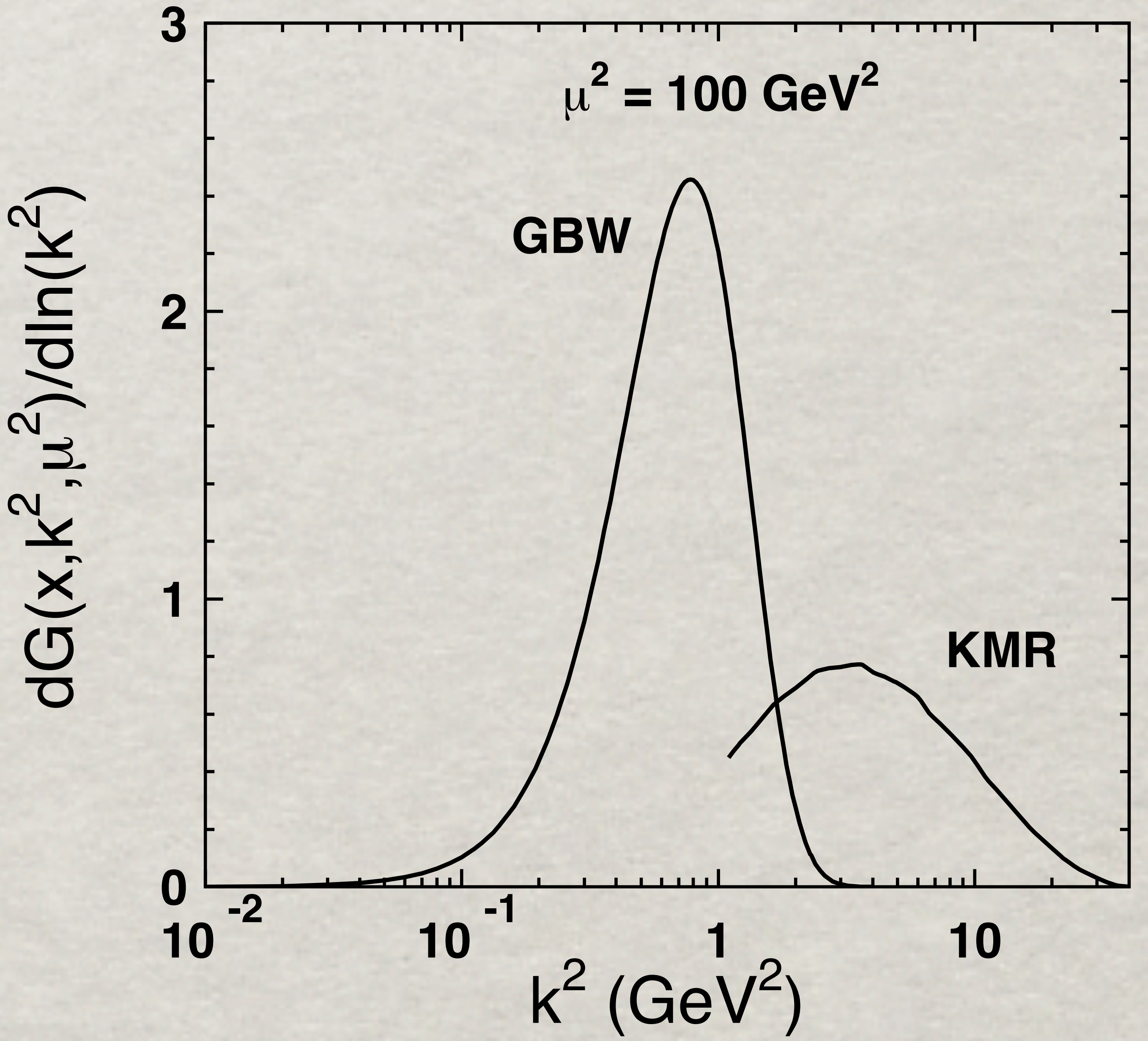
Cronin effect at RHIC: predicted and observed



$$\mathrm{GBW:} \qquad \sigma(\mathbf{r_T},\mathbf{x}) = \sigma_0 \left[1 - e^{-\mathbf{r}^2\, \mathbf{Q_s^2(x)}}\right]$$

More realistic parametrization for the unintegrated gluon distribution improves the shape

A.Martin, M.Ryskin & G.Watt, 2010



That was the only successful prediction

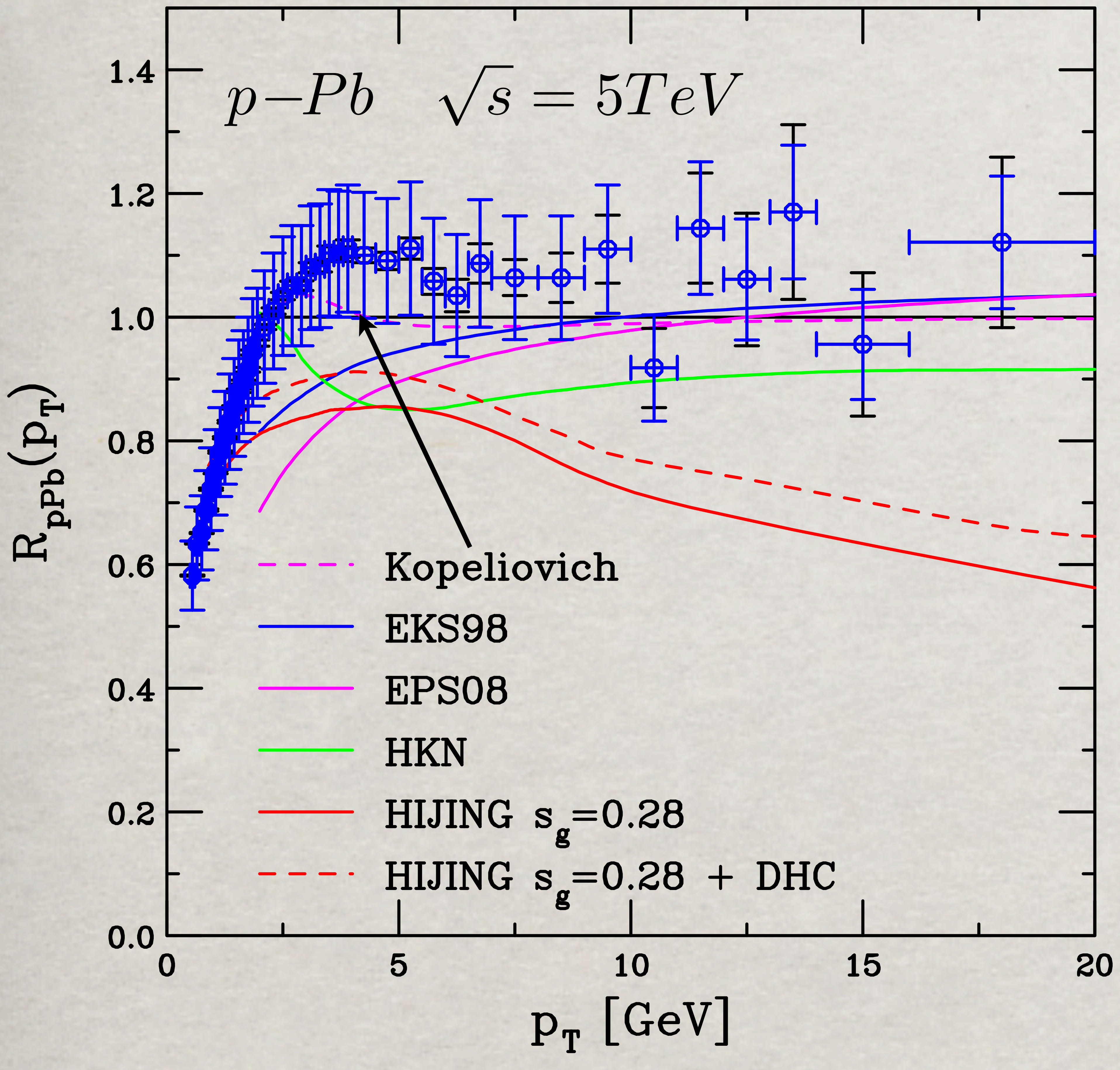
Other predictions

Color Glass Condensate models exaggerated the magnitude of the effects $R_{dA} = 0.75$

D.Kharzeev, E.Levin, L.McLerran (2003)

Cronin effect at LHC: predicted and observed

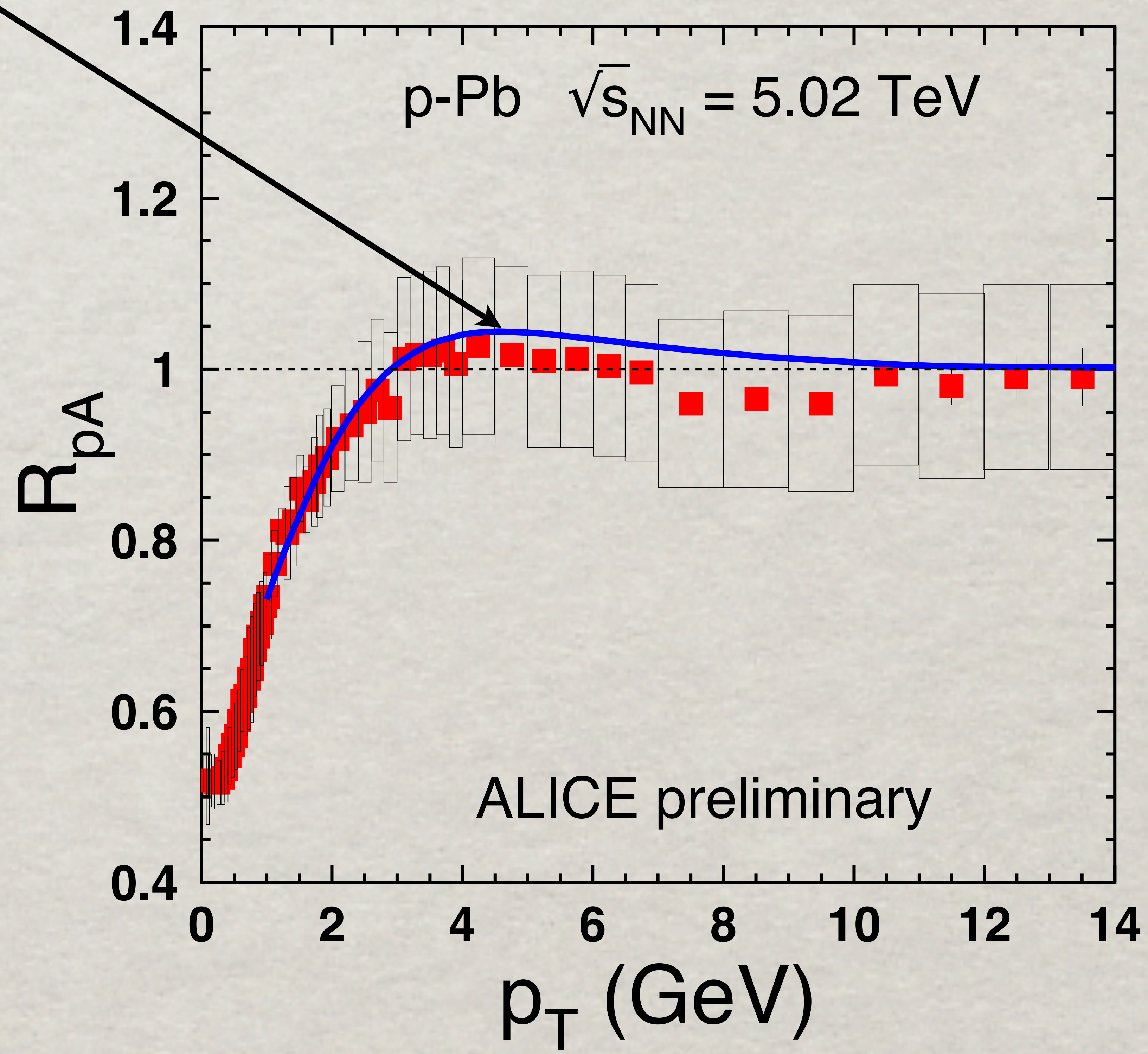
R.Vogt et al, arXiv: 1301.3395



J.Bartels, K.J.Golec-Biernat & H.Kowalsky, 2002

With the more realistic parametrization of the dipole cross section

$$\mathrm{BGBW}: \sigma(\mathbf{r_T},\mathbf{x}) = \sigma_\mathbf{0}\left[\mathbf{1} - \exp\left(-\frac{\pi^\mathbf{2}\mathbf{r}_\mathbf{T}^\mathbf{2}\alpha_\mathbf{s}\mathbf{x}\mathbf{g}(\mathbf{x},\mu^\mathbf{2})}{\mathbf{3}\sigma_\mathbf{0}}\right)\right]$$



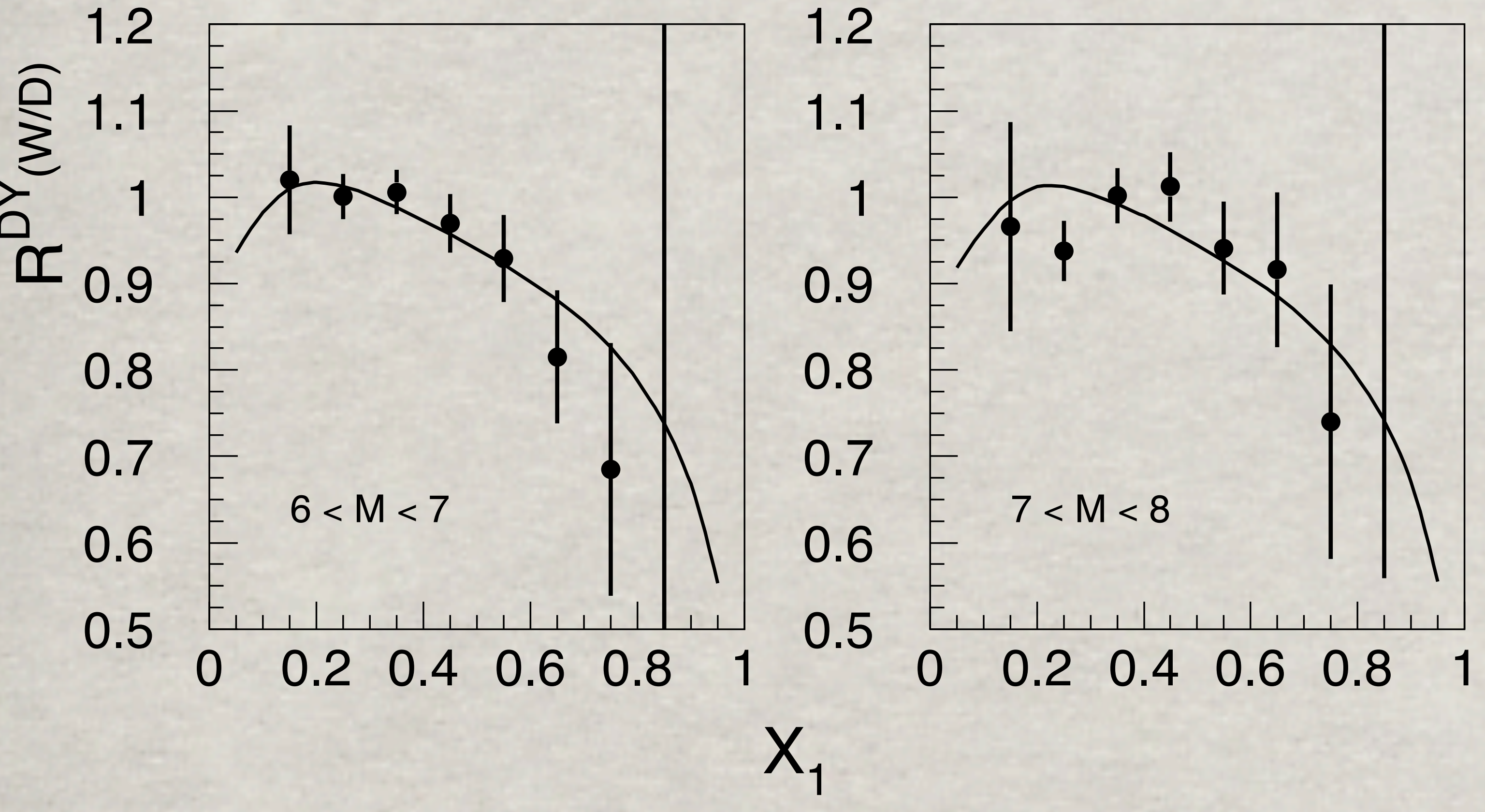
Again the only successful prediction

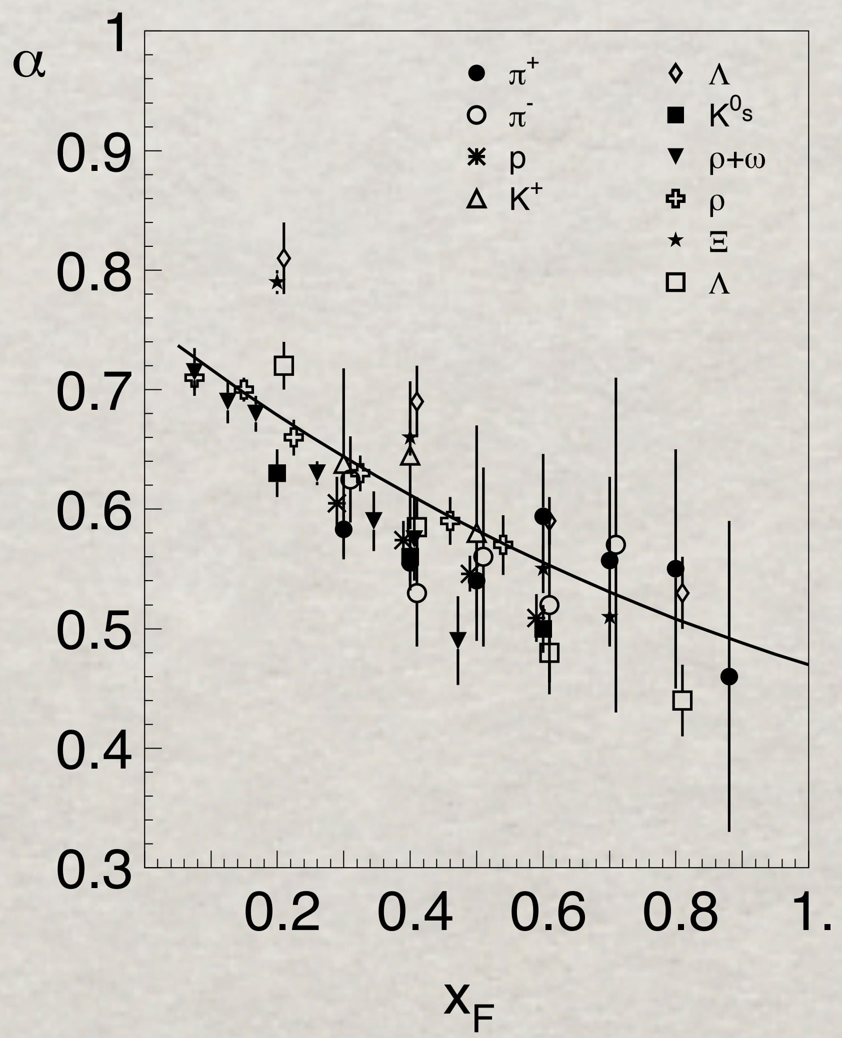
Most of the models, including CGC exaggerated the magnitude of gluon shadowing

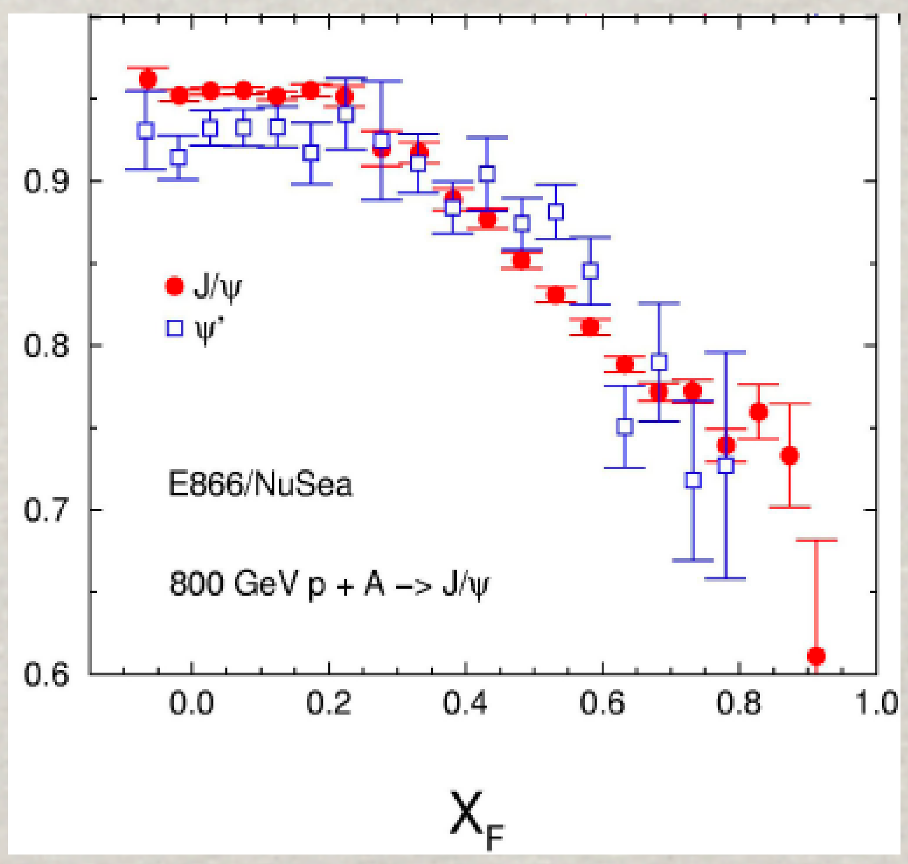
Deficit of energy towards the kinematical bound

The projectile hadron can be expanded over Fock states, some of which are resolved by the target, some not. A nucleus has a better resolution due to multiple interactions and resolves higher Fock components containing more constituents in the projectile hadron. The more participants it has, the more difficult is to give the main fraction of the beam energy to one of them. So on a nuclear target the projectile parton distribution falls off at $x \to 1$ steeper than on a proton.

Any process is suppressed at forward rapidities


Drell-Yan reaction (Elab = 800 GeV)


Small-pT hadrons, A^{α}
(70– 400 GeV)

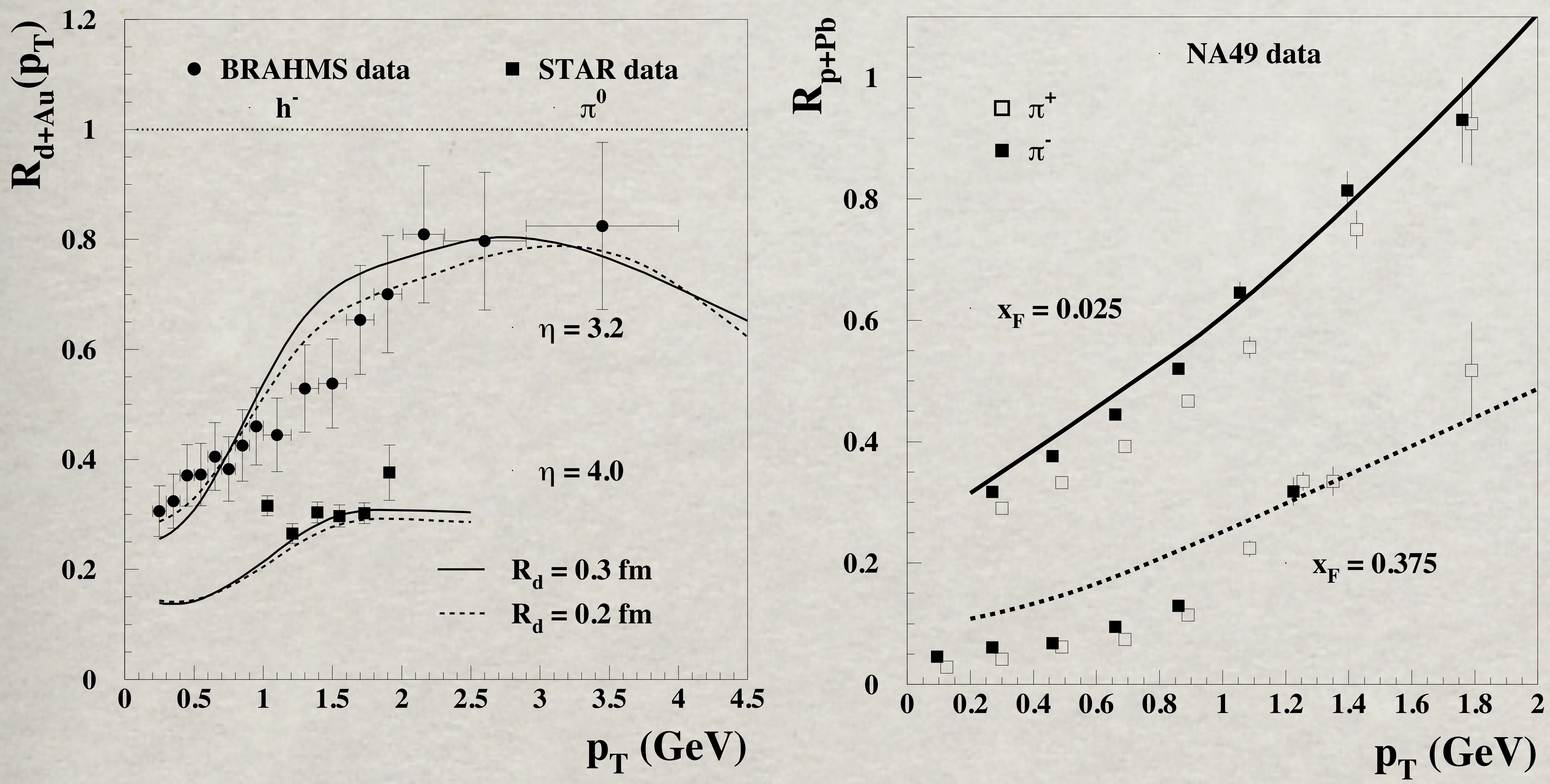

J/ψ and ψ′ production (800 GeV)

Cronin effect at forward rapidities

Initial state energy loss leads to an additional suppression at large x_L or x_T

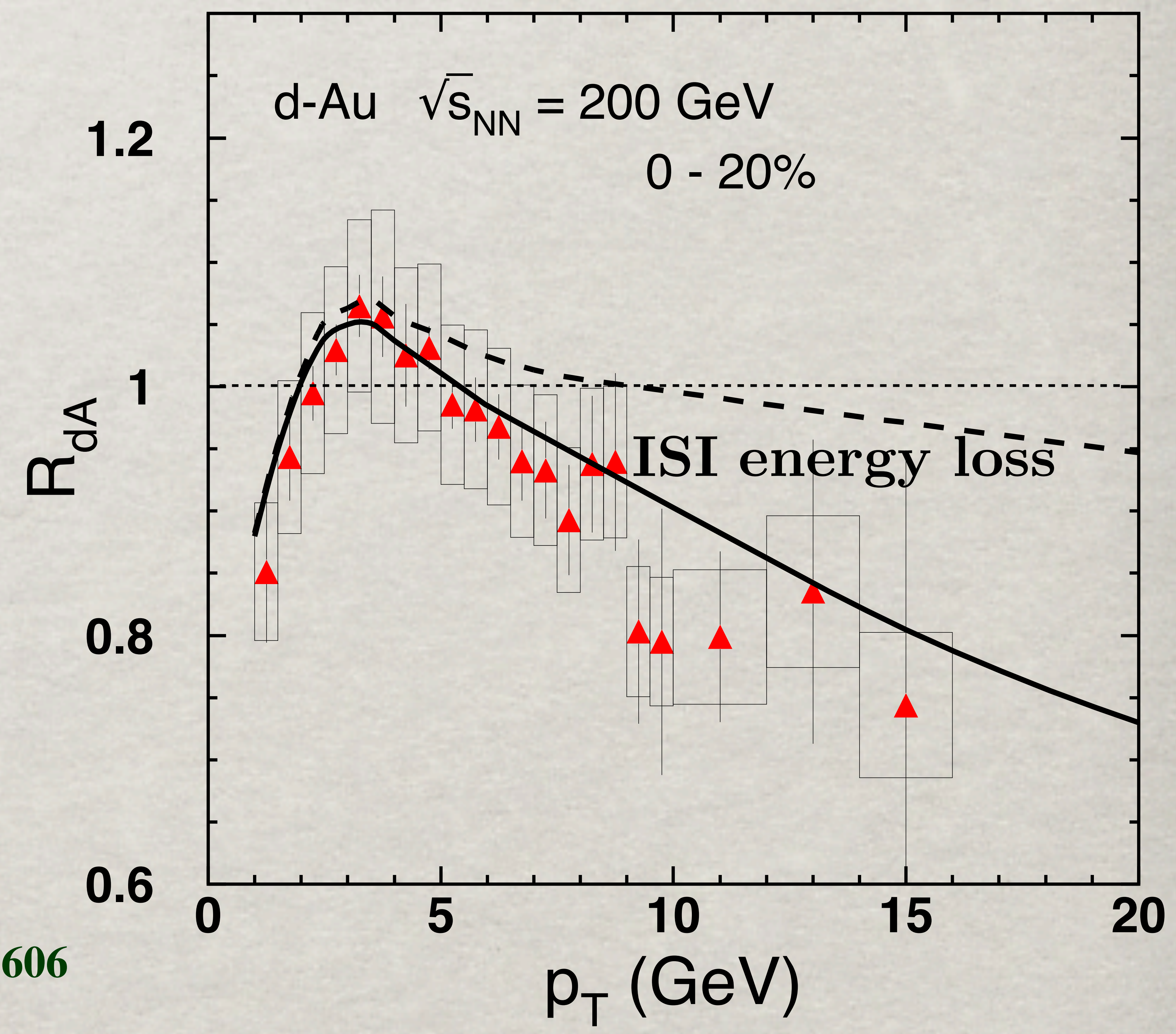
Examples

Suppression at forward rapidities



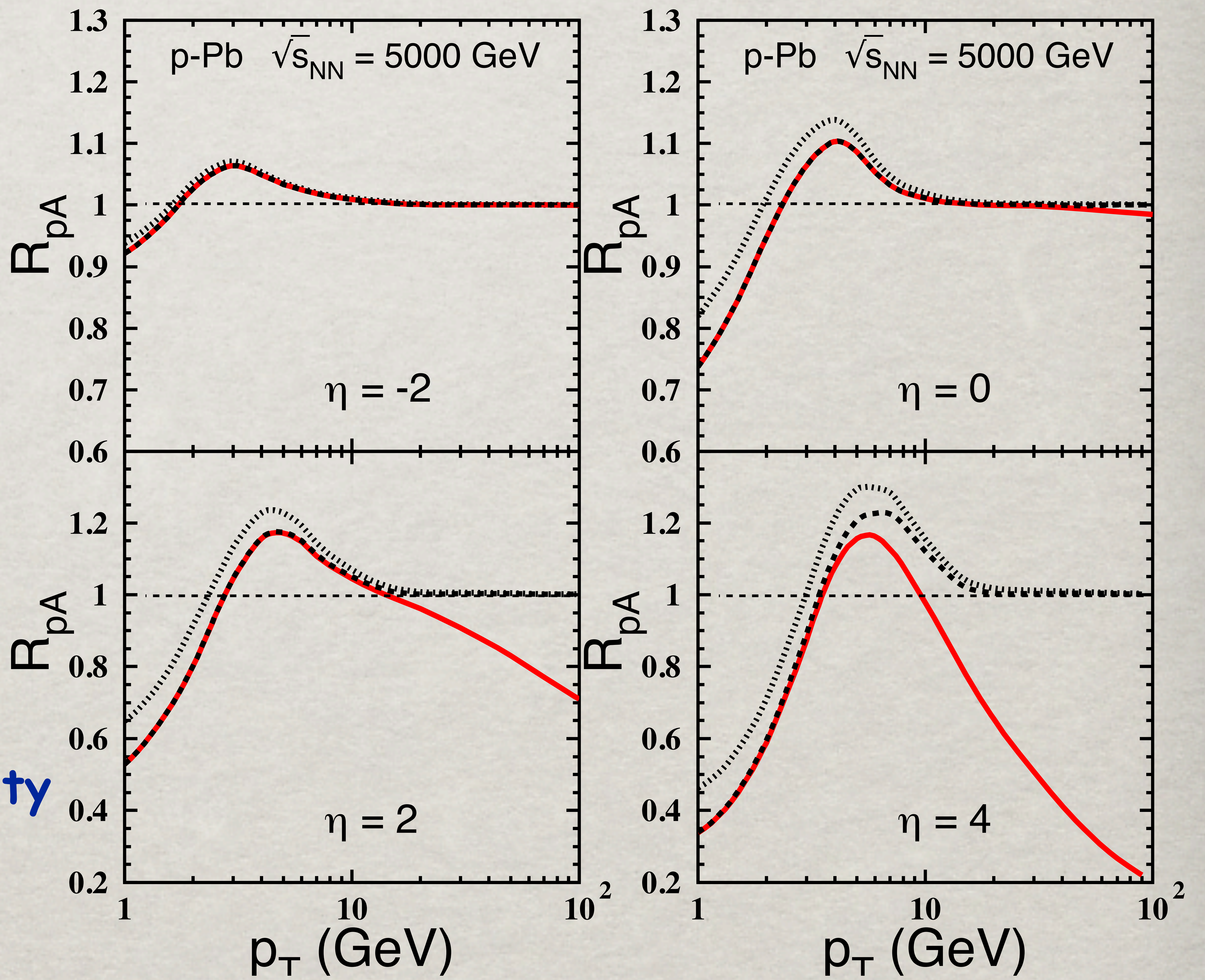
B.K., J.Nemchik, I.Potashnikova, M.Johnson & I.Schmidt, Phys.Rev. C72(2005)054606

One can also approach the kinematic limit at the mid rapidity, but high pT.



Cronin ratio at LHC at forward rapidities

One can enhance the role of ISI energy loss either moving to forward rapidities, or higher pT, or both



······· no shadowing

----- KST shadowing

— ISI E-loss added

KMR unintegrated gluon density

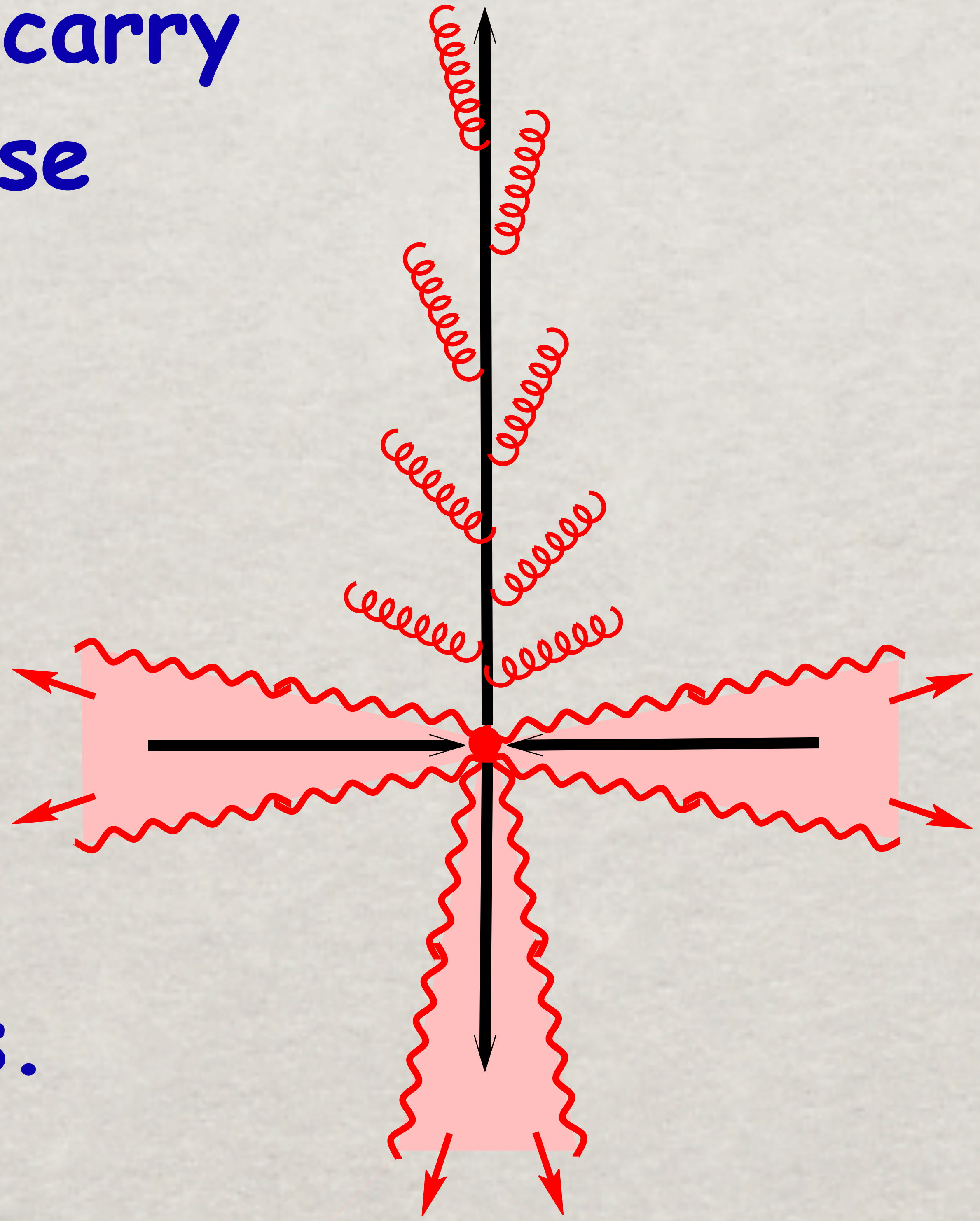
Hard parton collision

High-pt parton scattering leads to formation of 4 cones of gluon radiation:

(i) the color field of the colliding partons is shaken off in forward-backward directions.

(ii) the scattered partons carry no field up to transverse momenta kt<pt.

The final state partons are regenerating the lost color field by radiating gluons and forming the up-down jets.



The coherence length/time of gluon radiation

$$l_c = \frac{2E\,x(1-x)}{k_T^2 + x^2 m_q^2} \approx \frac{2\,\omega}{k_T^2}$$

First are radiated gluons with small longitudinal and large transverse momenta.

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Time dependent vacuum energy loss

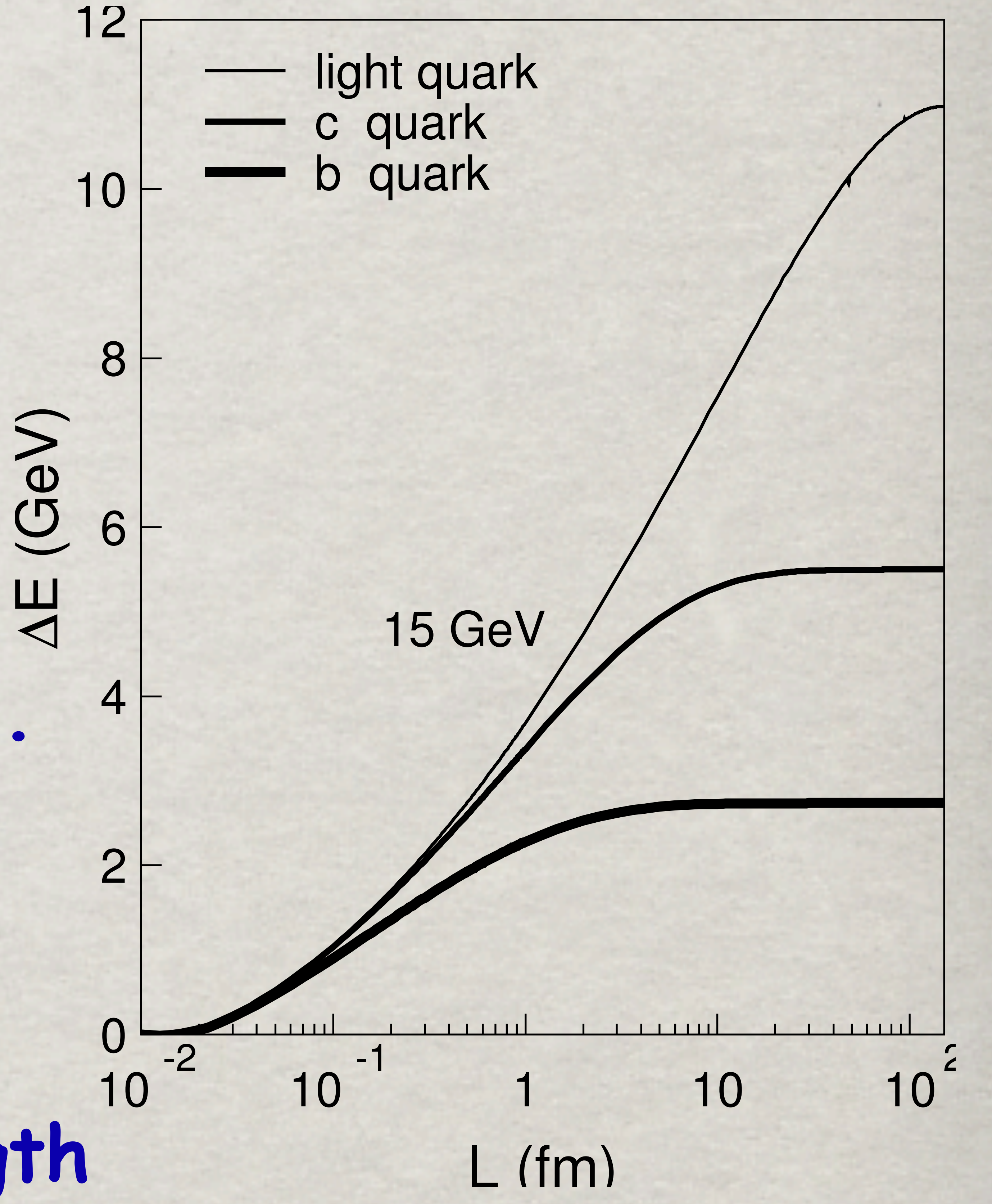
How much energy is radiated over the path length L?

$$\Delta E(L) = E \int_{\Lambda^2}^{Q^2} dk^2 \int_0^1 dx\, x \frac{dn_g}{dx\, dk^2} \Theta(L - l_c)$$

$$\frac{dn_g}{dx\, dk^2} = \frac{2\alpha_s(k^2)}{3\pi x} \frac{k^2[1+(1-x)^2]}{[k^2 + x^2 m_q^2]^2}$$

Dead-cone effect: gluons with $k^2 < x^2 m_q^2$ are suppressed.

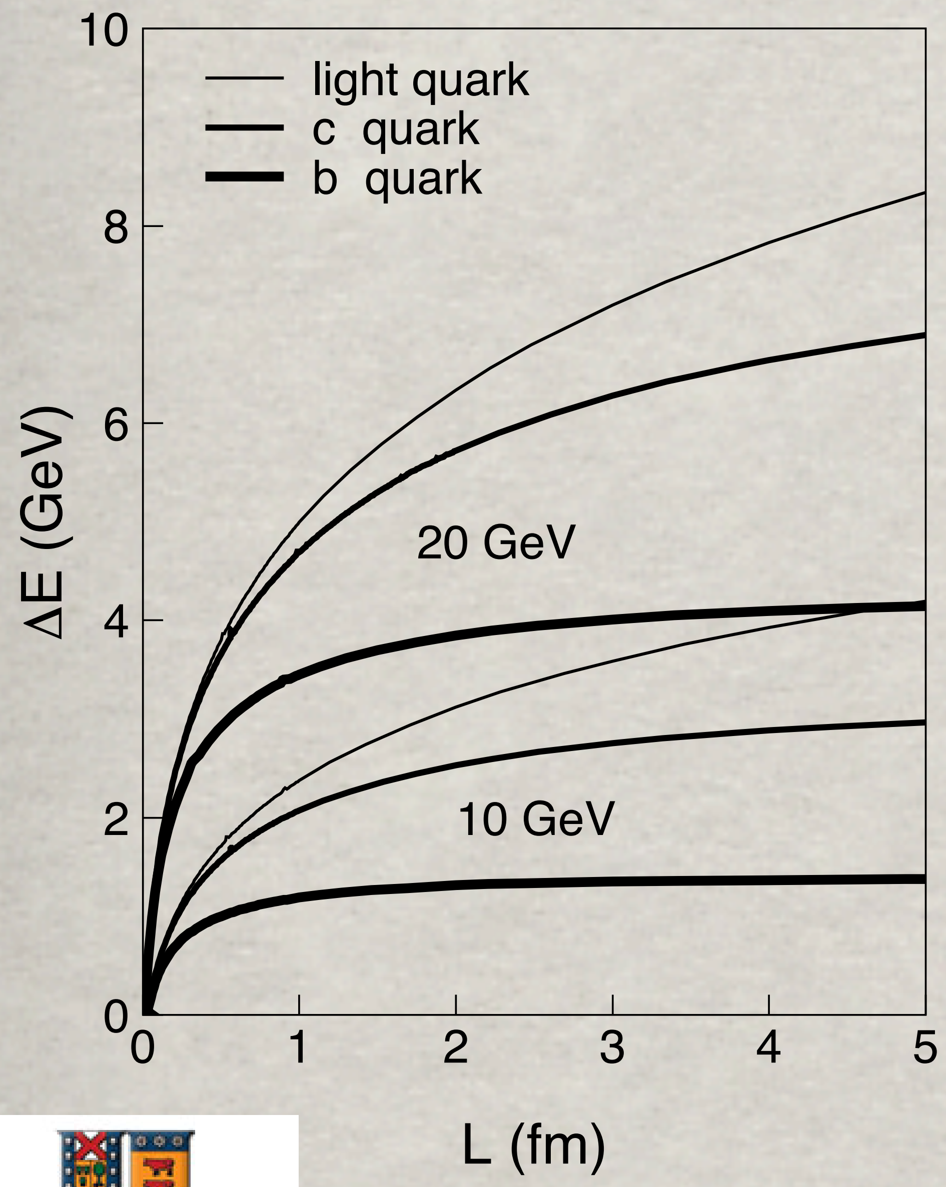
Heavy quarks radiate less energy than the light ones.



B.K., I.Potashnikova,I.Schmidt, PRC 82(2010)037901

Another dead cone: soft gluons cannot be radiated at short path length

$$k^2 > \frac{2Ex(1-x)}{L} - x^2 m_q^2$$



This is why heavy and light quarks radiate with similar rates at short time scales $L \lesssim \frac{Ex(1-x)}{x^2 m_q^2}$

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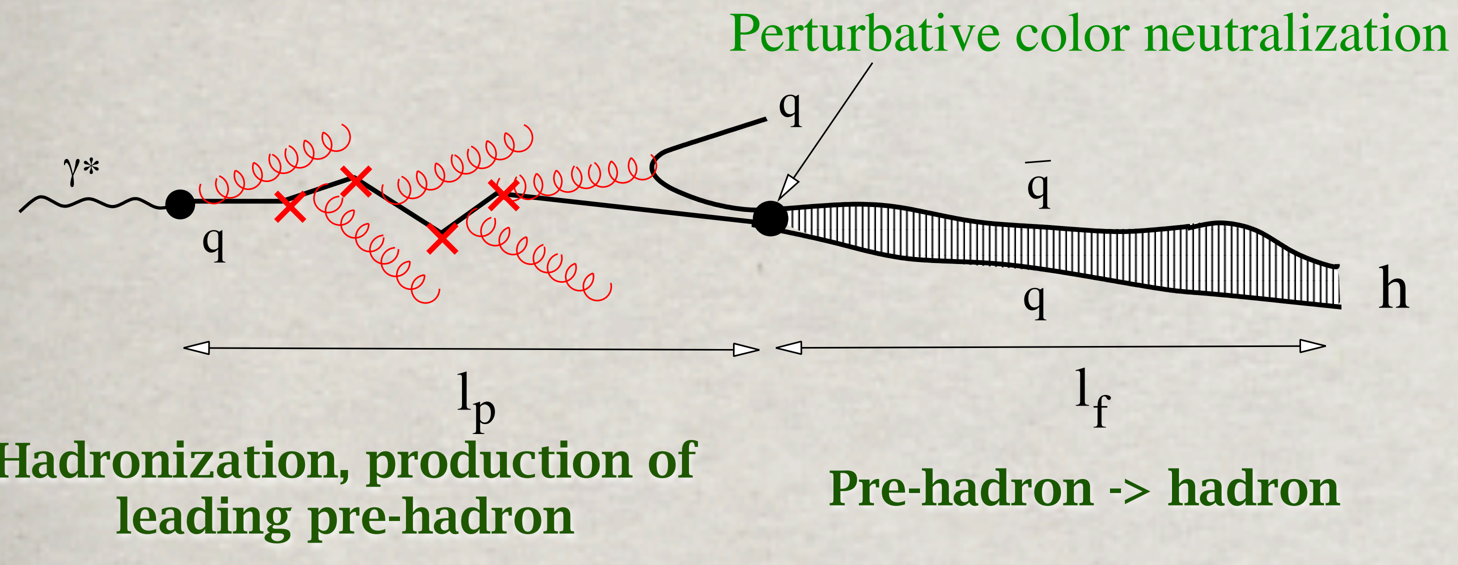
Hadronization in vacuum

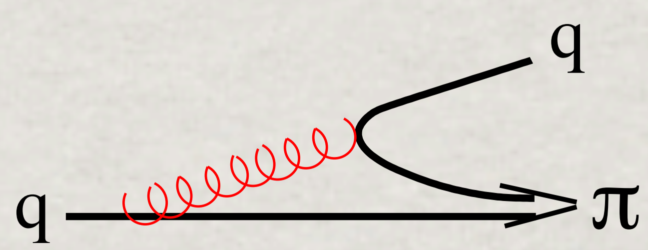


Perturbative color neutralization

Hadronization, production of leading pre-hadron

Pre-hadron -> hadron

Perturbative hadronization at large z_h



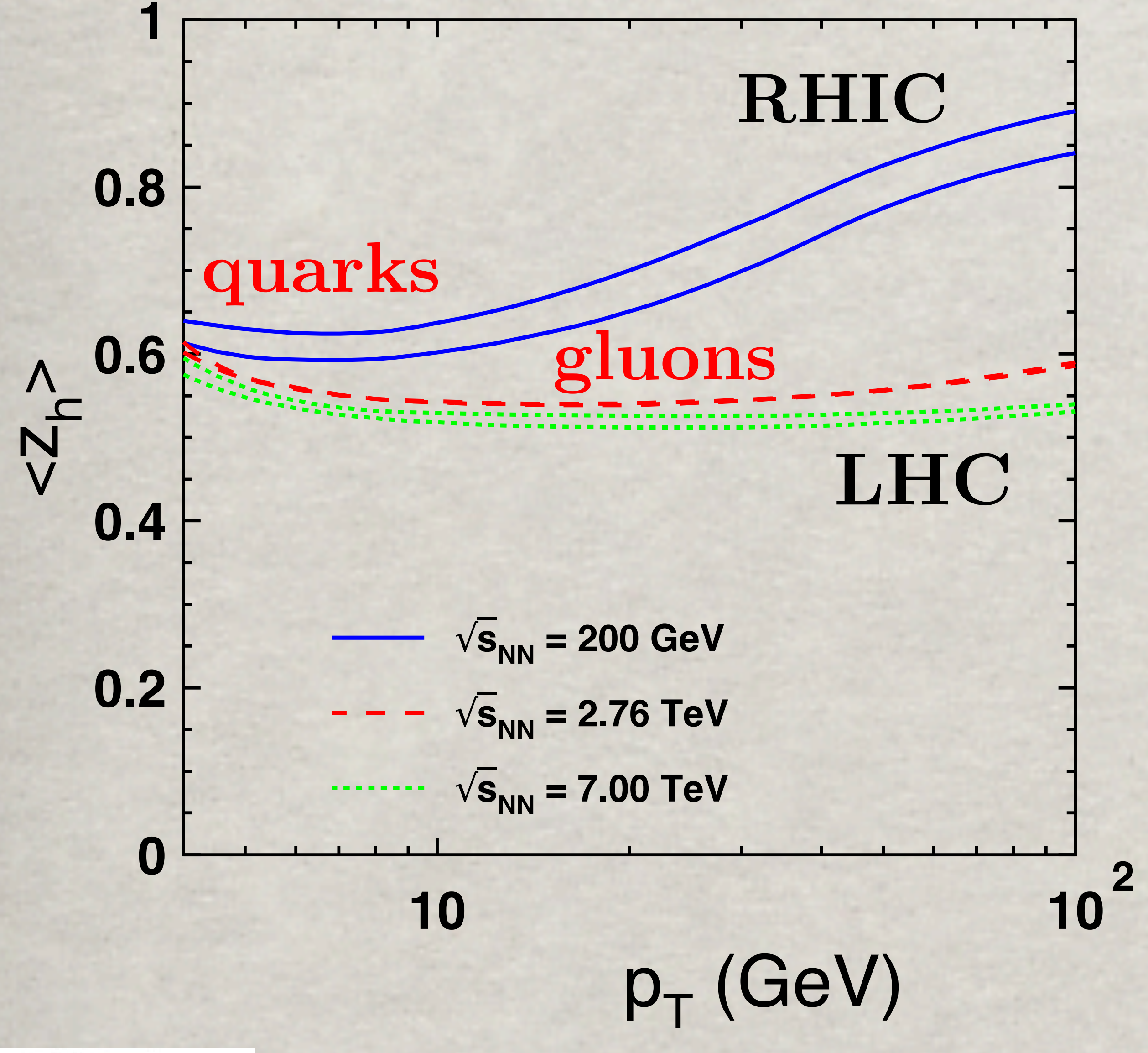
E. Berger, PLB 89(1980)241

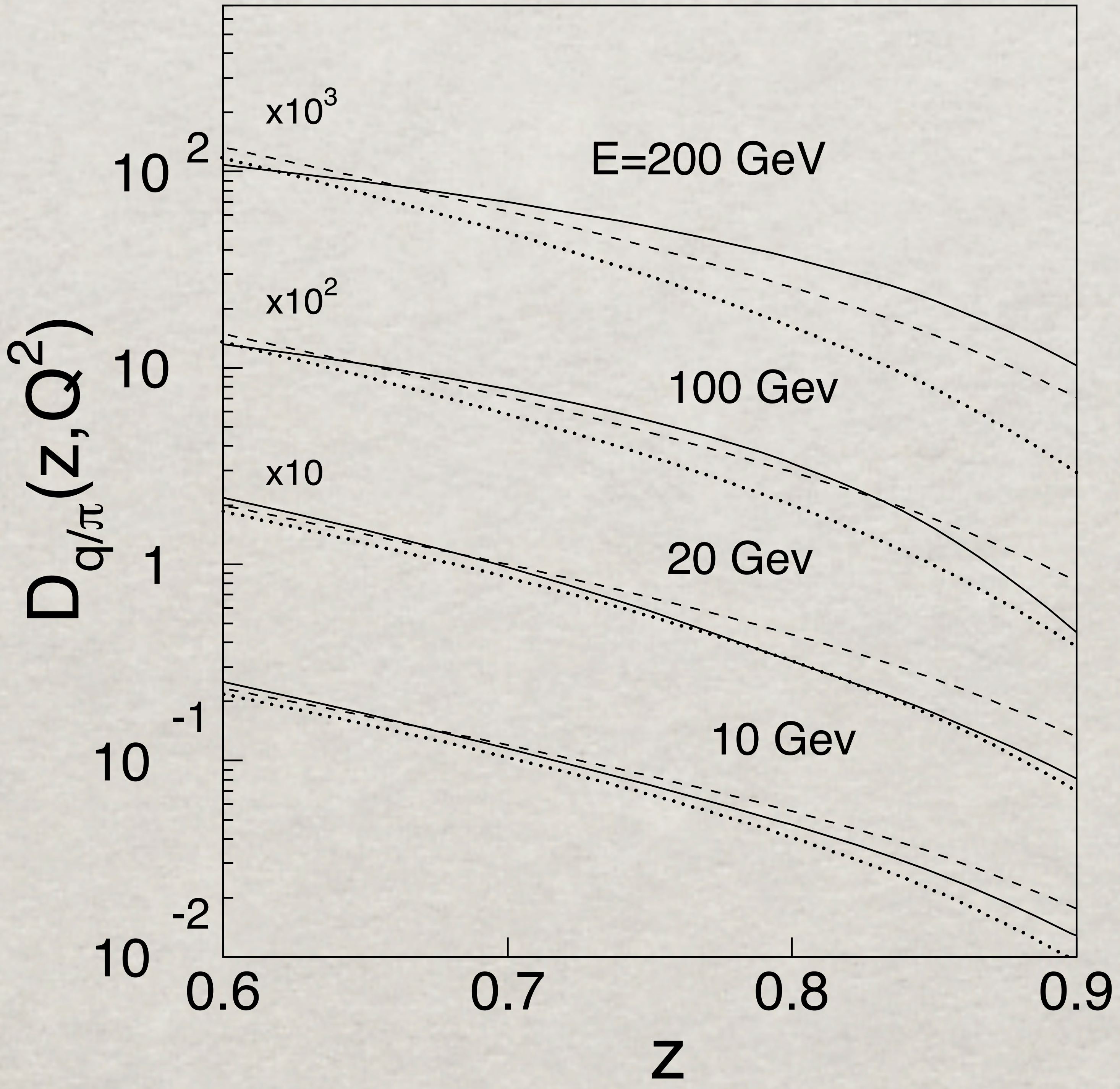
B.K., H.J.Pirner,I.Schmidt,A.Tarasov PRD 77(2008)054004

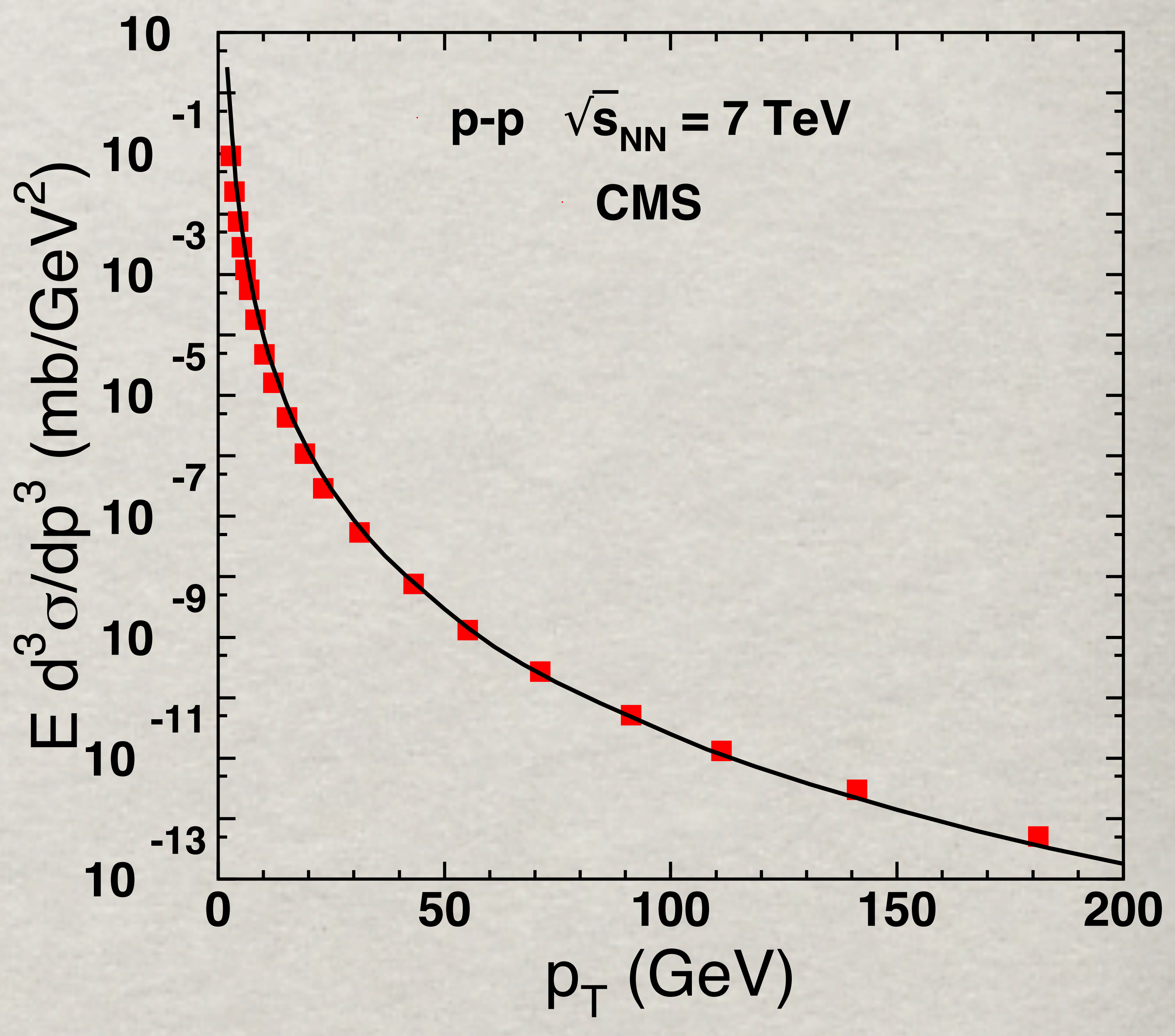
B.K., H.J.Pirner,I.Potashnikova,I.Schmidt, PLB 662(2008)117

Test vs KKP and BKK:

Mean value $\langle z_h \rangle$





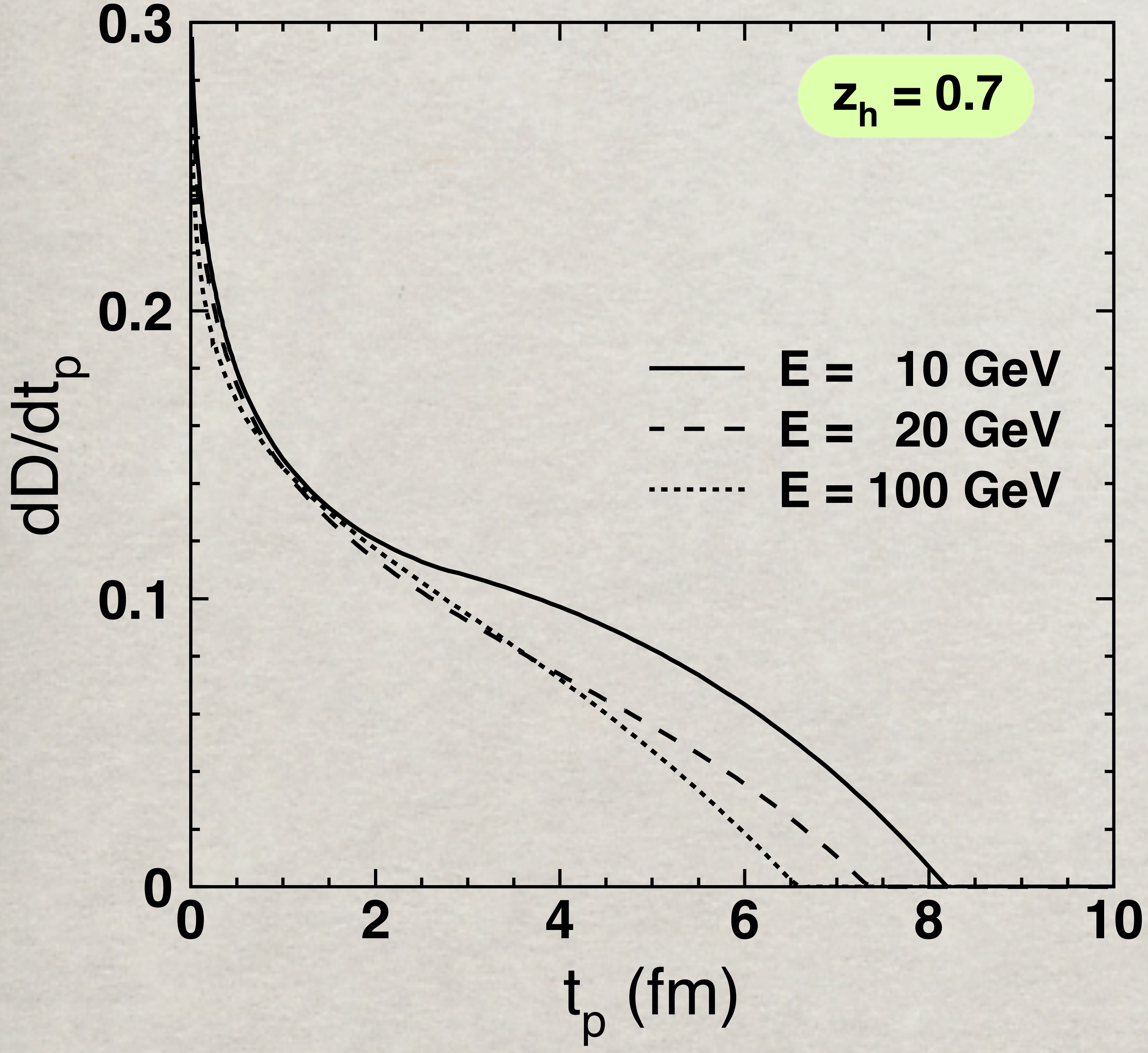


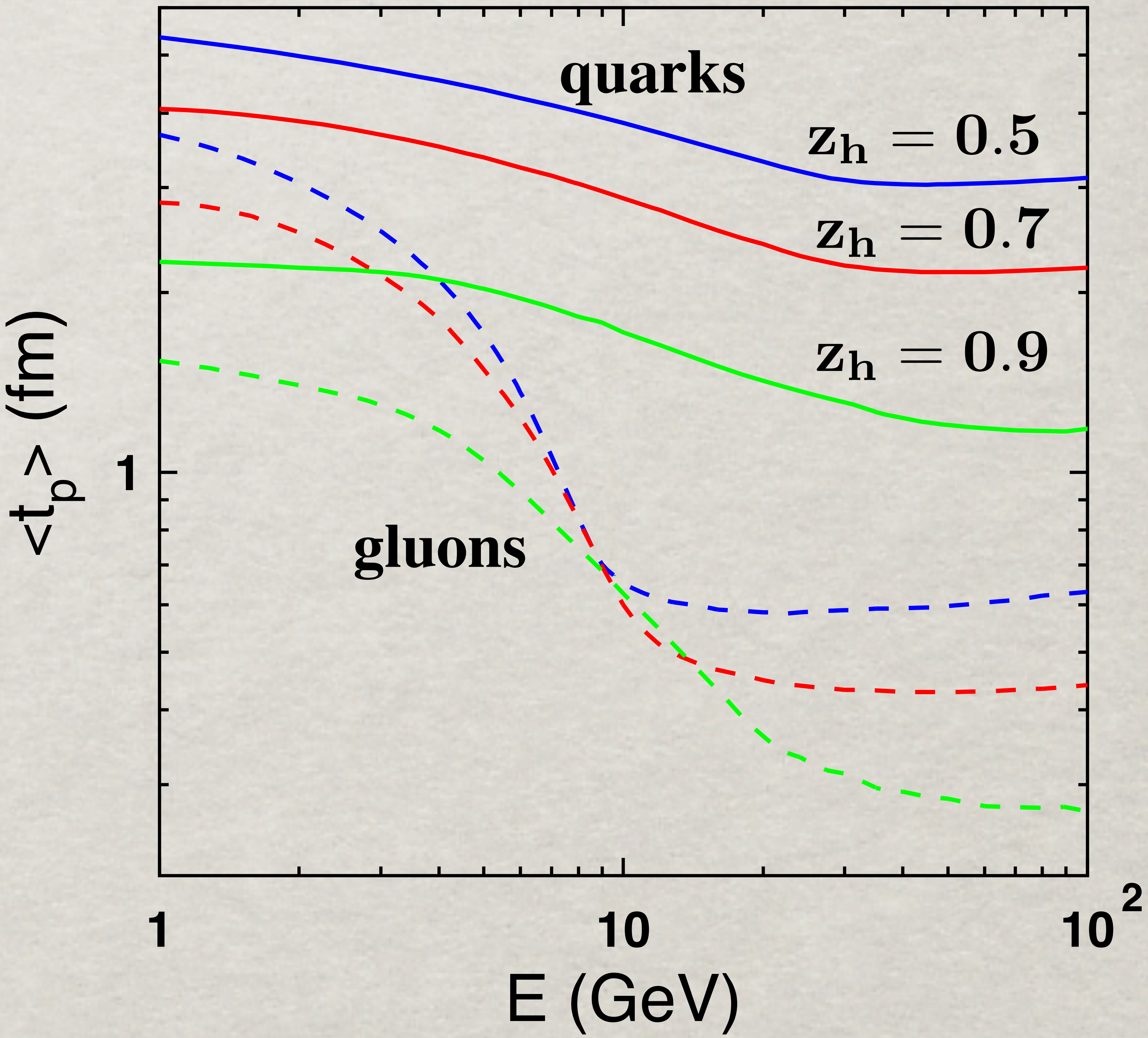
Production time/length

$\mathbf{t_p}$-dependent fragmentation function

$$\frac{\partial D_{\pi/q}(z_h, E)}{\partial t_p}$$

$$\langle t_p(z_h, E)\rangle = \frac{1}{D_{\pi/q}} \int dt_p\, t_p \frac{\partial D_{\pi/q}(z_h, E^2)}{\partial t_p}$$





Production time/length

Why the Lorentz factor does not make $\mathbf{l_p}$ longer at large $\mathbf{p_T}$?

Jet features depend on two parameters, the hard scale $\mathbf{Q^2}$ and jet energy E.

For the leading hadron energy conservation constraint: $\mathbf{l_p \lesssim \frac{E}{dE/dl}(1 - z_h)}$

Energy and scale dependences of $\mathbf{l_p}$ in SIDIS:

(i) Energy dependence at fixed $\mathbf{Q^2}$

$\mathbf{\langle dE/dl \rangle}$ is fixed, so $\mathbf{l_p \propto E}$

(ii) Scale dependence at fixed energy

$\mathbf{\langle dE/dl \rangle}$ rises with $\mathbf{Q^2}$, so $\mathbf{l_p(Q^2)}$ is falling

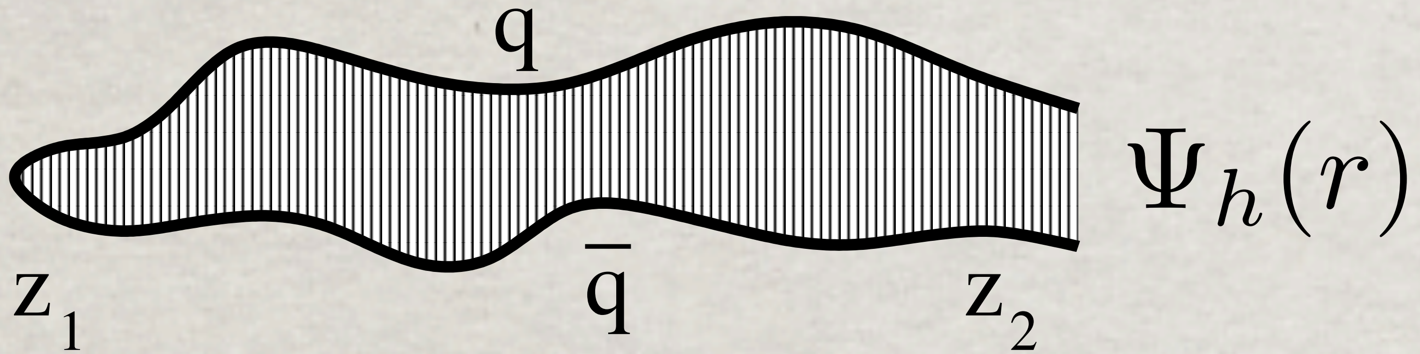
★ **Specifics of high-pT jets:** $\mathbf{E = p_T}$; $\mathbf{Q^2 = p_T^2}$

Quenching of high-p_T hadrons

Exact solution: path integrals

BK, B.Zakharov, Phys.Rev. D44(1991)3466

One has to sum up all quark trajectories.



$$G_{\bar{q}q}(z_1,0;z_2,r)$$

$$\left[i\frac{d}{dl_2}-\frac{m_q^2-\Delta_{r_2}}{p_T/2}-V_{\bar{q}q}(l_2,r_2)\right]G_{\bar{q}q}(l_1,r_1;l_2,r_2)=0$$

$$\mathrm{Im}V_{\bar{q}q}(l,r)=-\frac{1}{4}\,\hat{q}(l)\,r^2$$

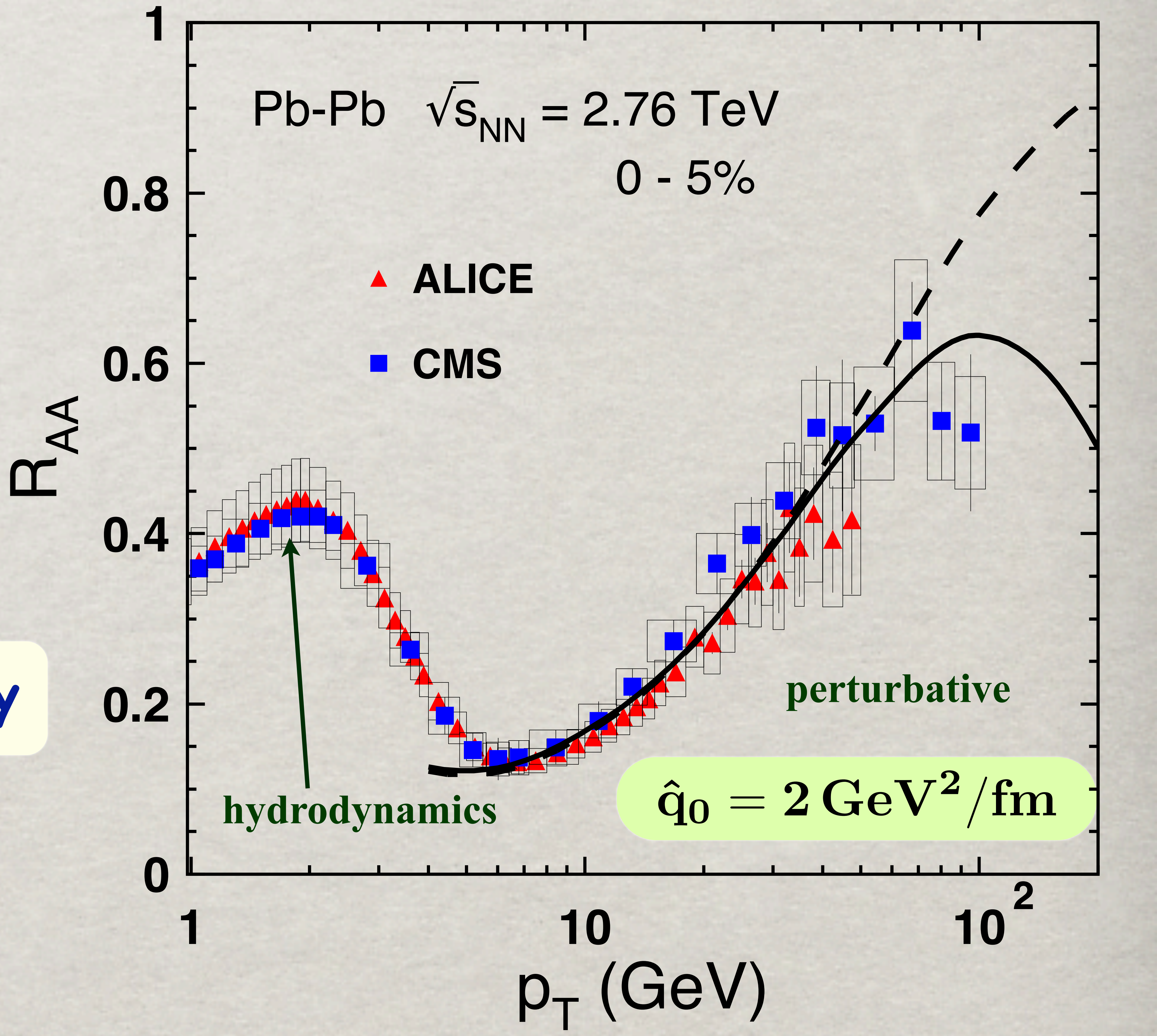
R_{AA} **rises with** p_T **due to color transparency**

The model for time and position dependent $\hat{q}$

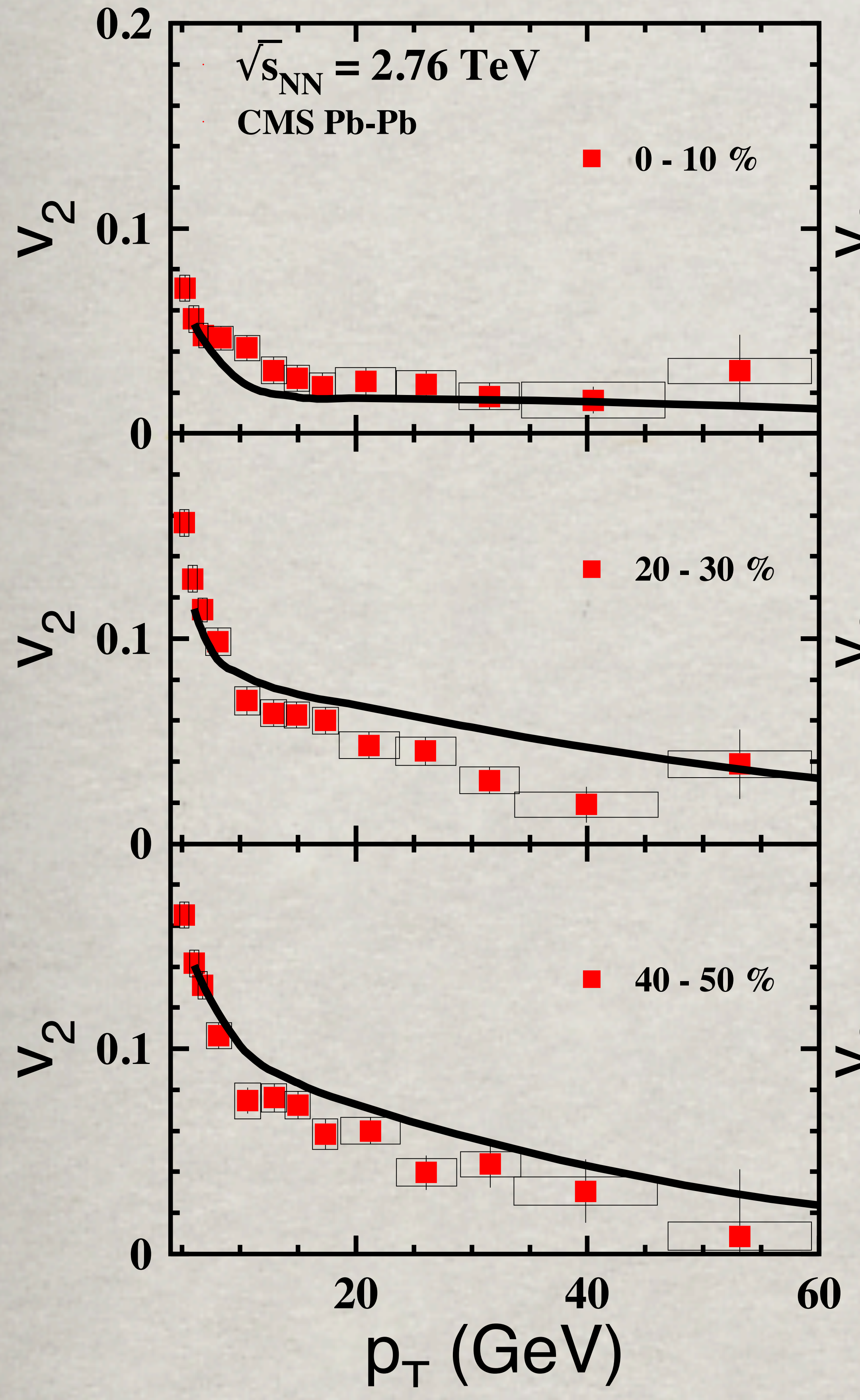
$$\hat{q}(l,\vec{b},\vec{\tau})=\frac{\hat{q}_0\,l_0}{l}\,\frac{n_{part}(\vec{b},\vec{\tau})}{n_{part}(0,0)}$$

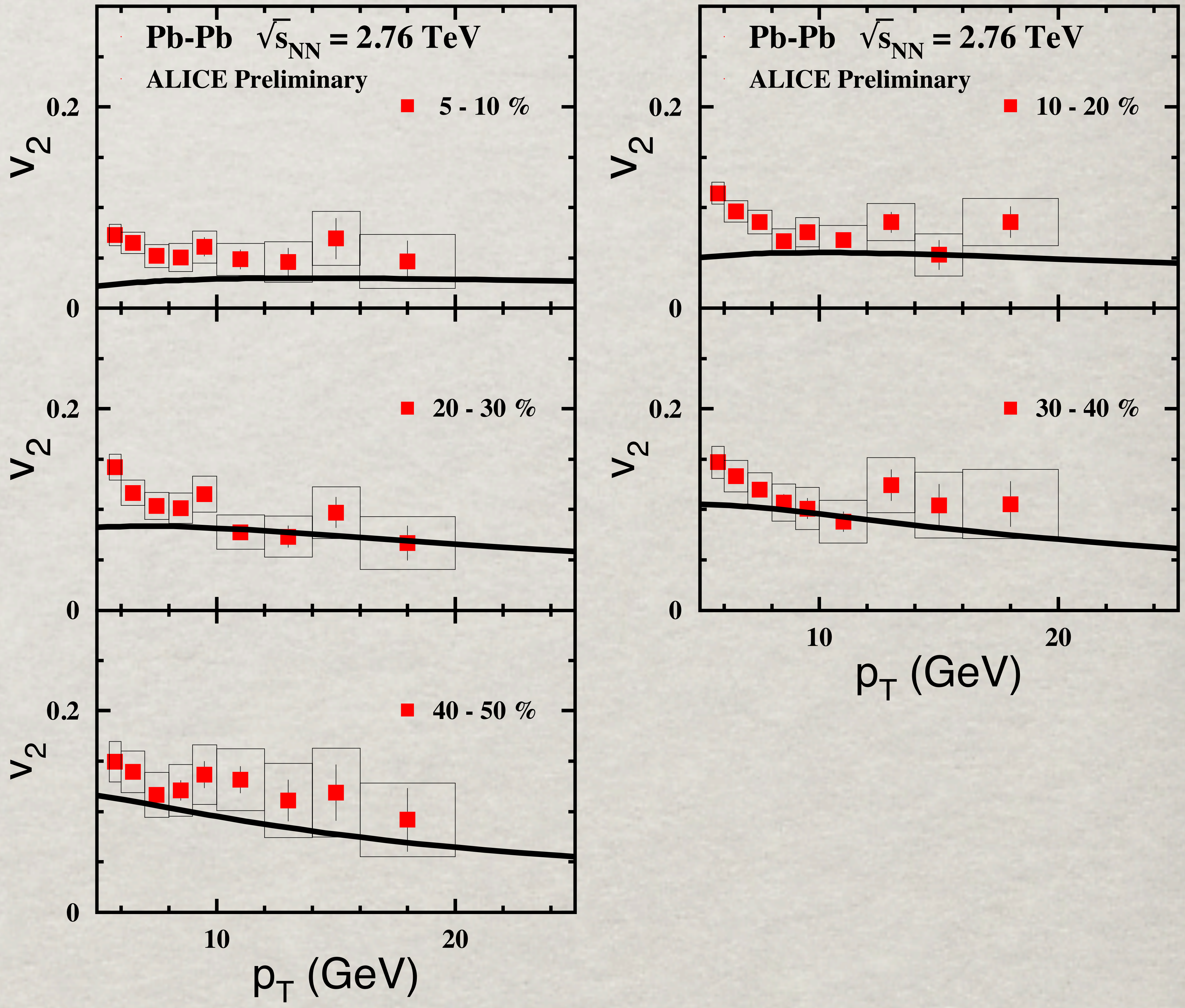
BK,,I.Potashnikova, I.Schmidt
Phys.Rev.C83(2011)021901

BK, J.Nemchik, I.Potashnikova, I.Schmidt
Phys.Rev. C86(2012)054904



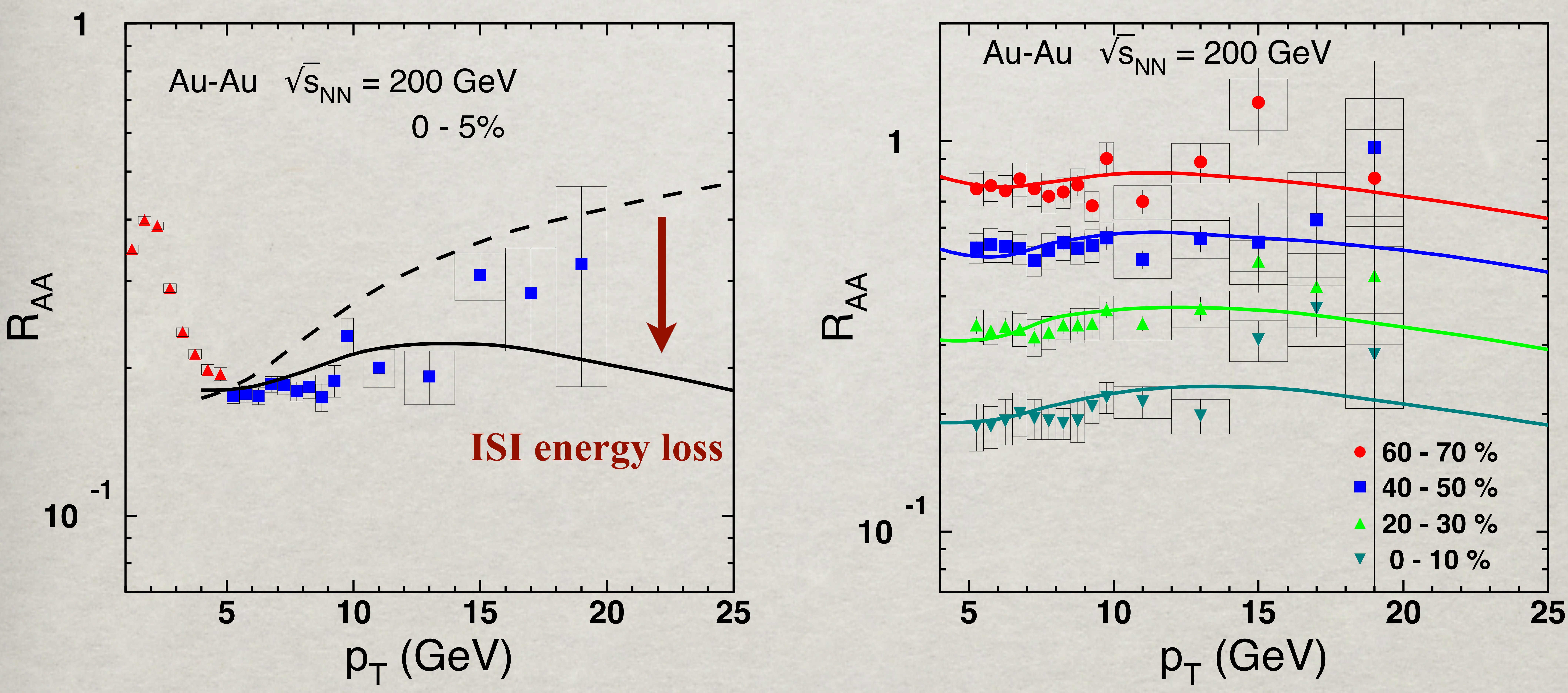
Azimuthal asymmetry





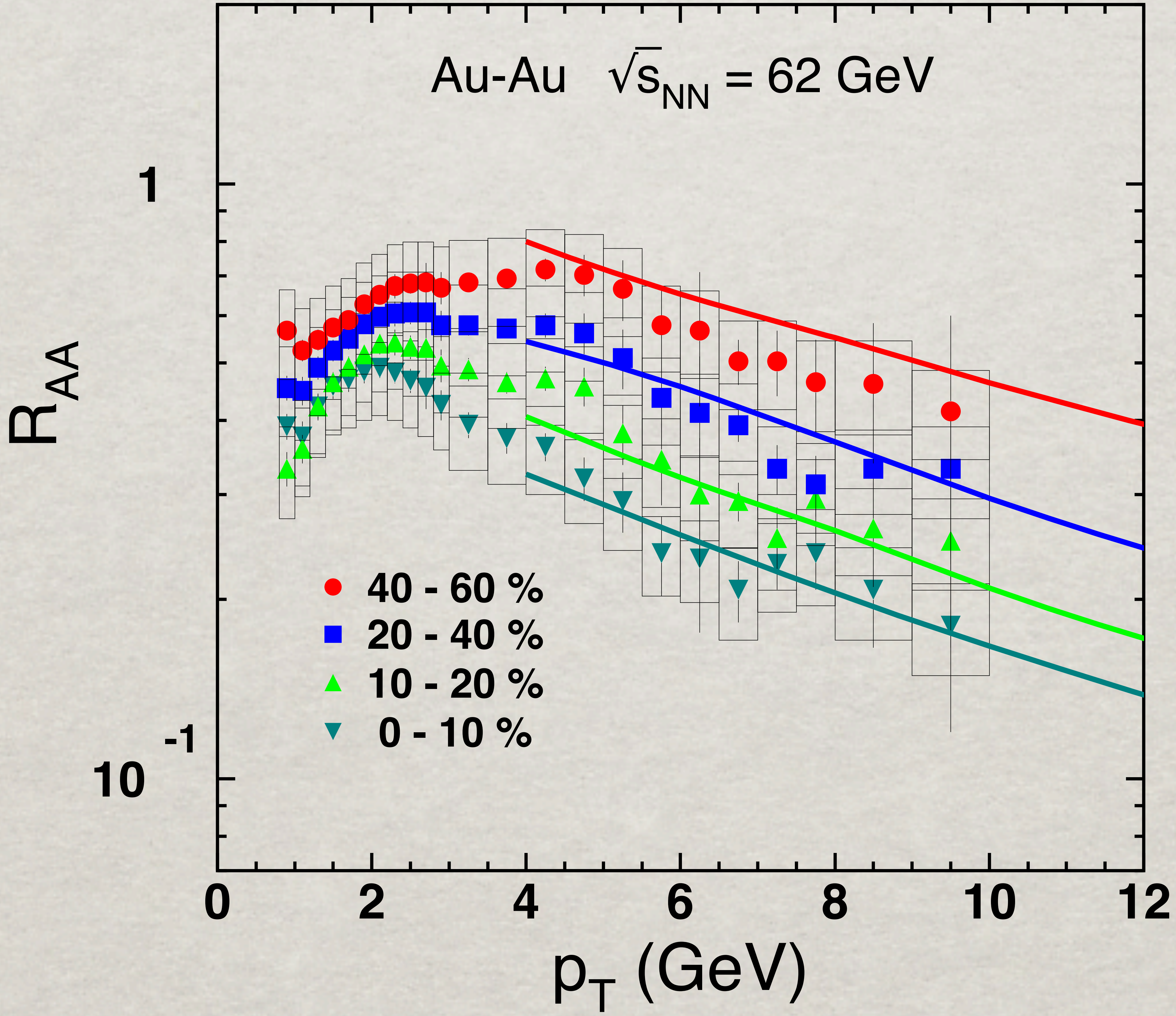
Down to the RHIC energies

$$\hat{q}_0 = 1.6\,\mathrm{GeV}^2/\mathrm{fm}$$



The lower the energy is, the higher is x_T

$$\hat{q}_0 = 1.2\,\mathrm{GeV}^2/\mathrm{fm}$$



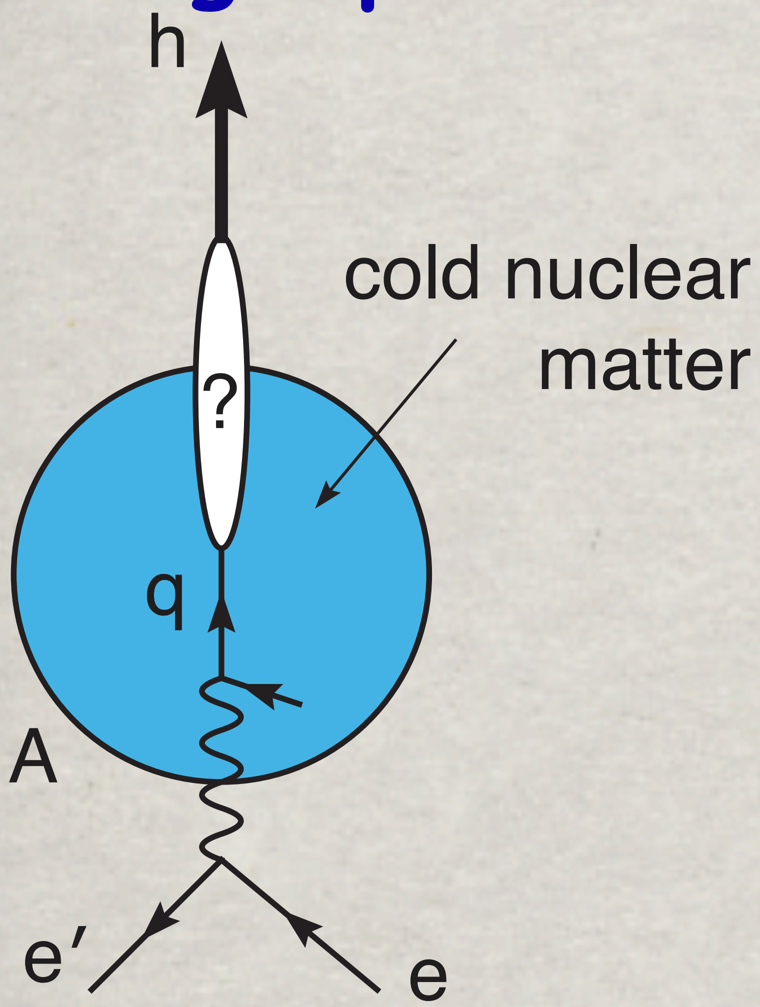
Energy-loss scenario

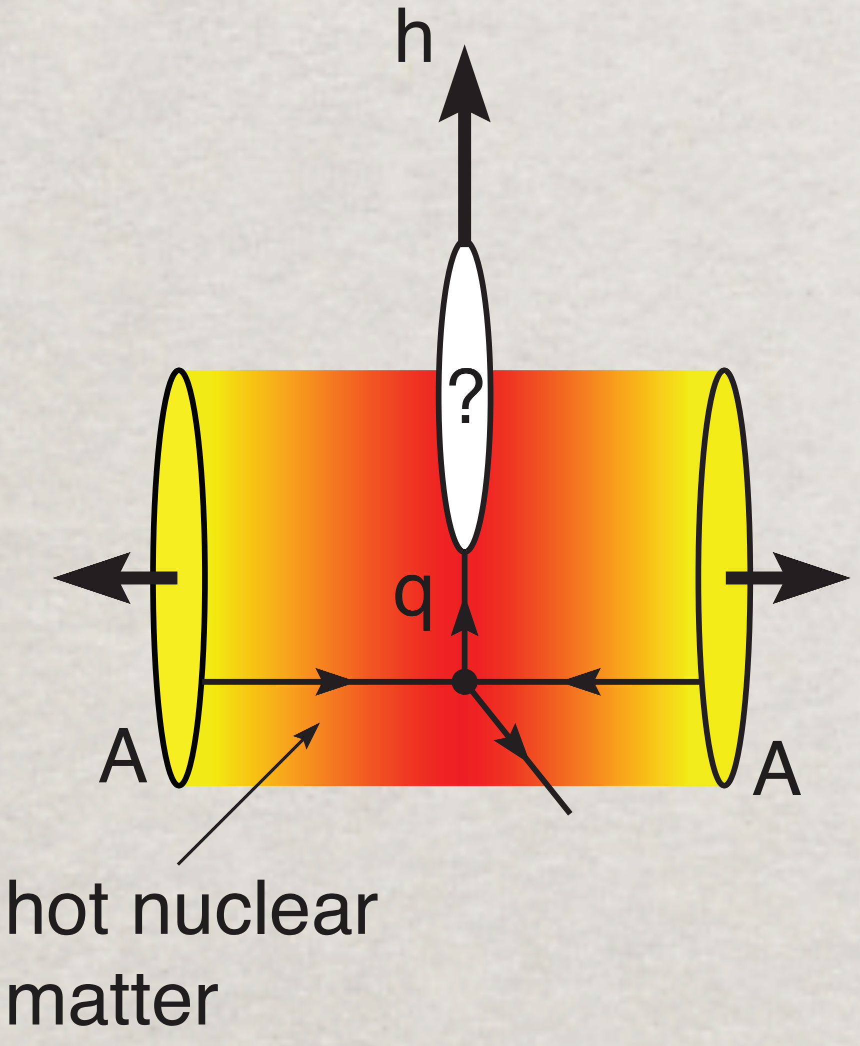
Problems

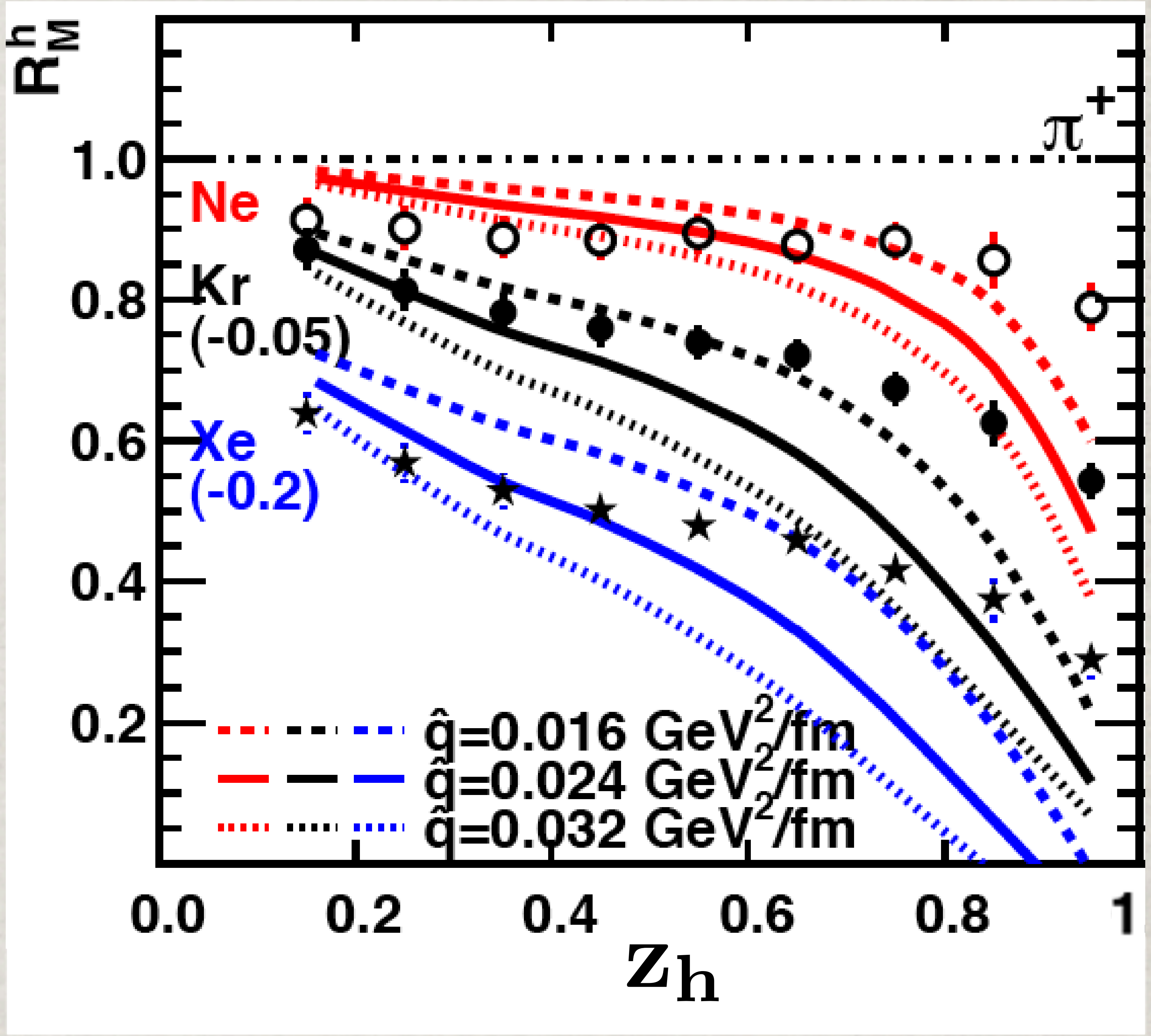
- E-loss scenario fails to explain suppression of leading hadrons in SIDIS on nuclei
- The transport coefficient fitted to data, $\hat{q}_0 = 13\,\mathrm{GeV}^2/\mathrm{fm}$ is too big compared with expected (BDMPS), $\hat{q}_0 \approx 1\,\mathrm{GeV}^2/\mathrm{fm}$
- The alternative probe, J/Psi suppression, leads to a different value of $\hat{q}_0 \approx 1\,\mathrm{GeV}^2/\mathrm{fm}$
- Differently from the expectations based on the dead-cone effect, b-quarks and light flavors are suppressed similarly
- No broadening was observed in back-to-back photon-jet azimuthal correlation

SIDIS: testing hadronization models

Semi-inclusive deep-inelastic processes (SIDIS) can be used as a test for the suppression mechanism of high-pT hadrons.







W.T. Deng & X.N. Wang: Phys.Rev. C81

Advantages:

- The medium density and geometry are well known;
- $\hat{q}$ is known;
- The jet energy and scale can be varied independently

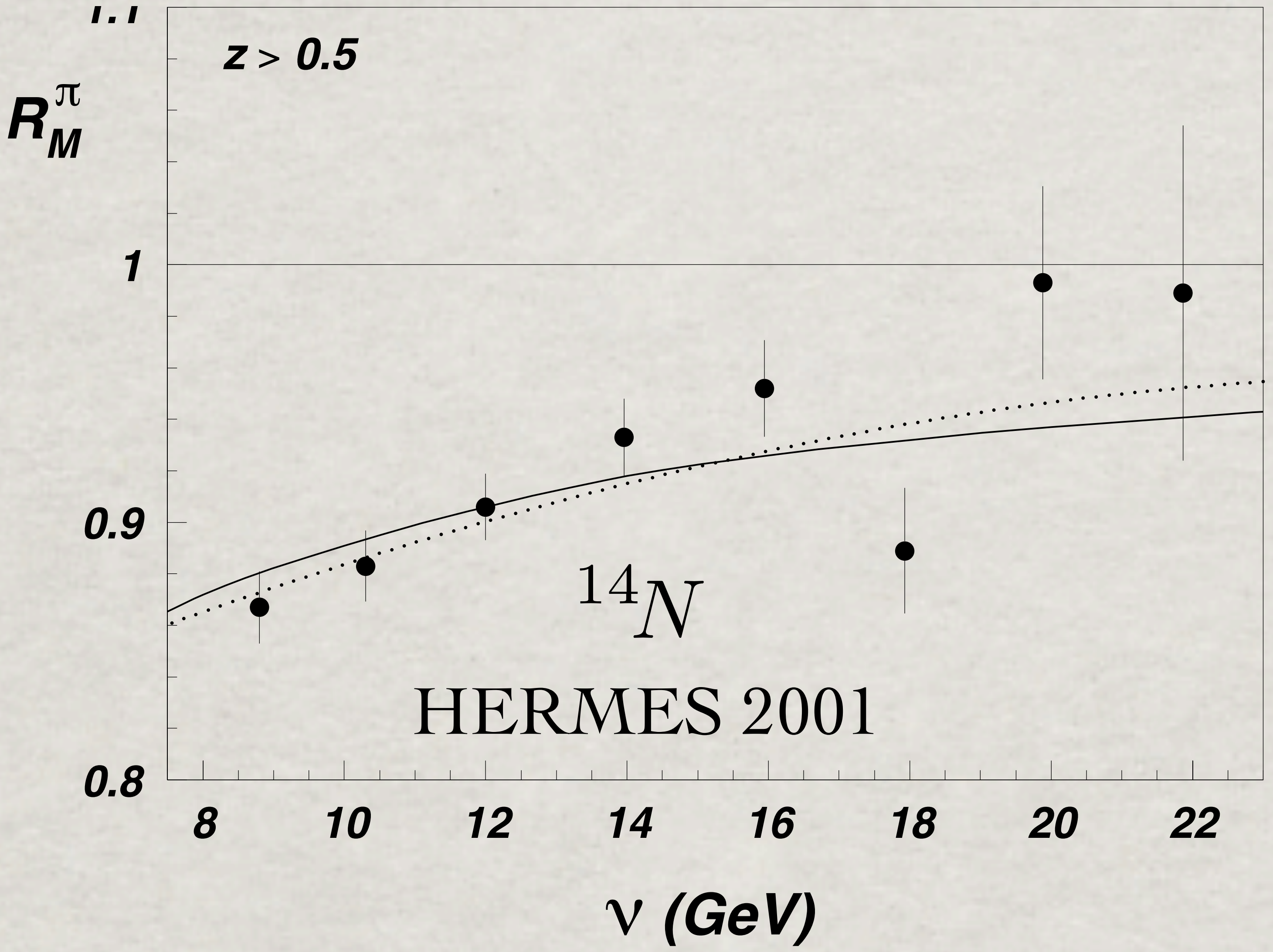
Fails at large z_h, most important for high p_T hadrons.

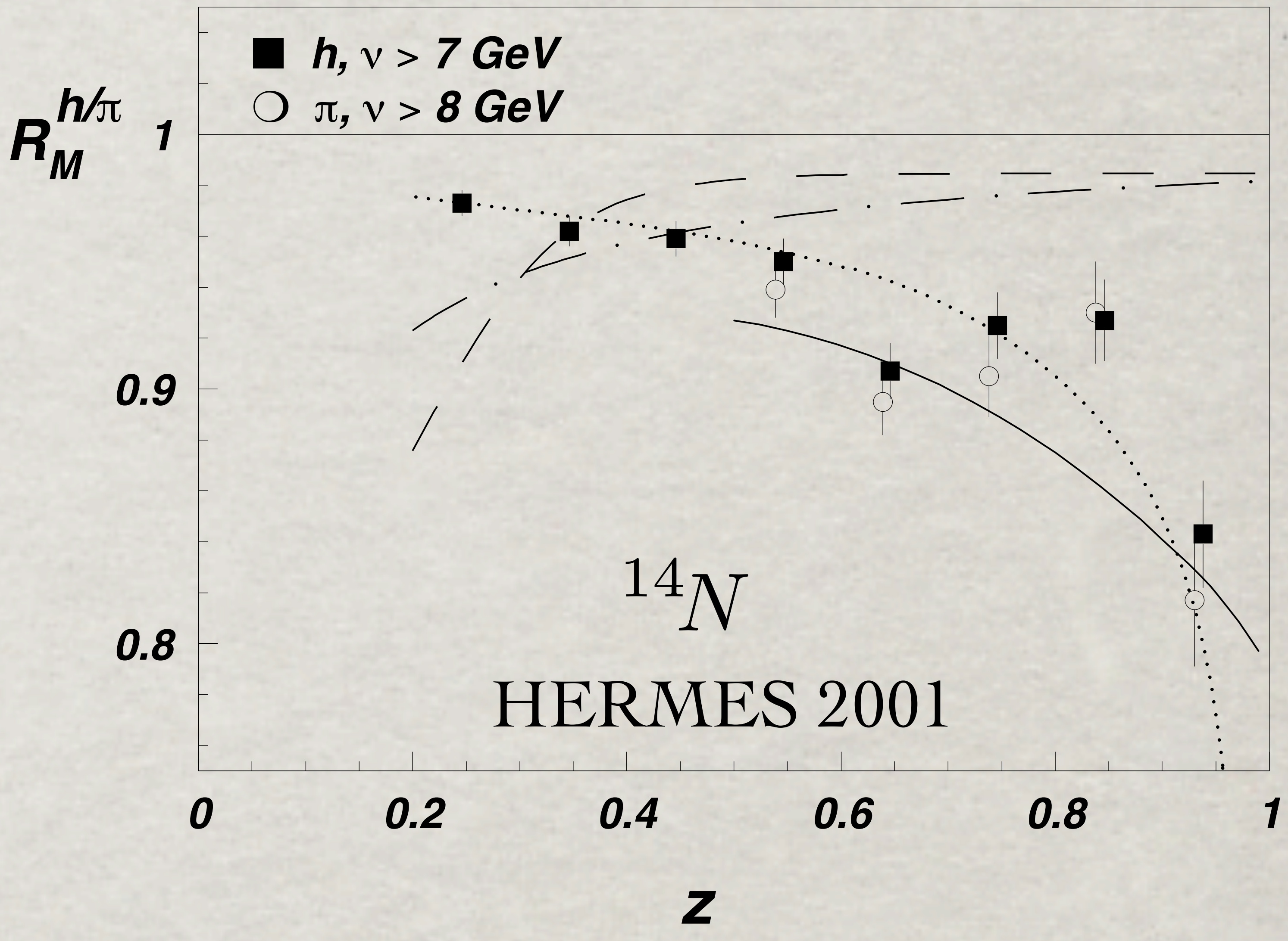
Testing the models in SIDIS

Finite l_p:
E-loss + absorption

Predictions

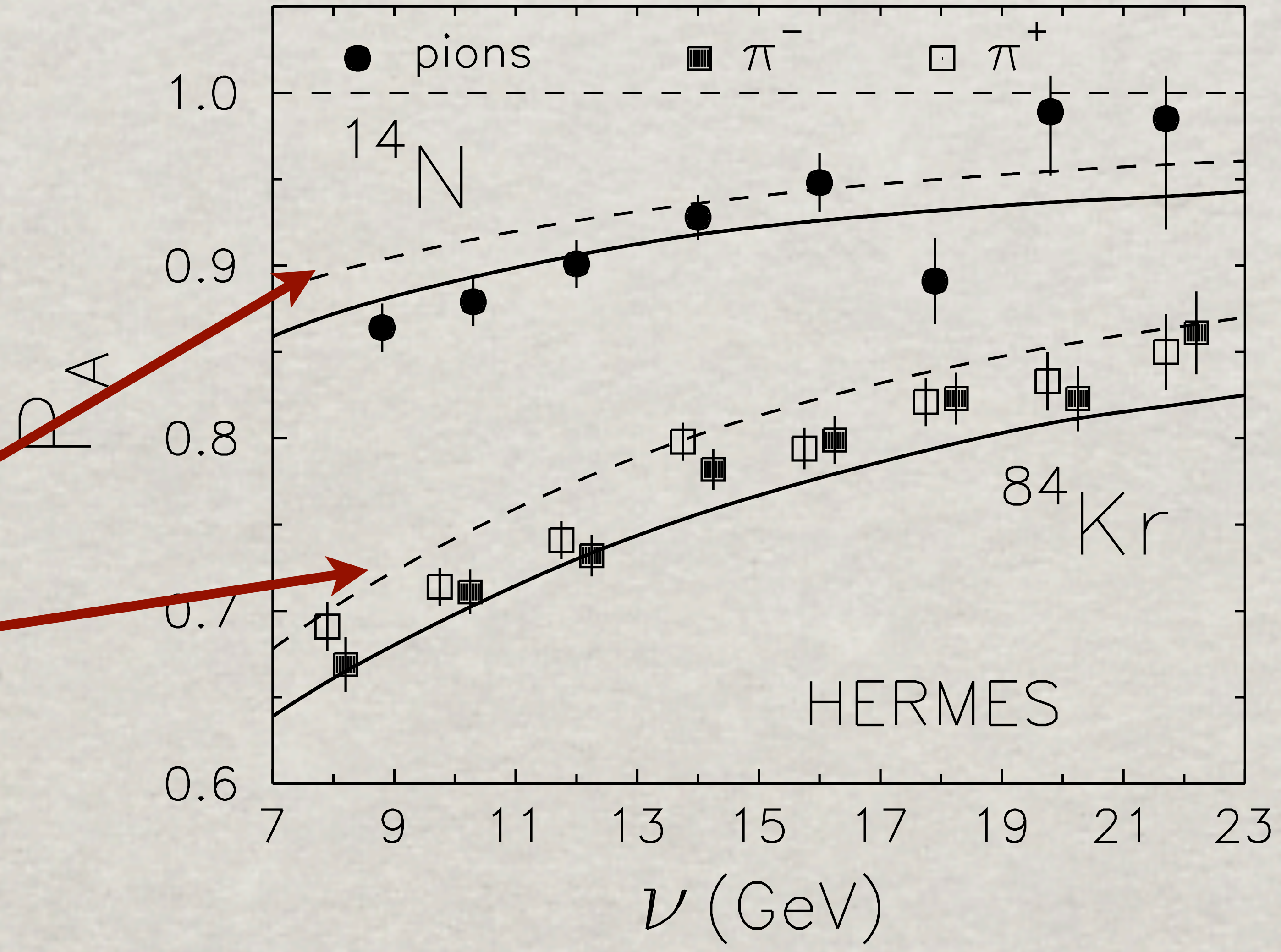
B.K., J. Nemchik, E. Predazzi
1996

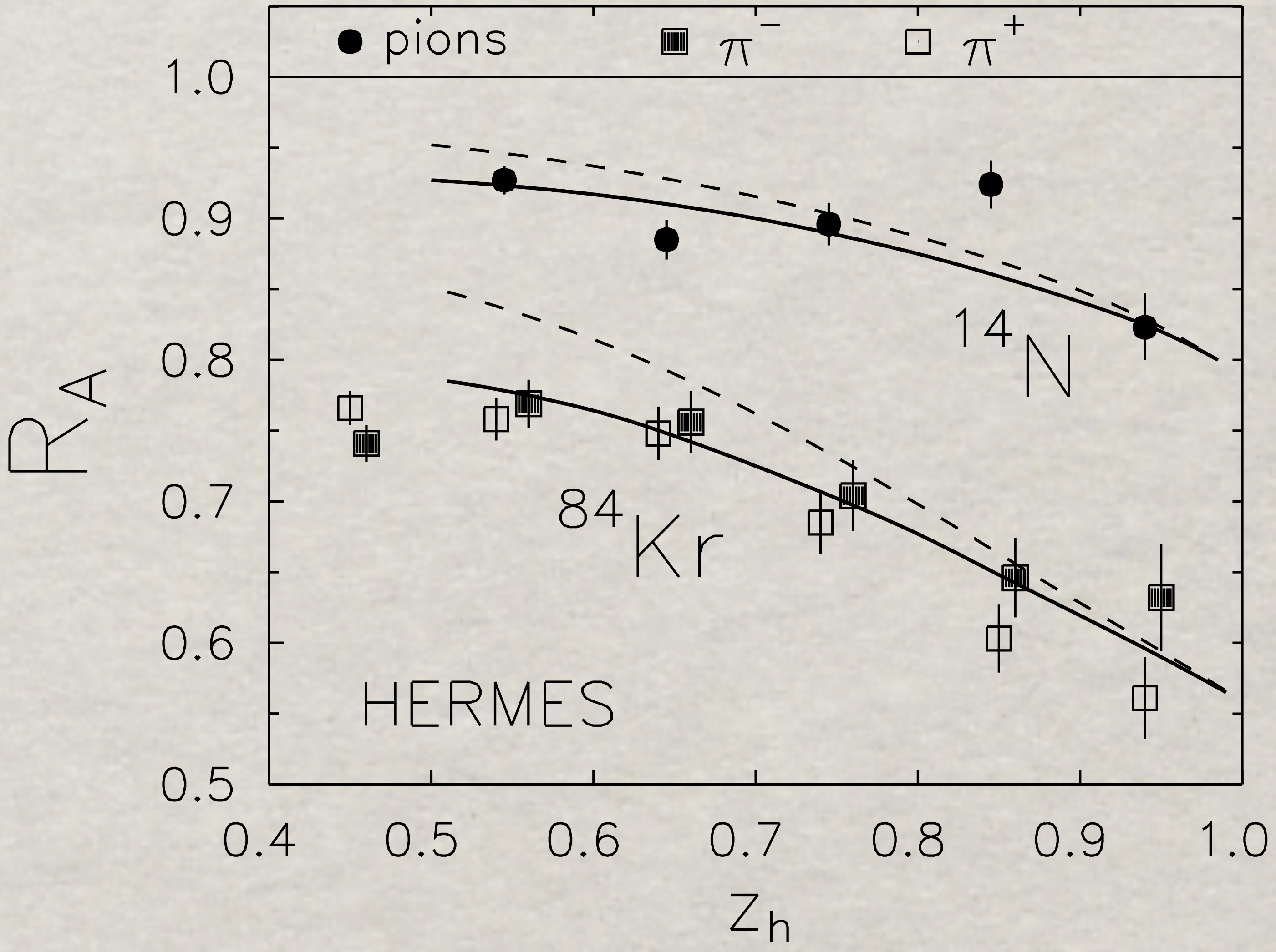




B.K., J. Nemchik, E. Predazzi
&A. Hayashigaki
Nucl. Phys. A 740, 211 (2004)

Only absorption





Summary

- The dipole description is found to be successful and having a strong predictive power. The magnitude of the Cronin effect was well predicted prior the measurements at RHIC and LHC.

- ALICE data for the Cronin effect provided the first direct evidence for weakness of gluon shadowing, proposed theoretically and by some analyses of DIS data. Most of the popular models, EKS98, EPS08, EPS09, including CGC models, turned out to grossly exaggerate the magnitude of gluon shadowing.

- Energy deficit at large x_L and x_T due to initial dissipation of energy (proportional to the collision energy) in pA and AA collisions cause a suppression, observed in data.

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Summary

- A high-p_T jet with virtuality equal to its energy dissipates energy (in vacuum and in a medium) so fast that can produce a leading hadron (dipole) with large z_h only on a very short time scale. One should discriminate between single hadrons and jets, which take long time to be produced

- Attenuation of a high-p_T dipole is the main source of the observed suppression. R_{AA} rises with p_T due to color transparency. Dipoles experience no broadening in a medium.

- The model well describes available data on hadron suppression and azimuthal asymmetry at large p_T>7GeV with a single parameter $\hat{q}_0$=1-2GeV^2/fm, consistent with expectations and with J/Psi data.

- The energy loss model failed to pass the test with data on nuclear suppression of SIDIS at large z_h.