High-p_T hadrons from pA and AA collisions: Impact of energy conservation

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Valparaiso

Grenoble, Sept. 27, 2013

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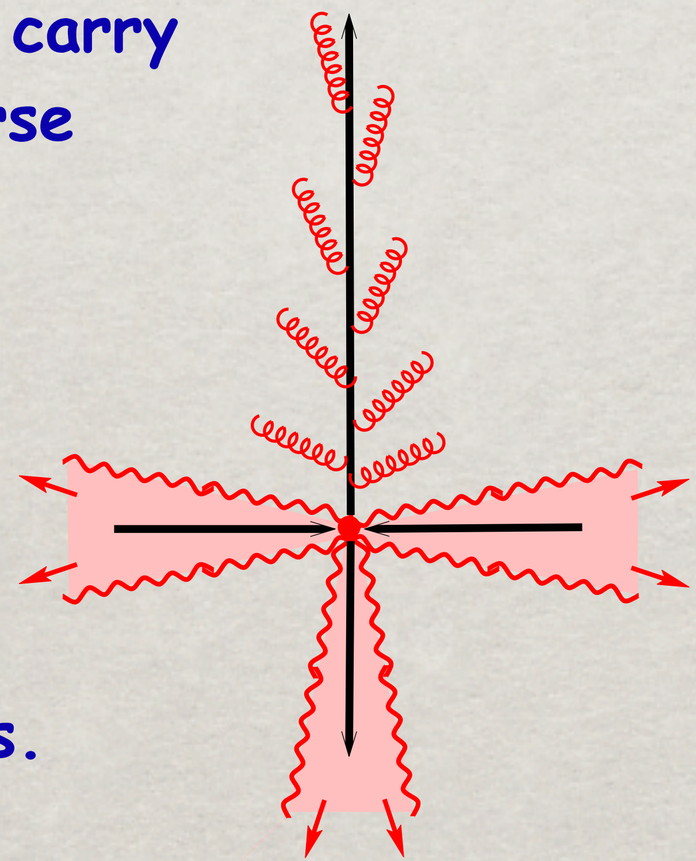
Hard parton collision

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

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

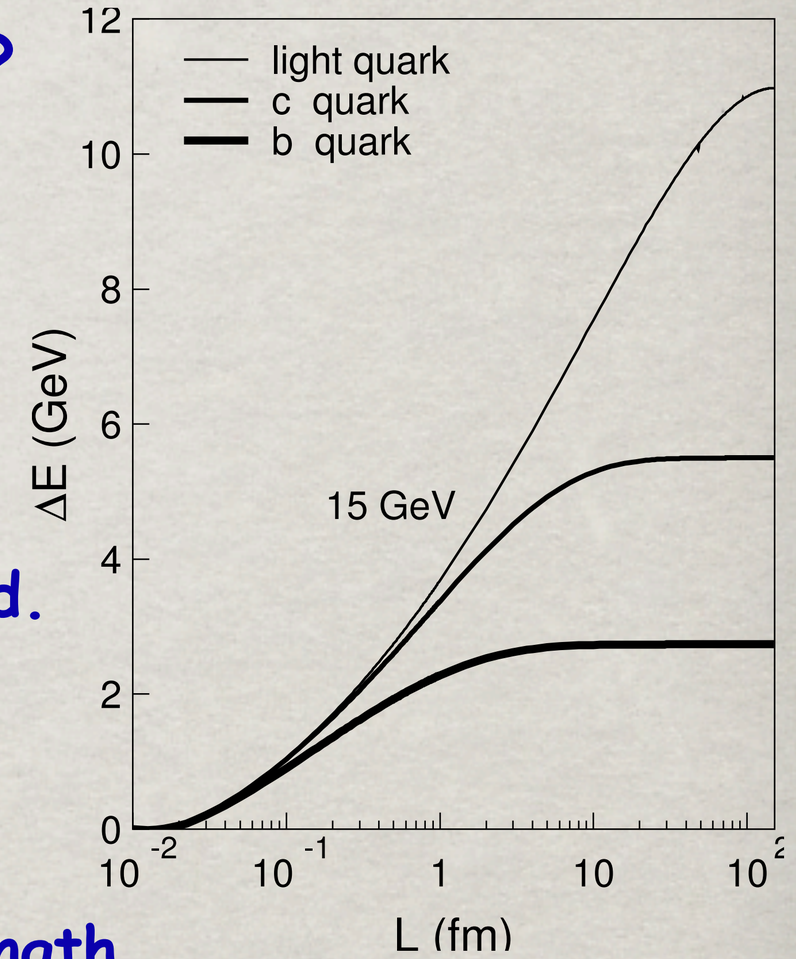
First are radiated gluons with small longitudinal and large transverse momenta.

Vacuum energy loss

How much energy is radiated over the path length L?

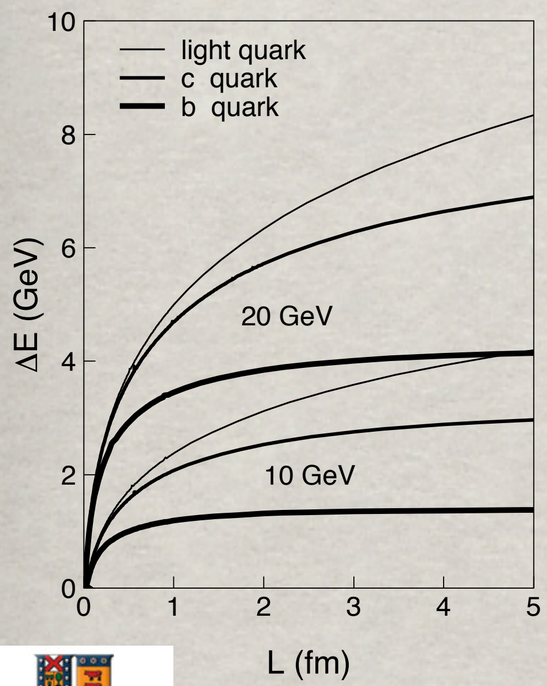
$$\Delta E(L) = E \int_{\Lambda^2}^{Q^2} dk^2 \int_0^1 dx\, x \frac{dn_g}{dx\, dk^2} \Theta(L - l_c)$$

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



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

Dead-cone effect: gluons with $k^2 < x^2 m_q^2$ are suppressed.
Heavy quarks radiate less energy than the light ones.



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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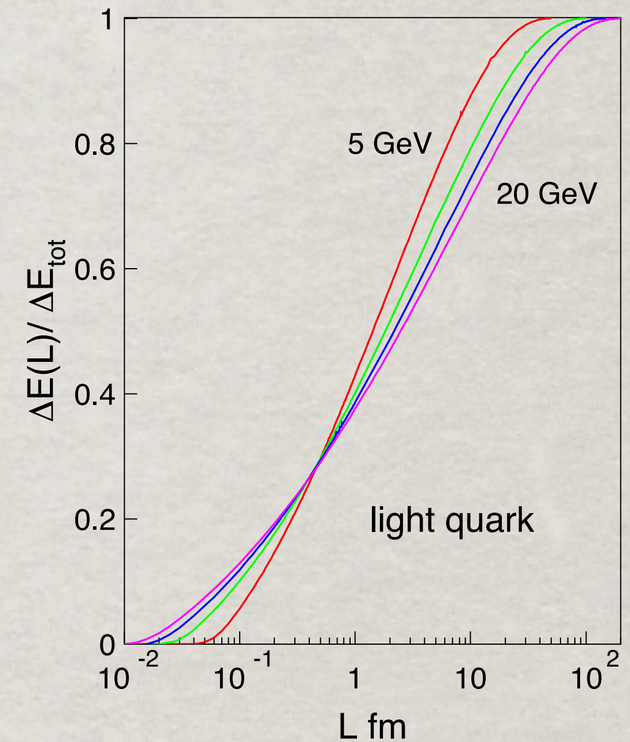
Vacuum energy loss

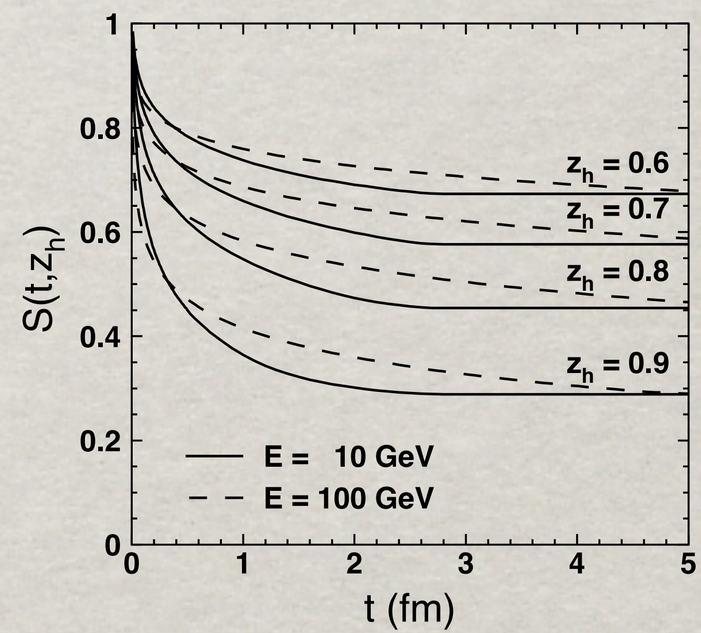
How fast is energy dissipation?

A light quark loses 40% of the total radiated energy during the first 1fm.

Energy conservation imposes severe restrictions on the production length l_p for hadrons with large fractional momentum z_h.

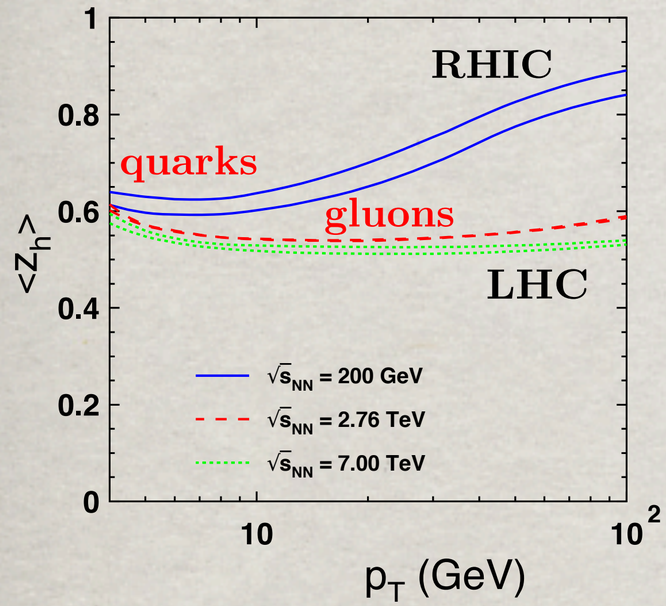


- Gluons with $x > 1 - z_h$ are forbidden, This leads to Sudakov suppression ⇒
- The hadron cannot be produced after the parton momentum falls below p_T, i.e. $\Delta E/E > 1 - z_h$

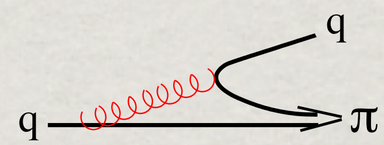


Hadronization in vacuum

The mean value $\langle z_h \rangle$



Perturbative hadronization at large z_h

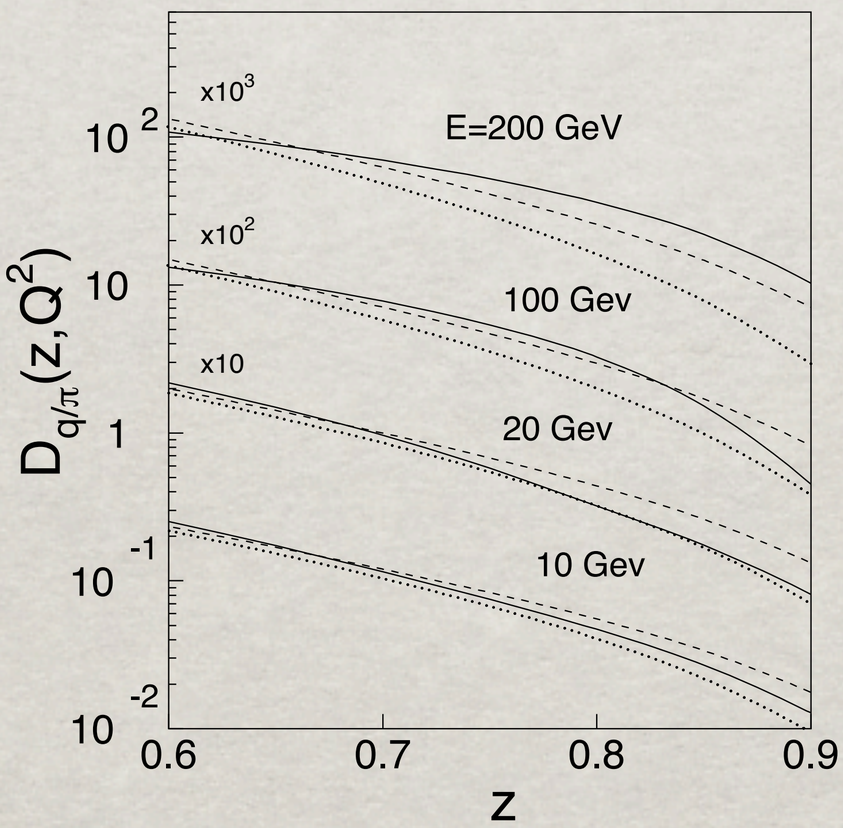


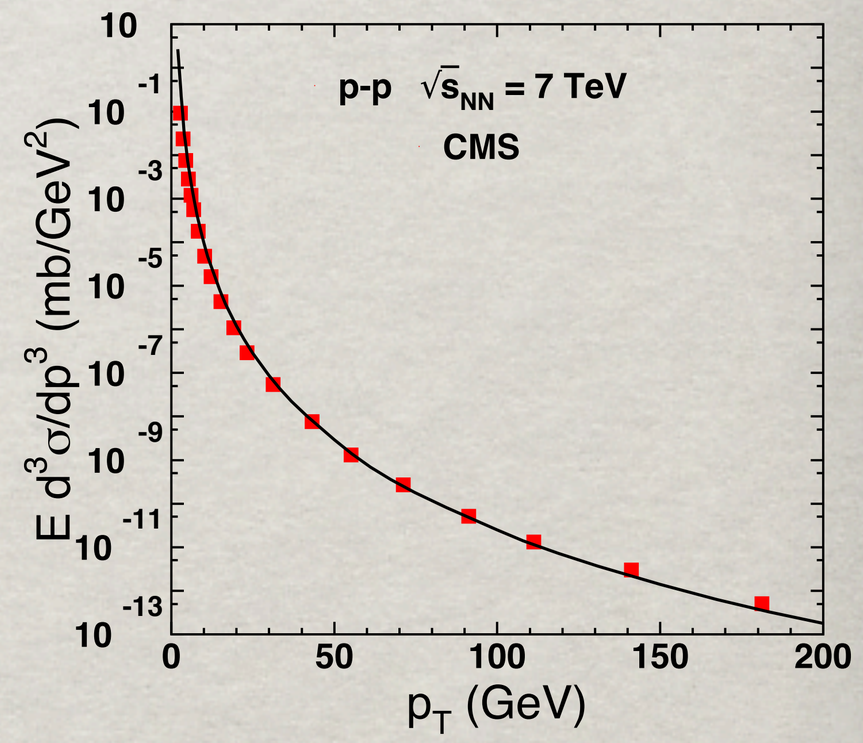
E. Berger, PLB 89(1980)241

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:





Production of heavy flavored mesons occur with larger z_h

$$\langle z_D \rangle = 0.76$$

$$\langle z_B \rangle = 0.89$$

$(\sqrt{s} = 7\,\mathrm{TeV})$

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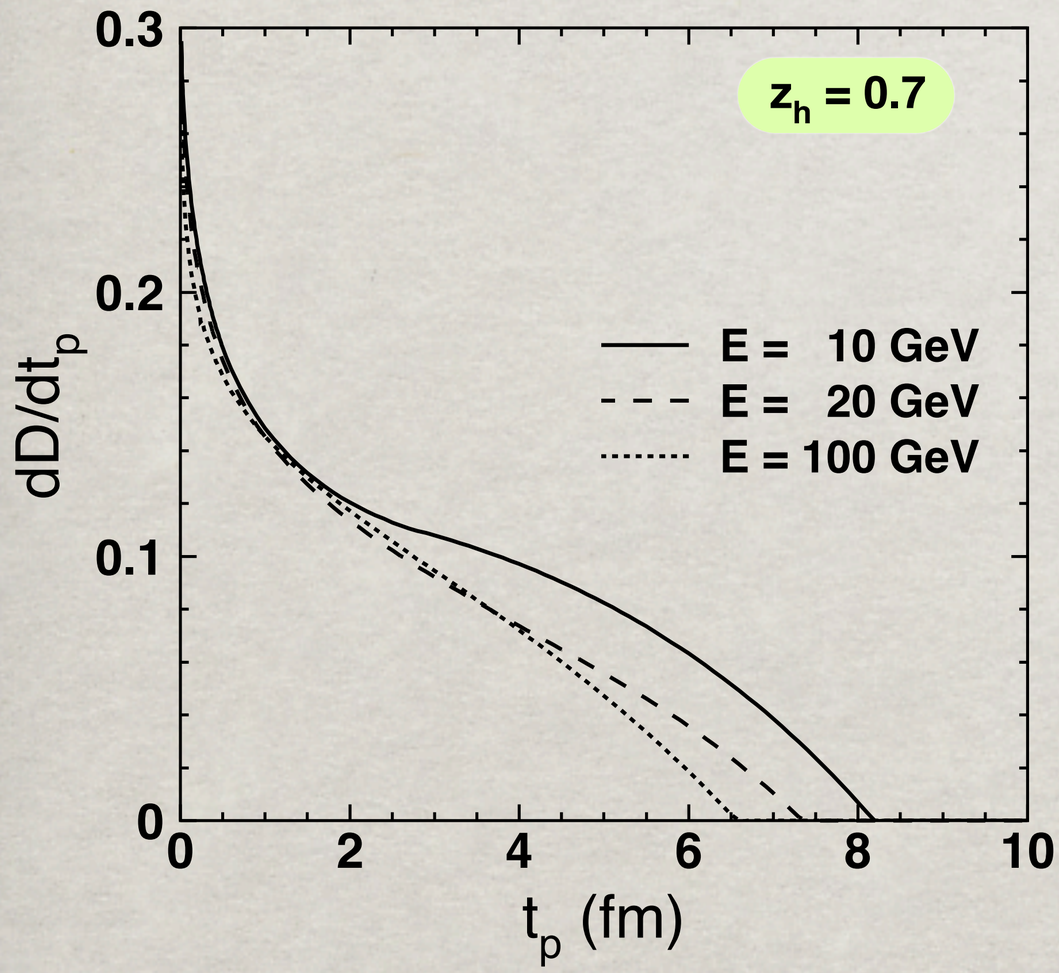
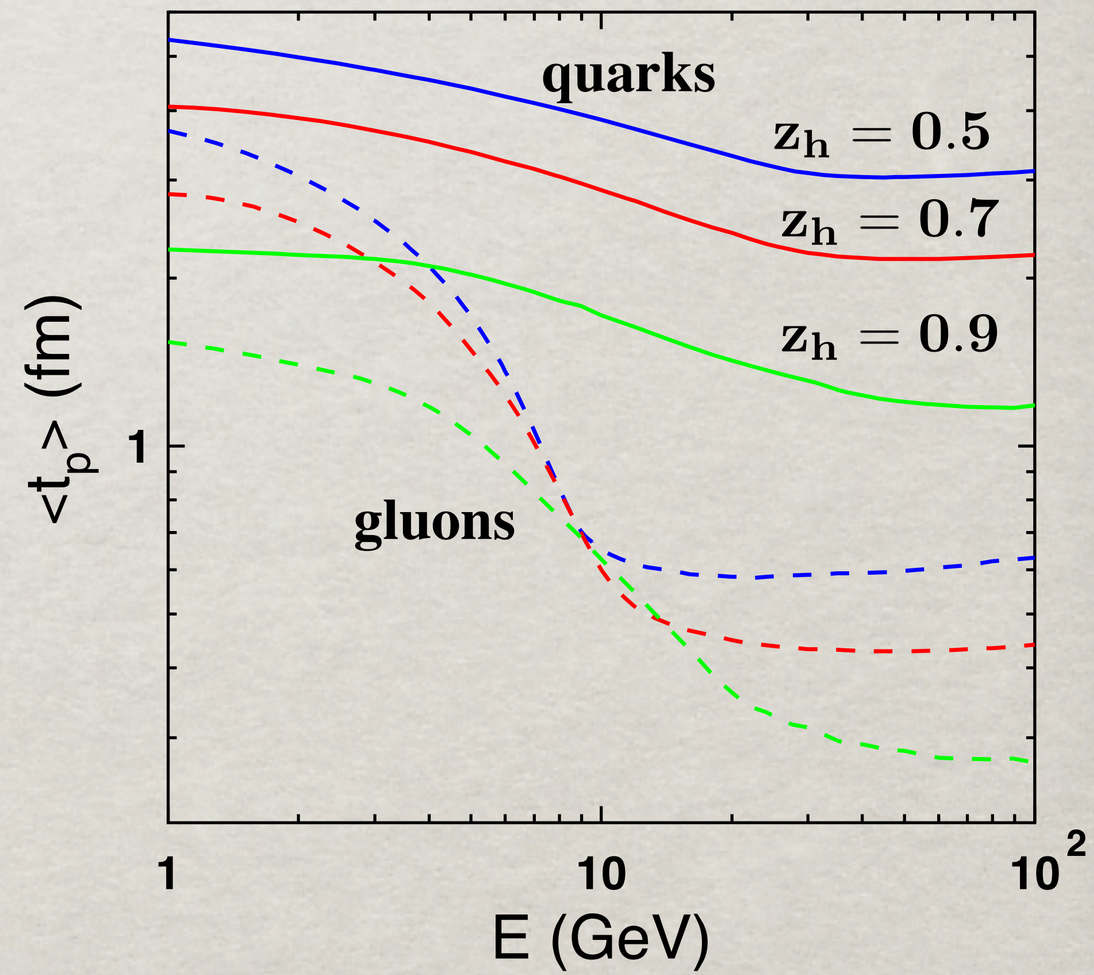
Production time/length

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 l_p longer at large p_T ?

Jet features depend on two parameters, the hard scale Q^2 and jet energy E.

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

Energy and scale dependences of l_p in **SIDIS:**

(i) Energy dependence at fixed Q^2

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

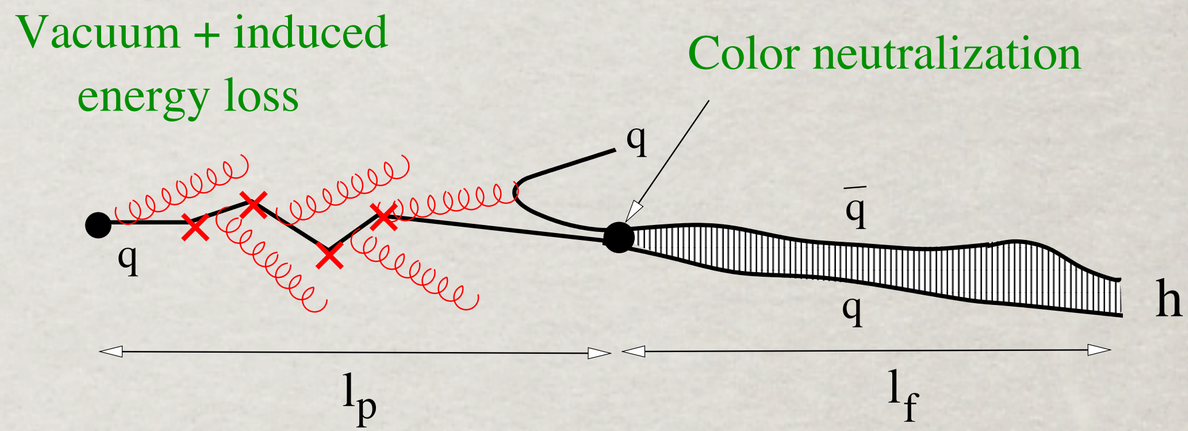
(ii) Scale dependence at fixed energy

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

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

In-medium attenuation of leading hadrons

As far as l_p is short, the main source of suppression is attenuation of the produce dipole in the medium.



The dipole is produced with a tiny initial transverse separation, $r_o^2 \sim \frac{8\, l_p}{p_T}$ and may survive even in a dense medium due to color transparency.

However the dipole is expanding enhancing attenuation. At higher pt expansion is Lorentz-delayed so transparency must rise with pt.

Quenching of high-p_T hadrons

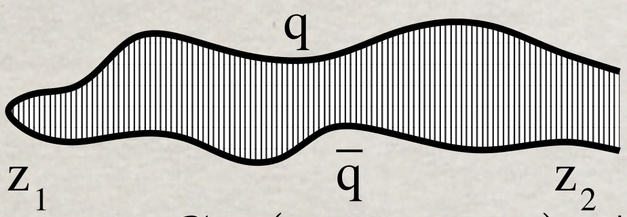
Exact solution: path integrals

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

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

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

One has to sum up all quark trajectories.



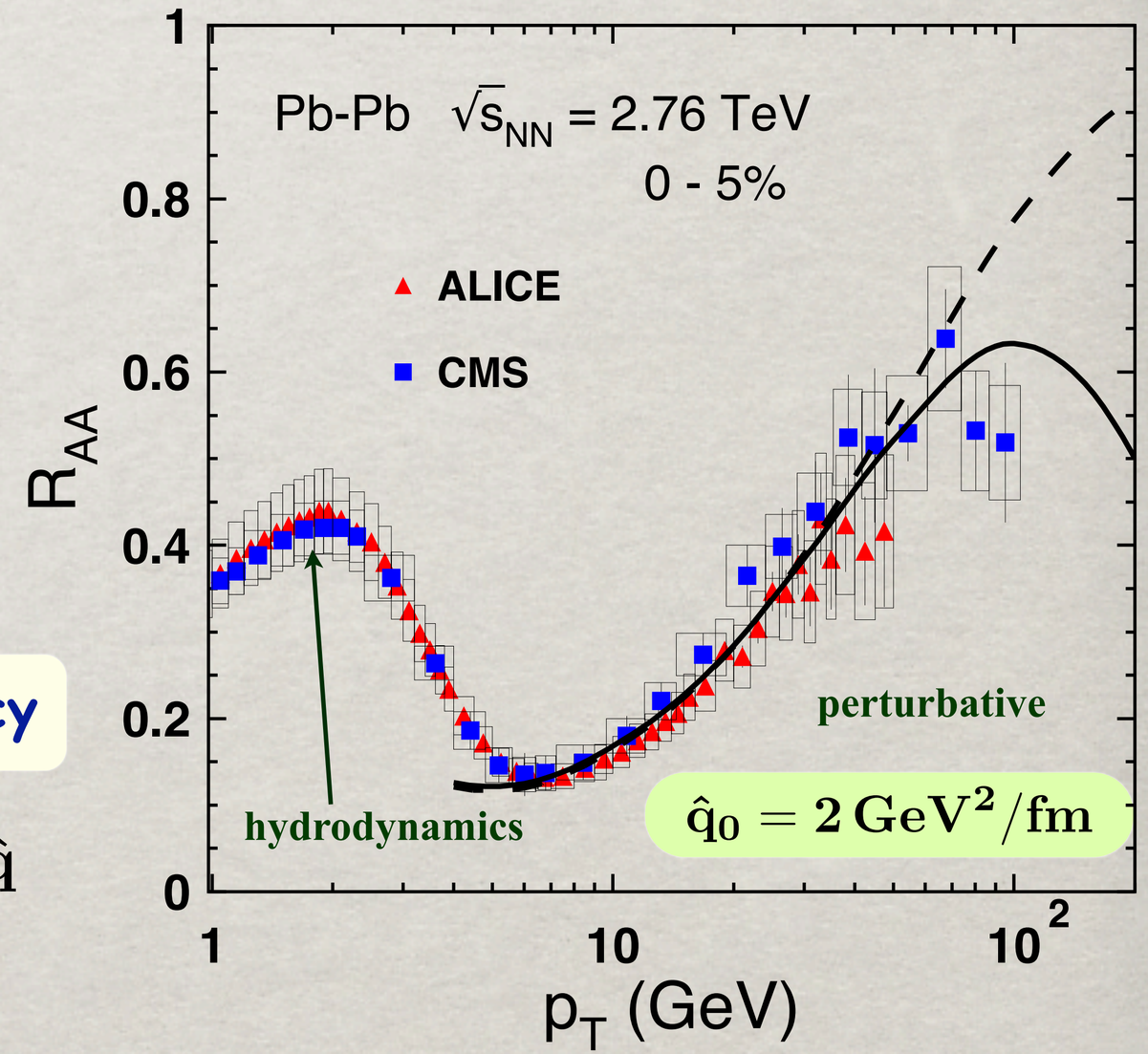
$\Psi_h(r)$

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

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

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

R_{AA} rises with p_T due to color transparency



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

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

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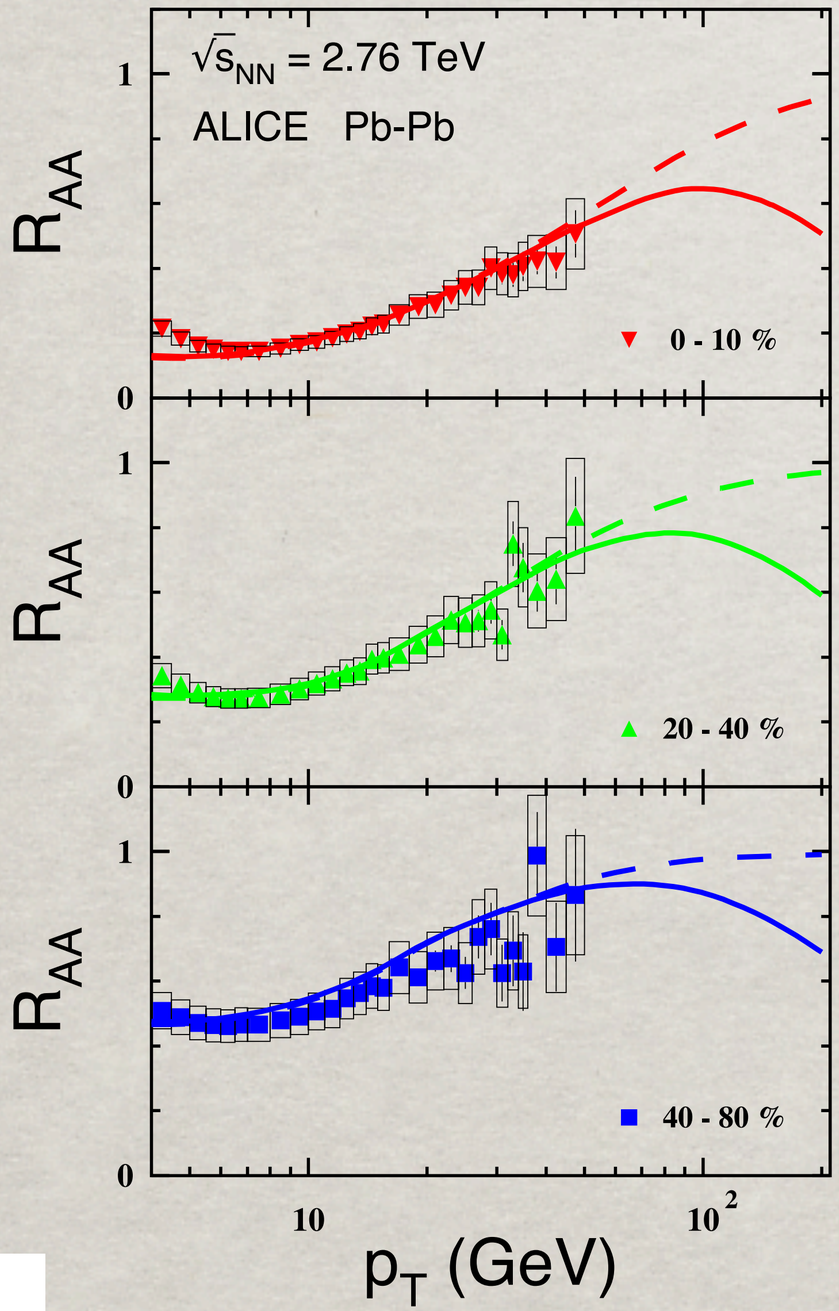
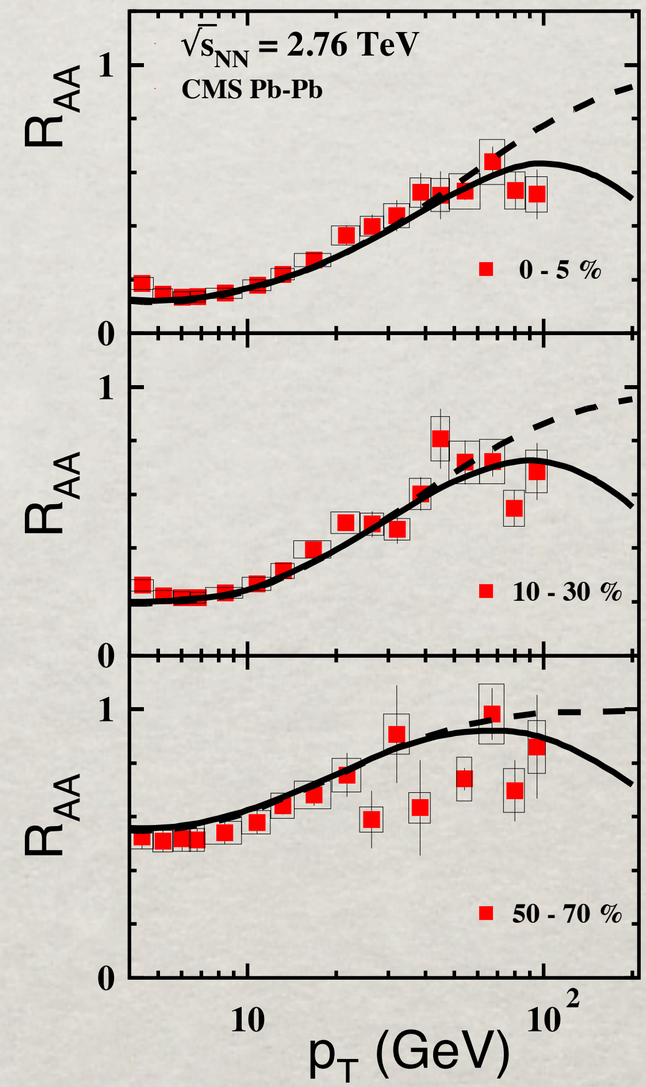
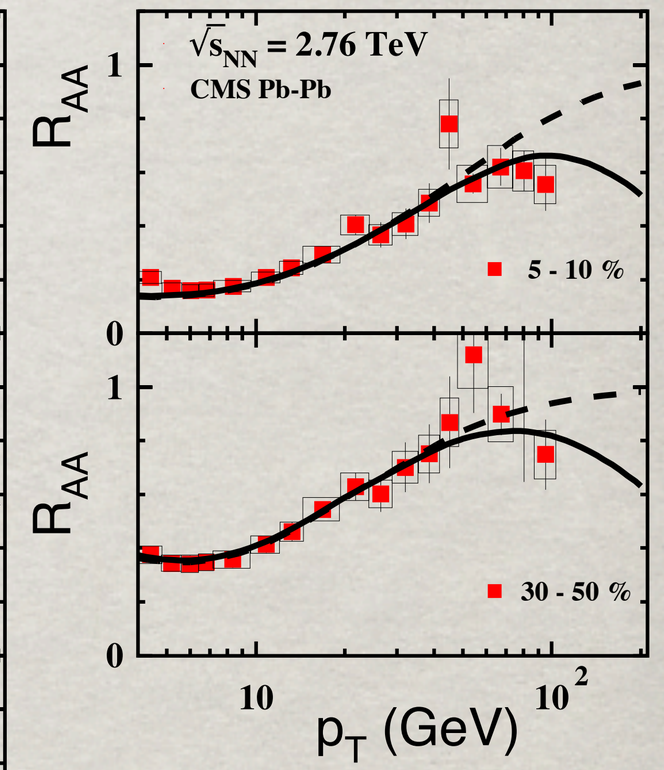
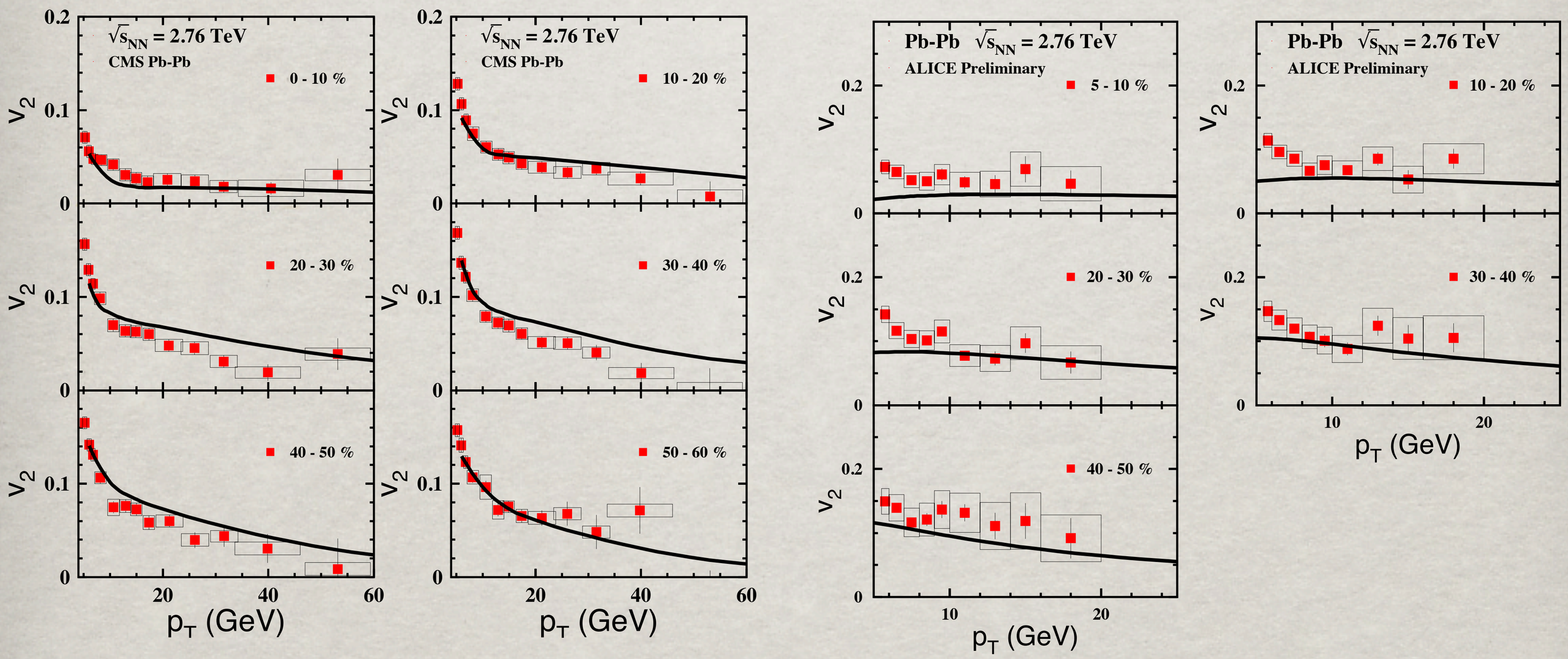
Quenching of high-p_T hadrons







Azimuthal asymmetry



Inclusive hadrons vs jets

ATTENTION!

The mean fractional momentum of hadrons in an averaged jet is quite small

$$\langle \mathbf{z_h} \rangle \approx \frac{\mathbf{0.1}}{\ln(\mathbf{p_T}/\lambda)} \approx \mathbf{0.03}$$

Therefore, a hadron with $p_T > 0.5$ is produced in extremely rare jets, in which the main fraction of the jet energy is carried by a single hadron.

Only such rare jets have a short production time.
An averaged jet is hadronizing long time, proportional to its energy.

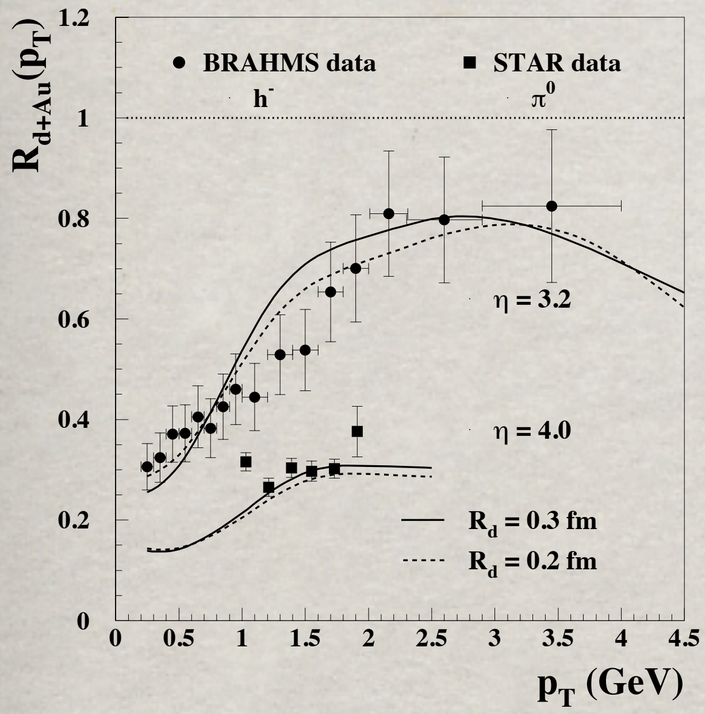
Lessons from pA

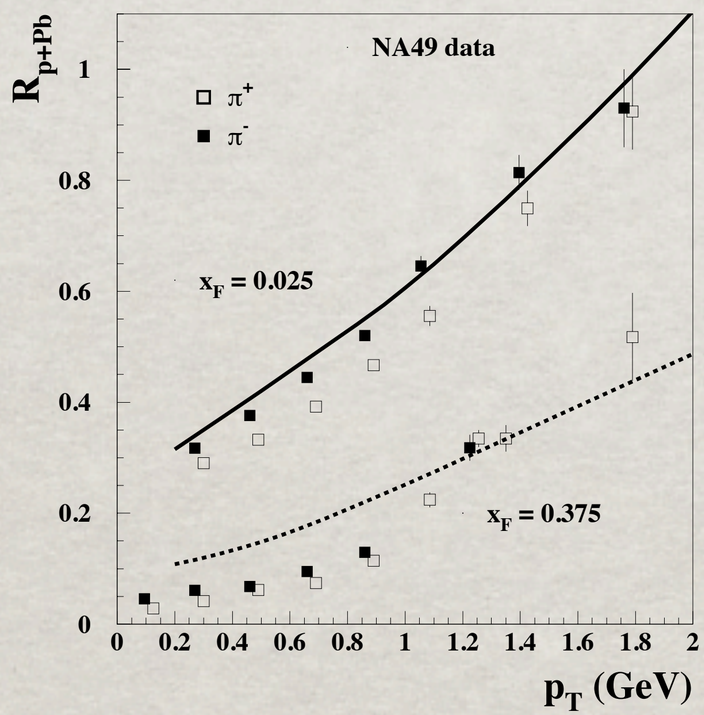
Initial state energy loss leads to an additional suppression at large x_L or x_T

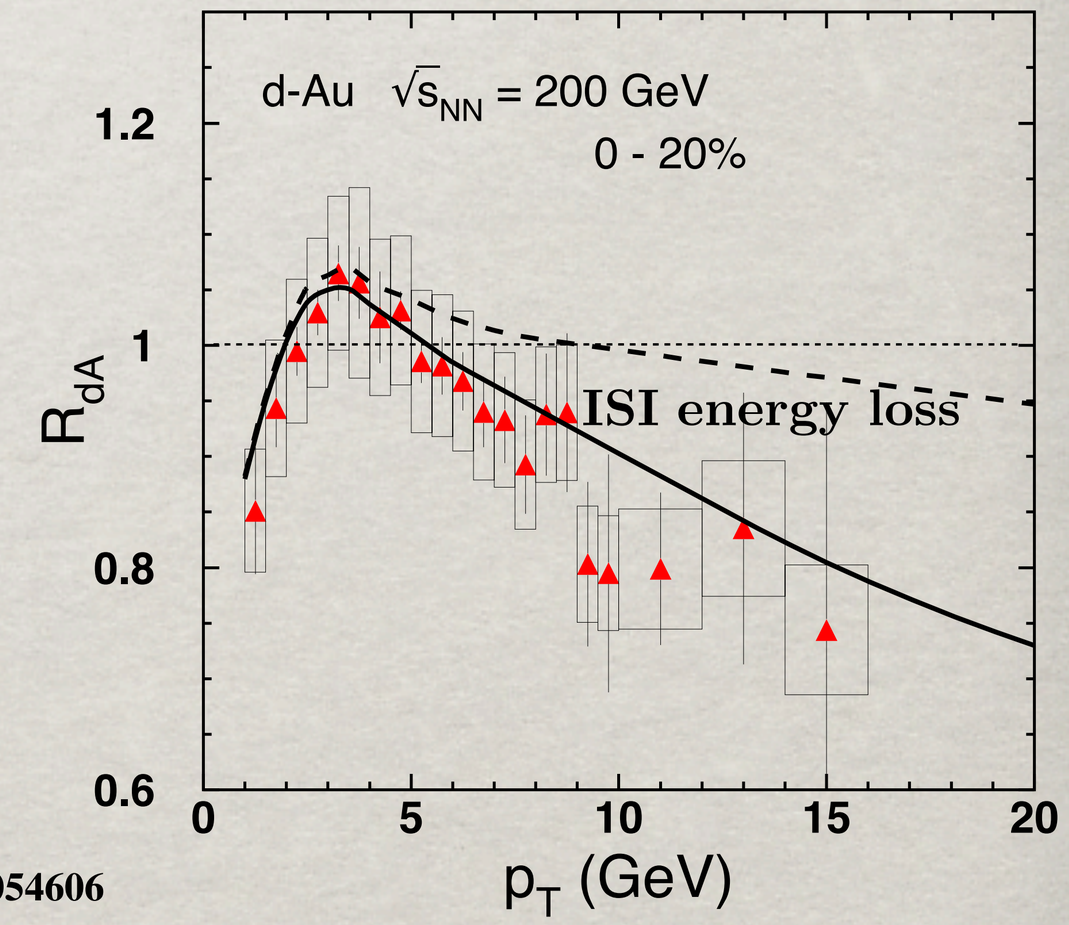
One can also approach the kinematic limit at the mid rapidity, but high pT.

Examples

Suppression at forward rapidities







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

Cronin ratio at LHC forward rapidities

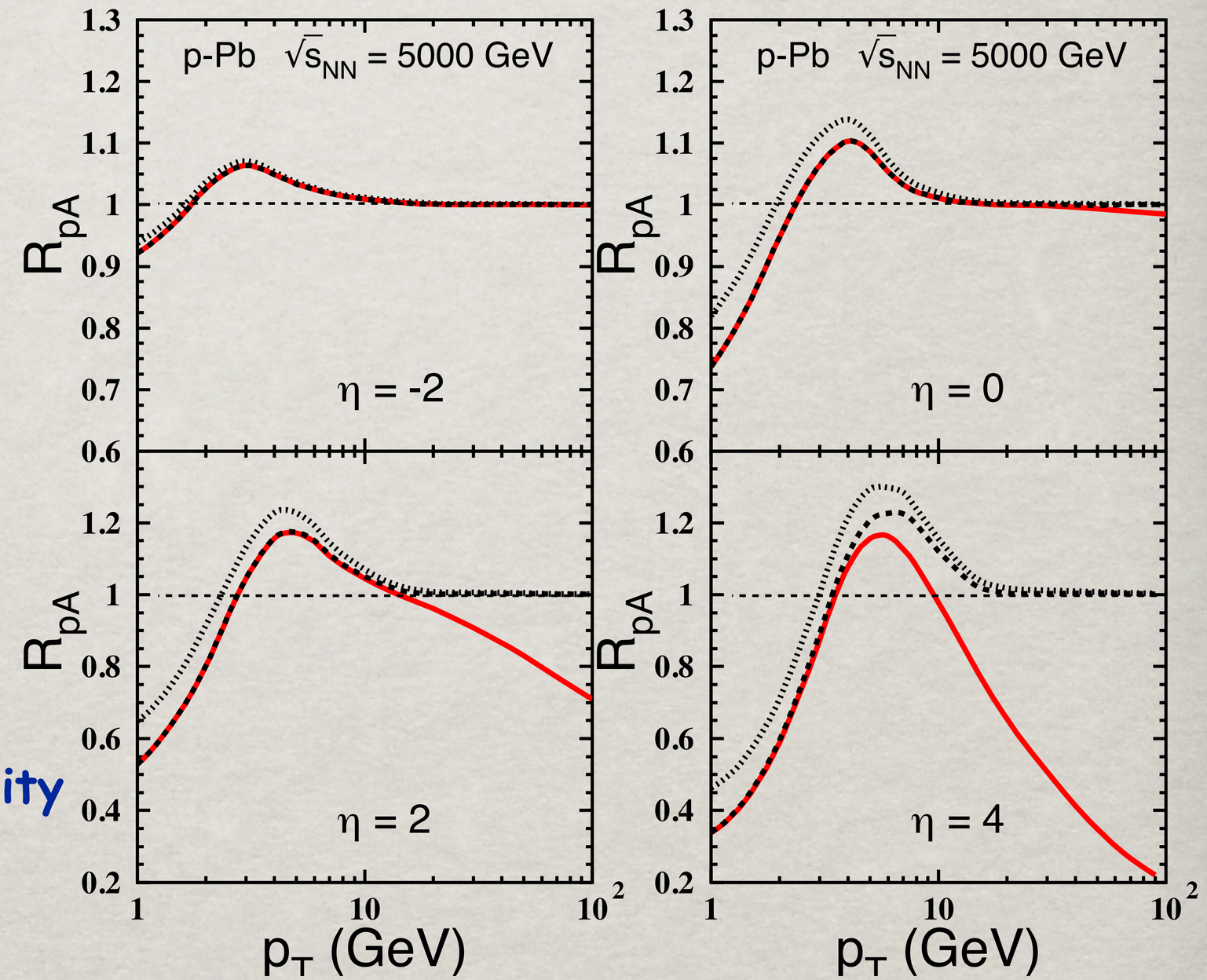
One can enhance the role of ISI energy loss either moving to forward rapidities, or higher pT, or both

····· no shadowing

----- KST shadowing

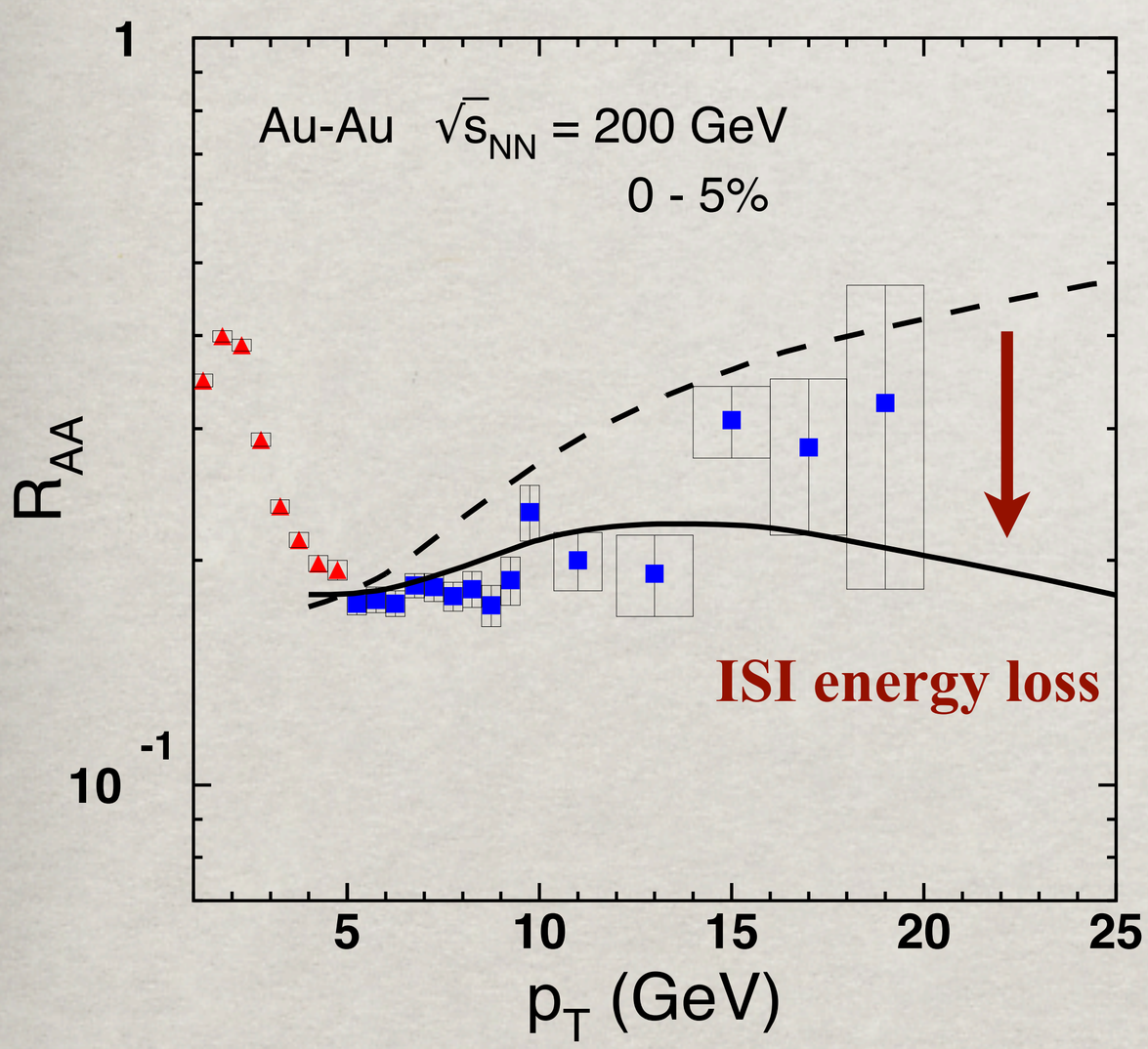
——— ISI E-loss added

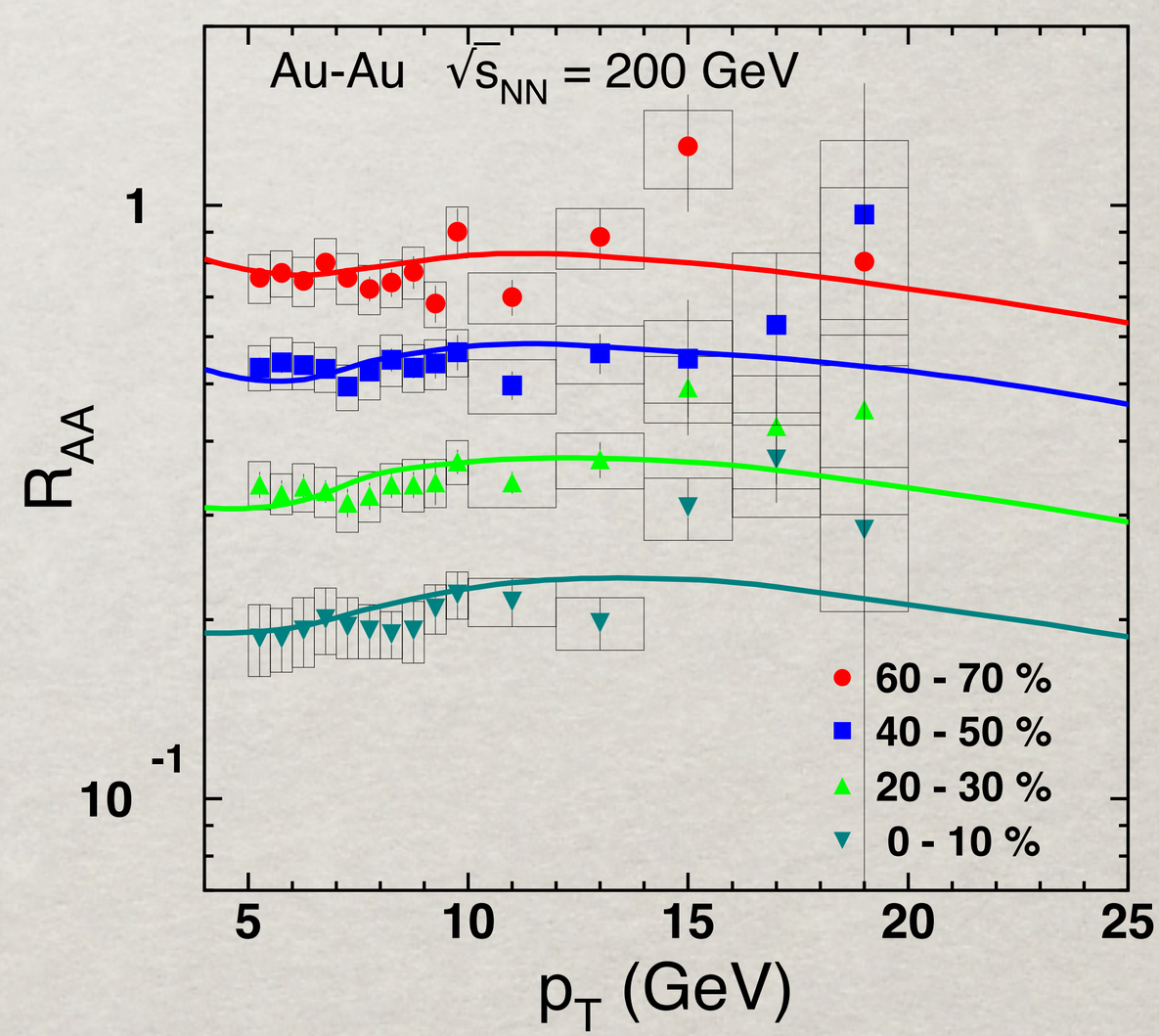
KMR unintegrated gluon density



Down to the RHIC energies

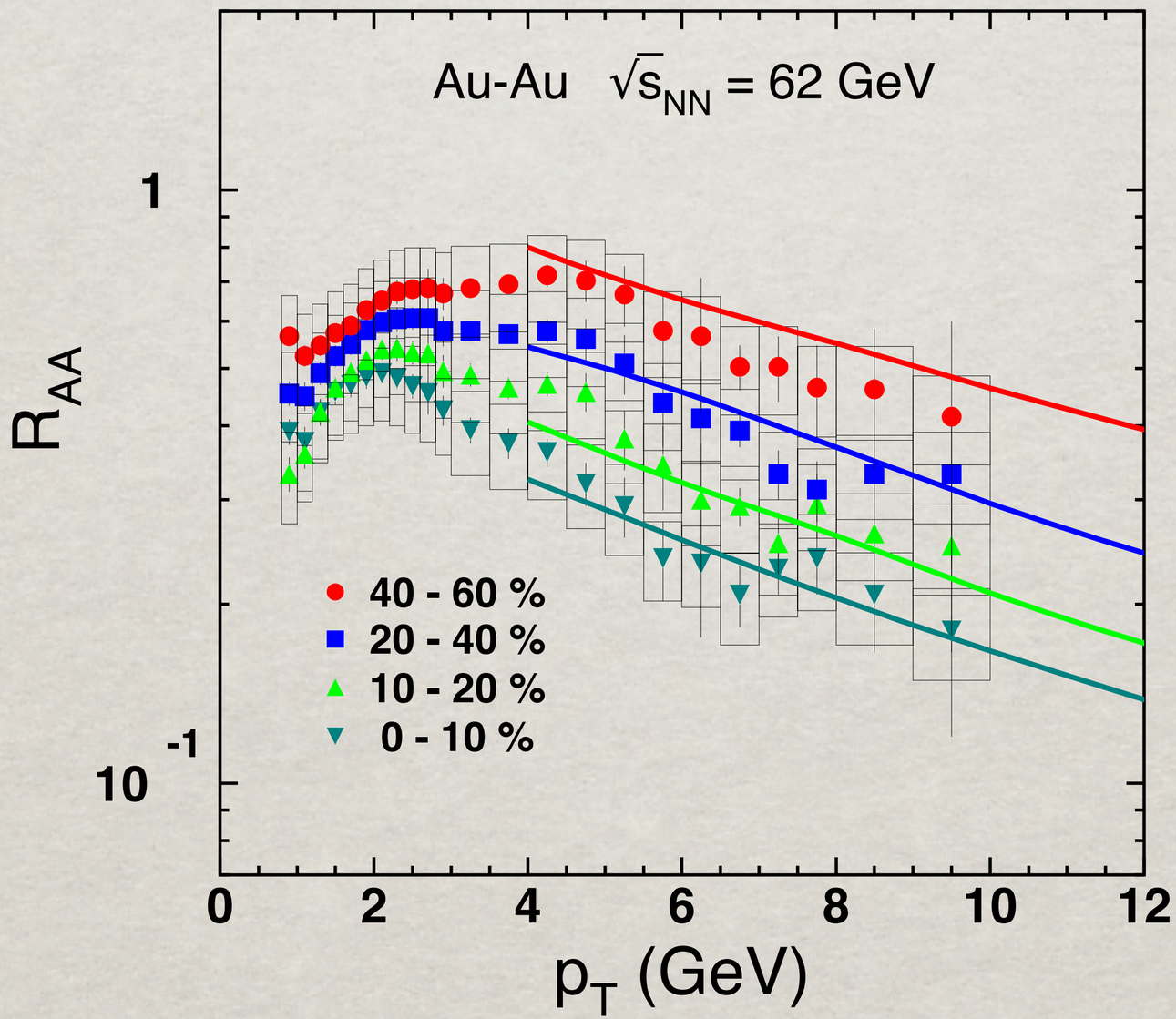
$$\hat{q}_0 = 1.6\,\mathrm{GeV}^2/\mathrm{fm}$$



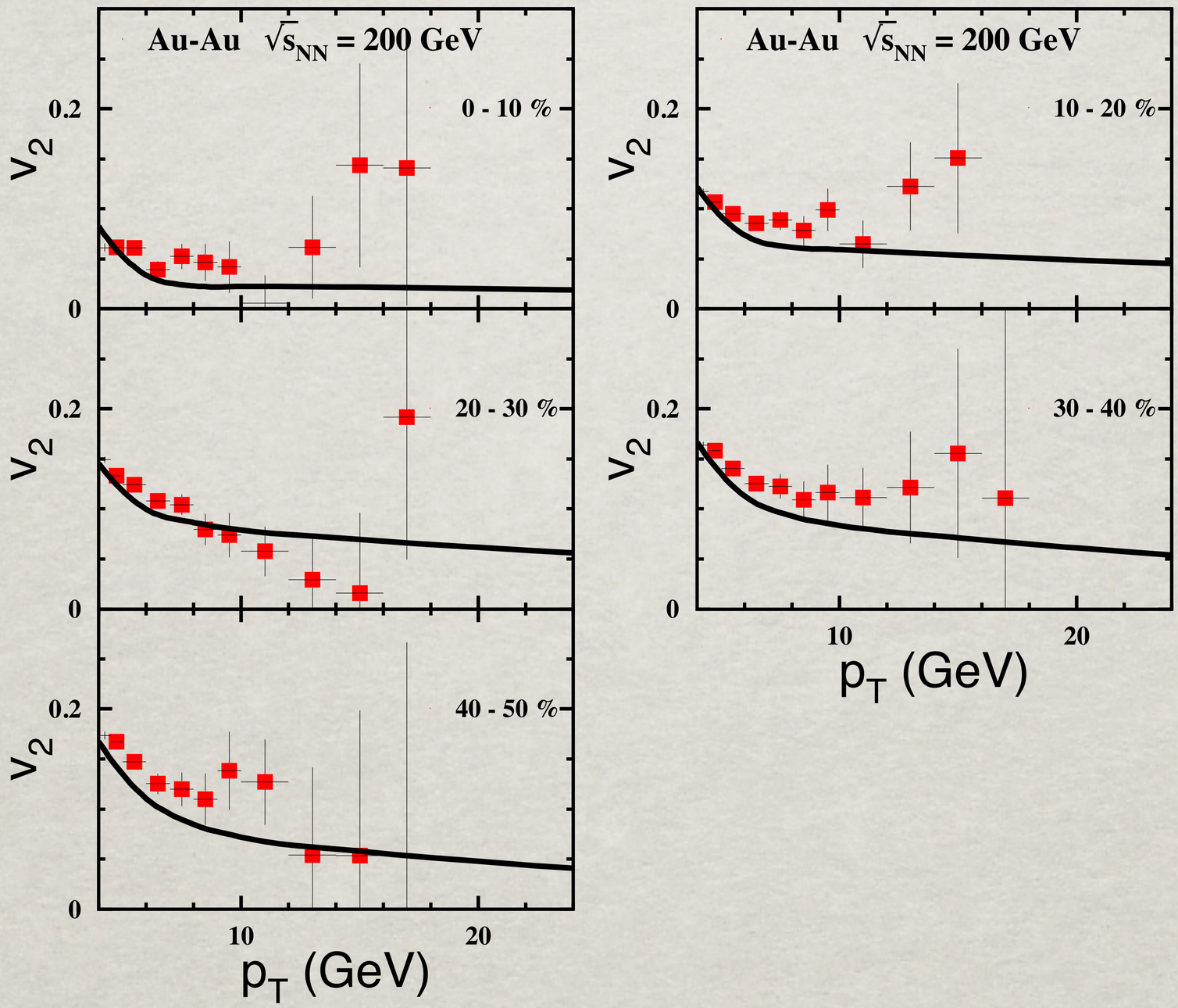


The lower the energy is, the higher is x_T

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



Azimuthal asymmetry



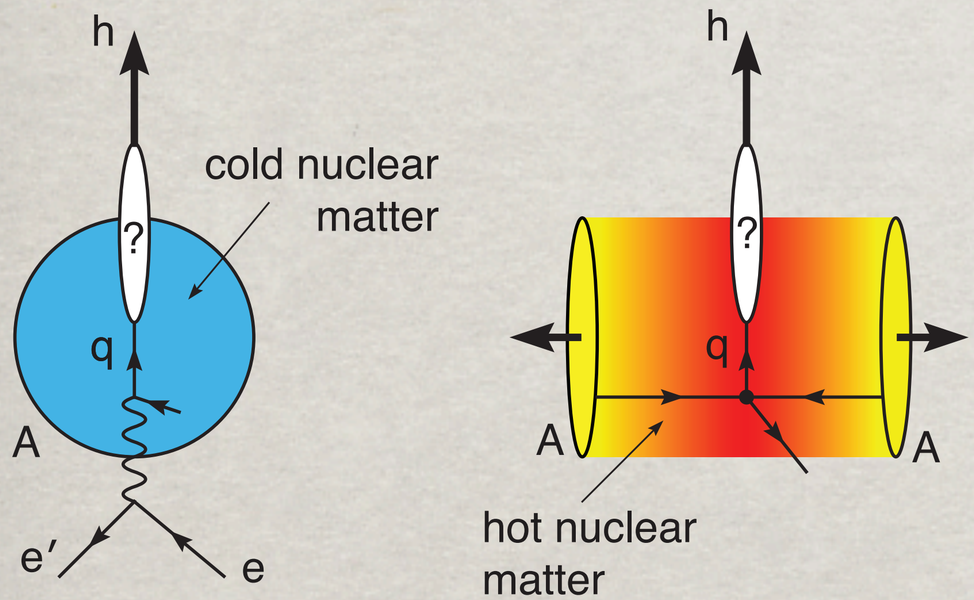
Energy-loss scenario

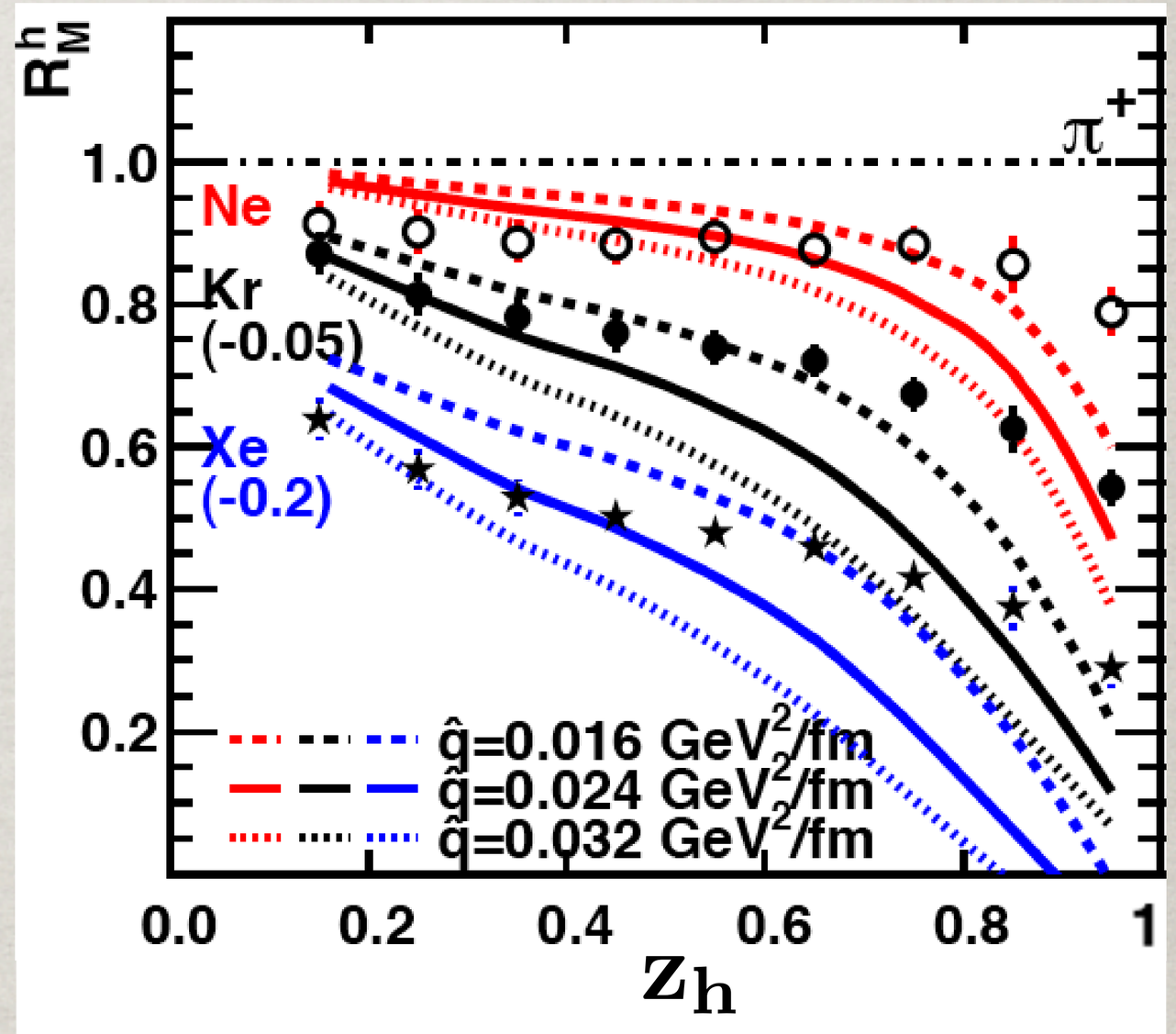
Problems

- 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 for induced radiation, heavy and light flavors are similarly suppressed
- 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 testing ground for the high-pT hadrons seeing in the c.m. of nuclear collisions





"At large values of z the agreement is not so well maybe due to other effects such as hadronic interaction [51, 52] that we have not taken into account."

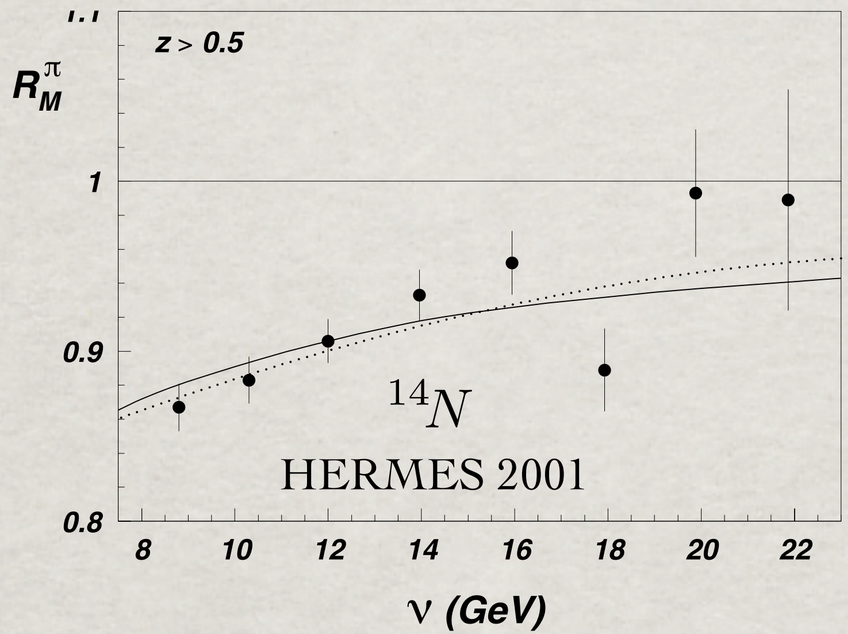
W.T. Deng & X.N. Wang: Phys.Rev. C81 (2010) 024902

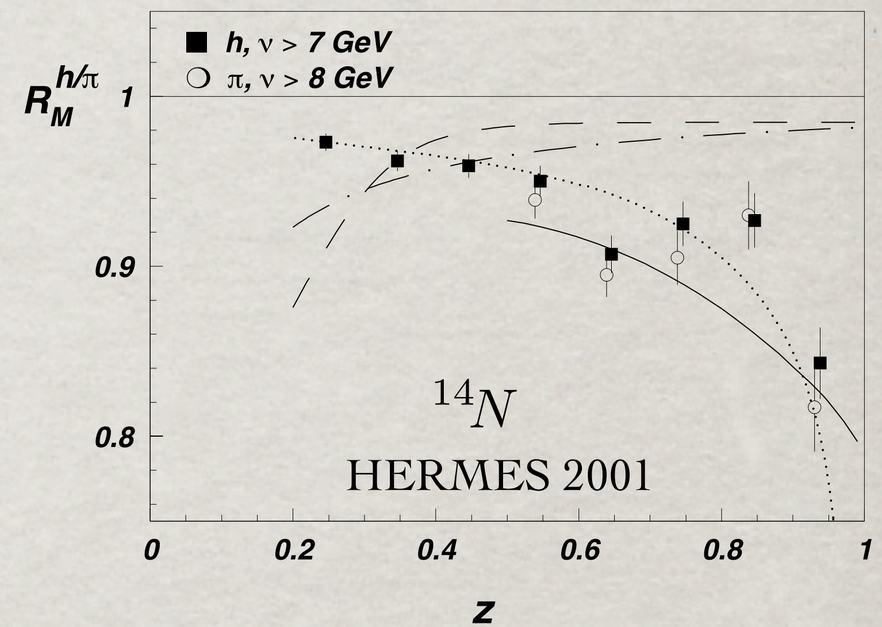
Testing the models in SIDIS

Finite l_p:
E-loss + absorption

Predictions

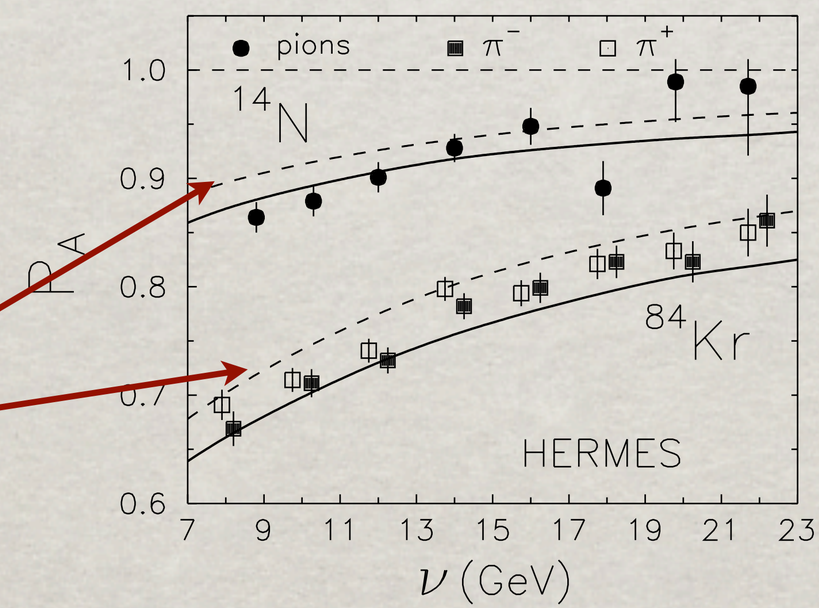
B.K., J. Nemchik, E. Predazzi
1996

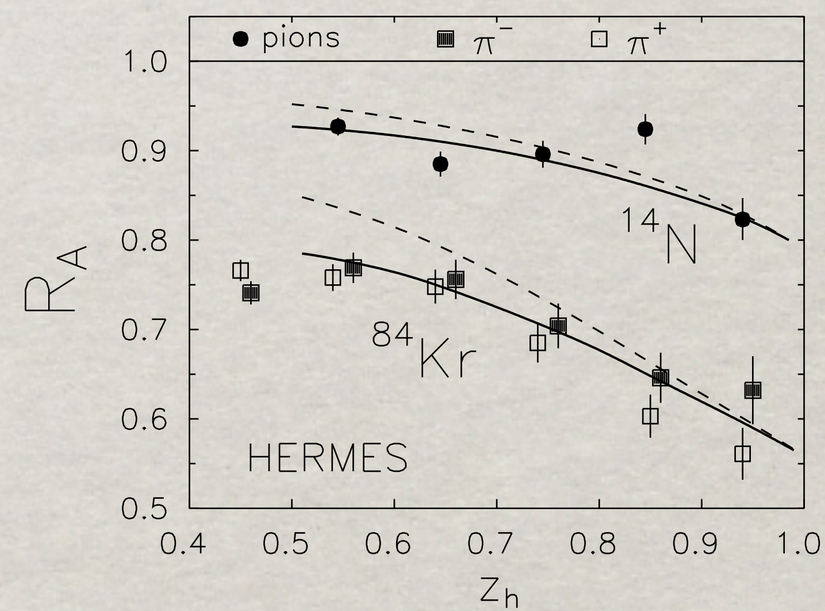




B.K., J. Nemchik, E. Predazzi
&A. Hayashigaki
Nucl. Phys. A 740, 211 (2004)

Only absorption





Suppression of heavy flavored hadrons

Specifics of heavy flavors

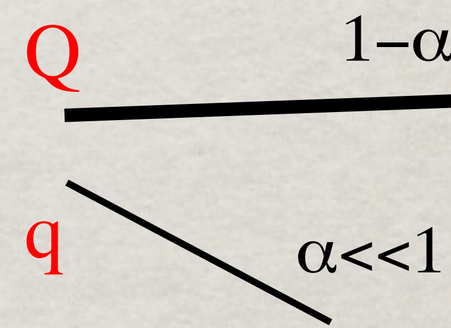
$$\langle z_D \rangle = 0.76$$
$$\langle z_B \rangle = 0.89$$
$$(\sqrt{s} = 7\,\mathrm{TeV})$$

- Production of heavy flavored mesons occur with larger z_h: Therefore, the production time l_p of a heavy-light dipole, is even shorter than for a light dipole.

- The light-cone momentum sharing in a heavy-light dipole, Qq, is very asymmetric, the light quark carries a small fraction $\alpha \ll 1$

$$\langle \alpha \rangle_c = 0.24 \qquad \langle \alpha \rangle_b = 0.088$$

- The expansion rate is $1/\alpha$ higher than for a qq dipole (at the same pt)



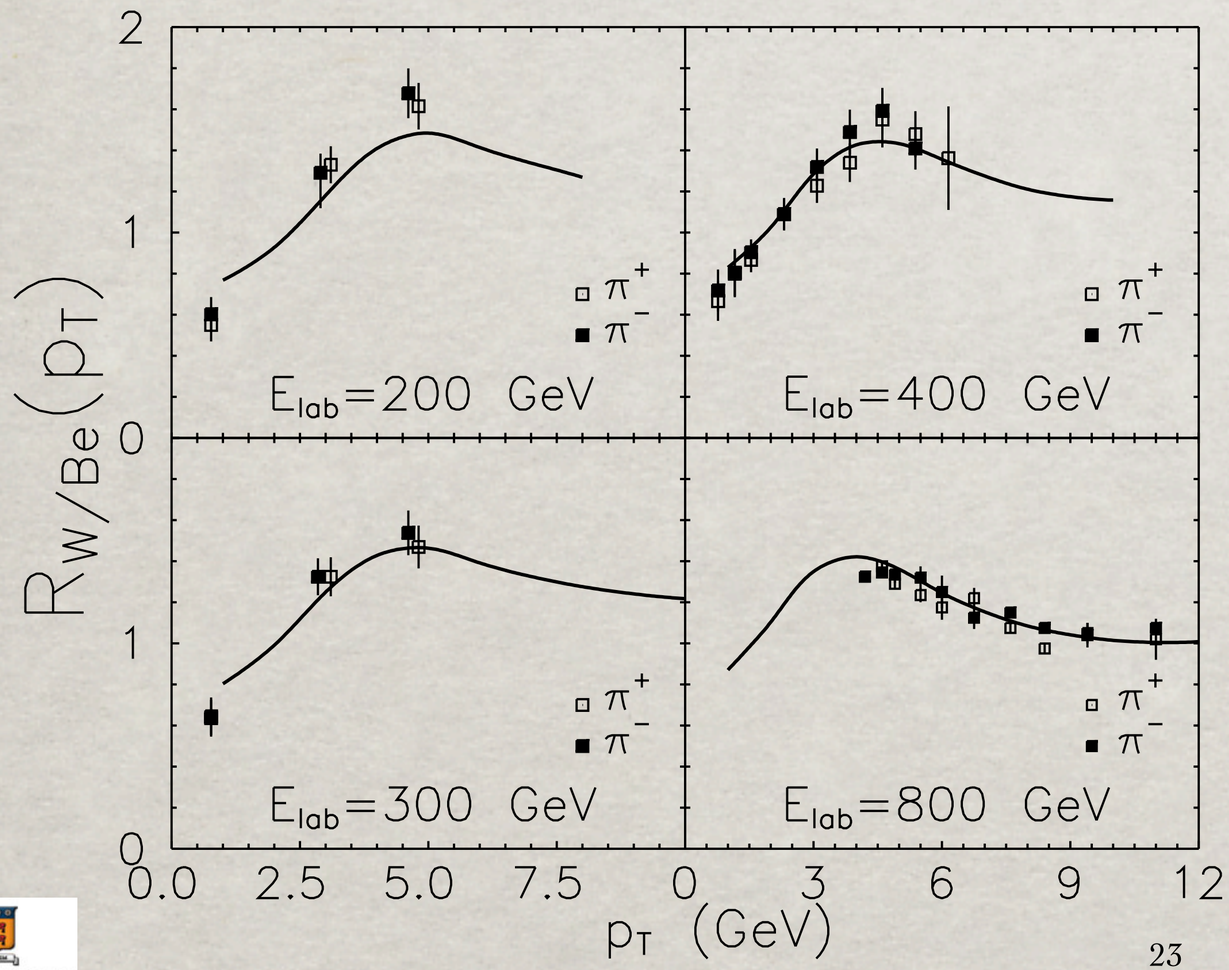
- The size of a Qq hadron is about twice as small as of qq

The last two features work in opposite directions, i.e. making the medium more opaque or transparent respectively.

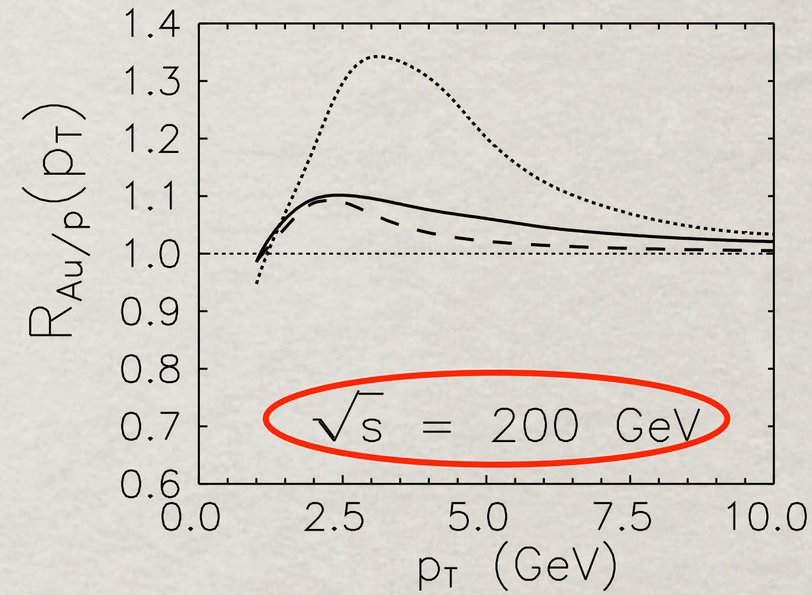
Calculations are in progress.

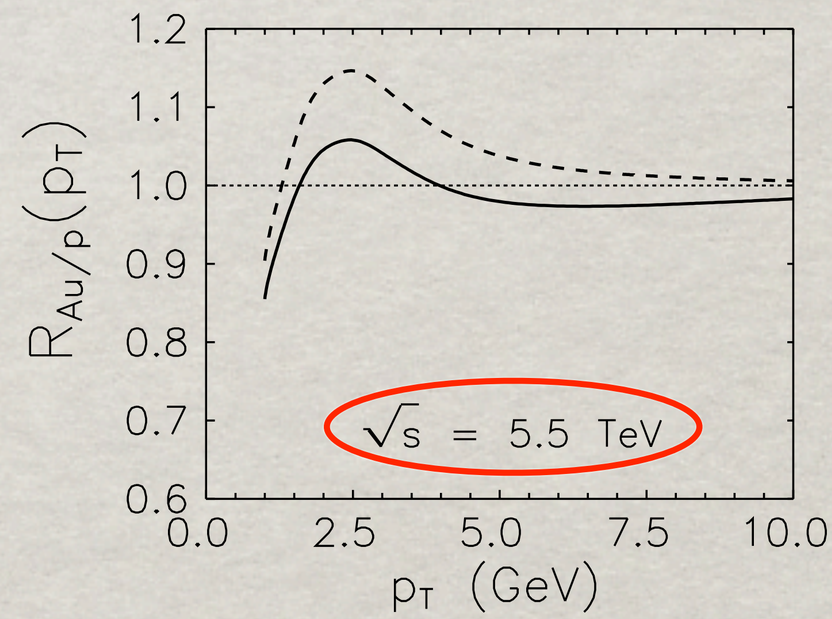
Cronin effect

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.



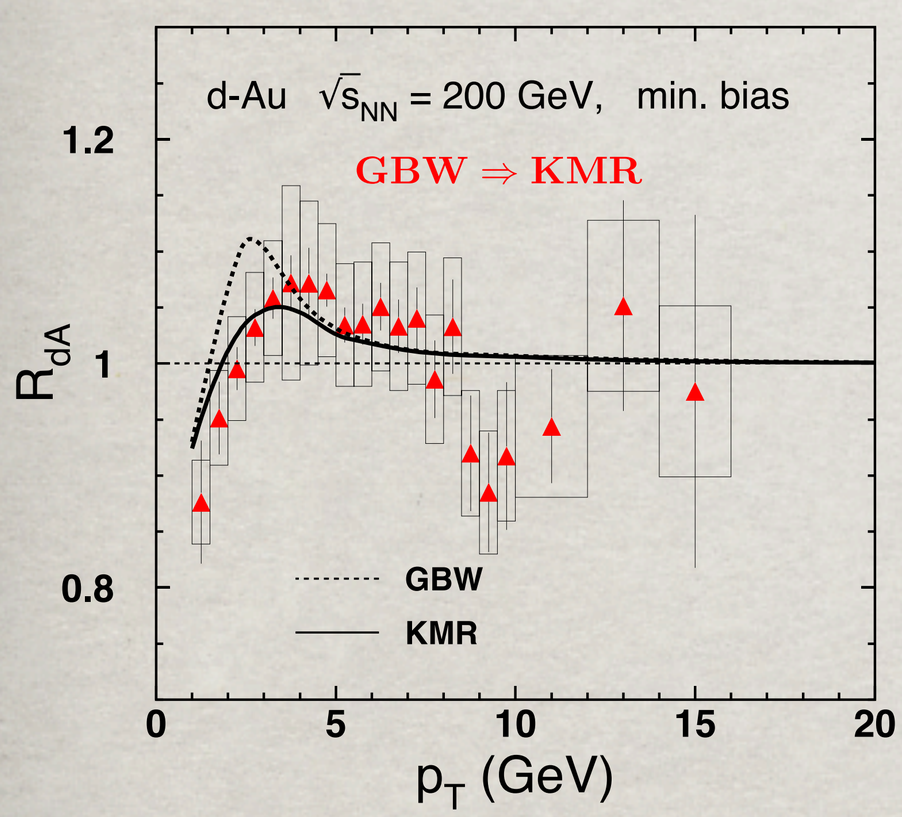
B.K., J.Nemchik, A.Schafer, A.Tarasov, PRL 88(2002)232303`





Cronin effect at RHIC: predicted and observed

The predicted magnitude was OK, but the shape was not. The employed unintegrated gluon density of K.J.Golec-Biernat & M.Wustoff, 1999 (GBW) peakes at too small pT.

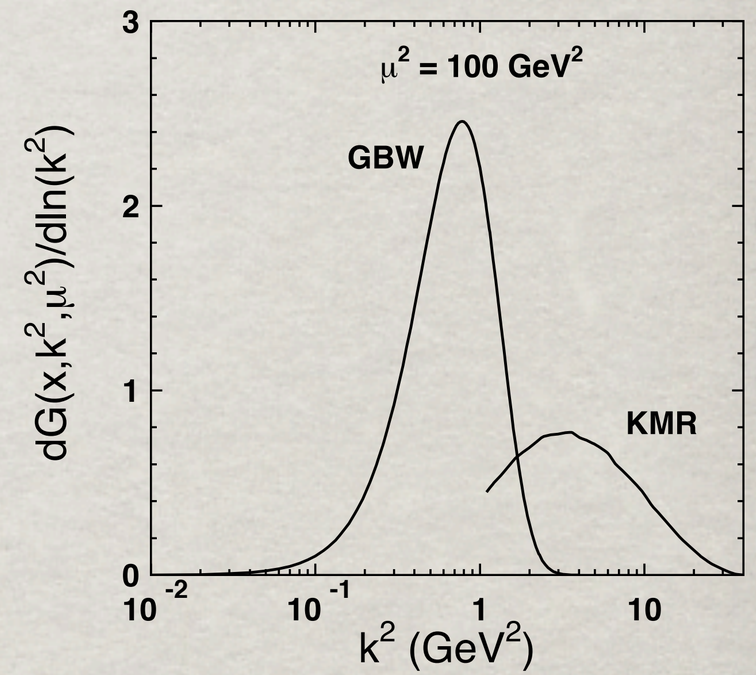


More realistic parametrization for the unintegrated gluon distribution proposed later,

M.Kimber, A.Martin & M.Ryskin, 2001 (KMR)

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

improves the shape (with no other modifications in the computing code).

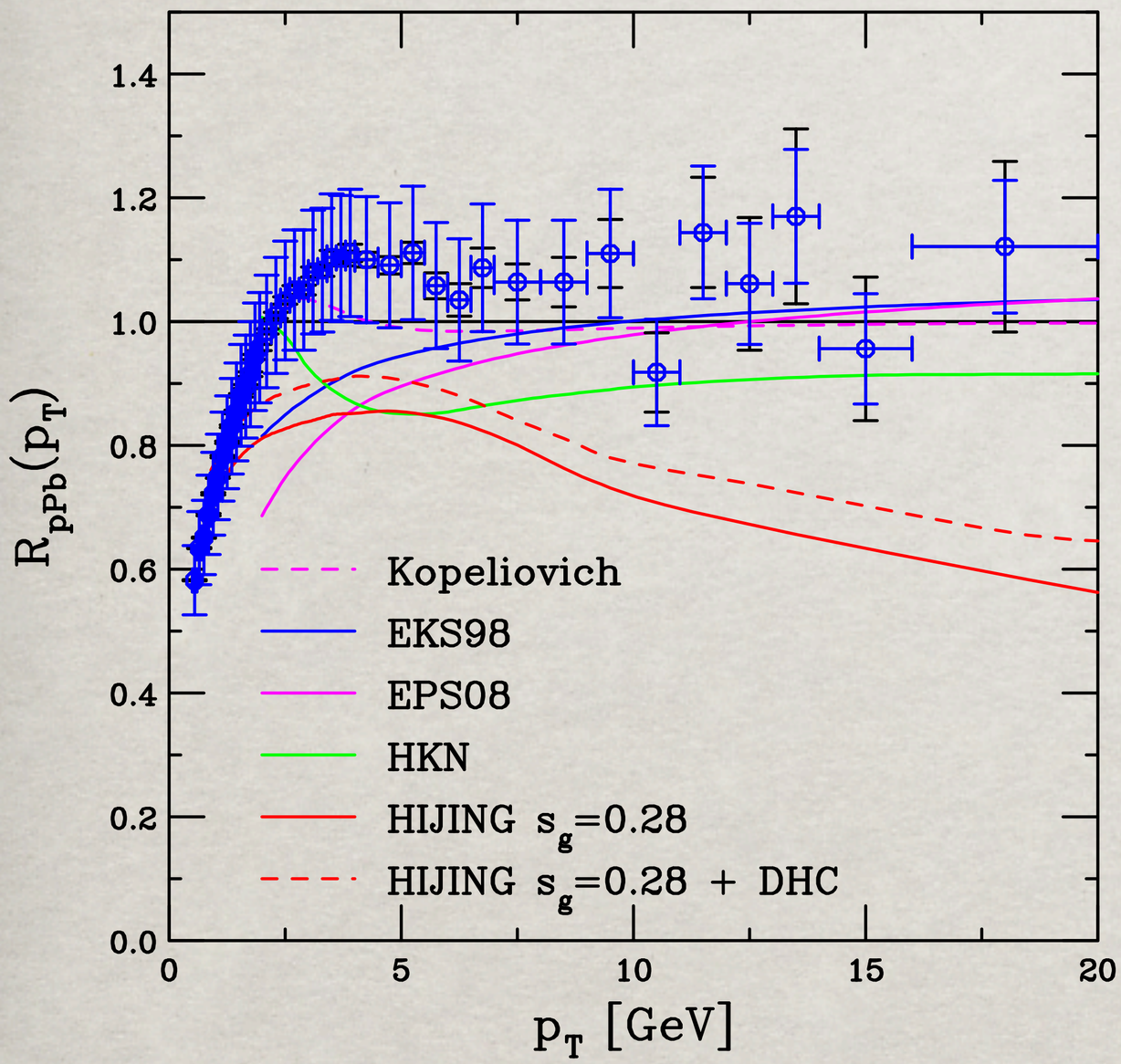


D.Kharzeev, E.Levin,L.McLerran, PL B561(2003)93:

Color Glass Condensate models exaggerated the magnitude of the coherence effects predicting a sizable suppression $\mathbf{R_{dA} = 0.75}$

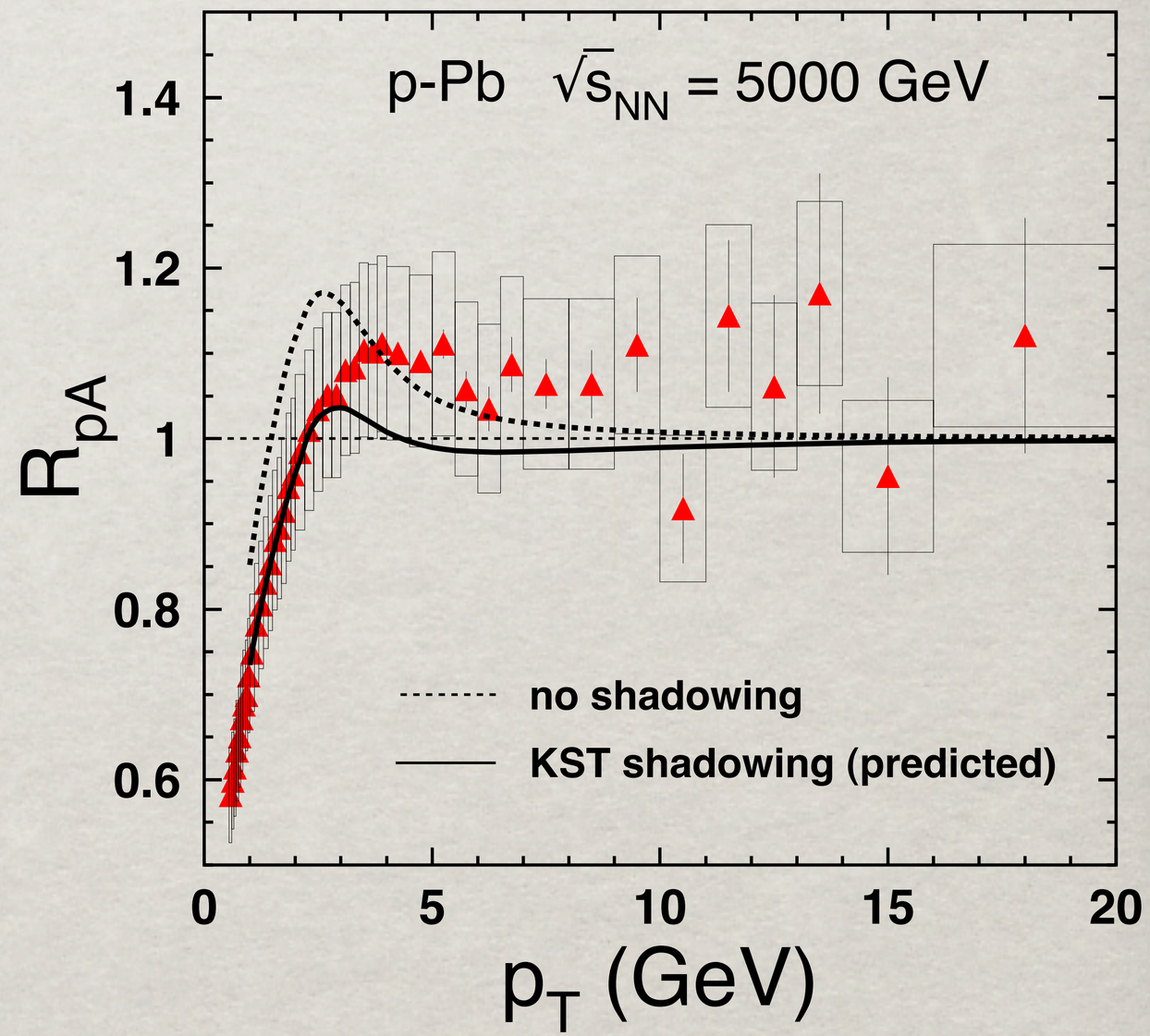
Cronin effect at LHC: predicted and observed

R.Vogt et al, arXiv: 1301.3395

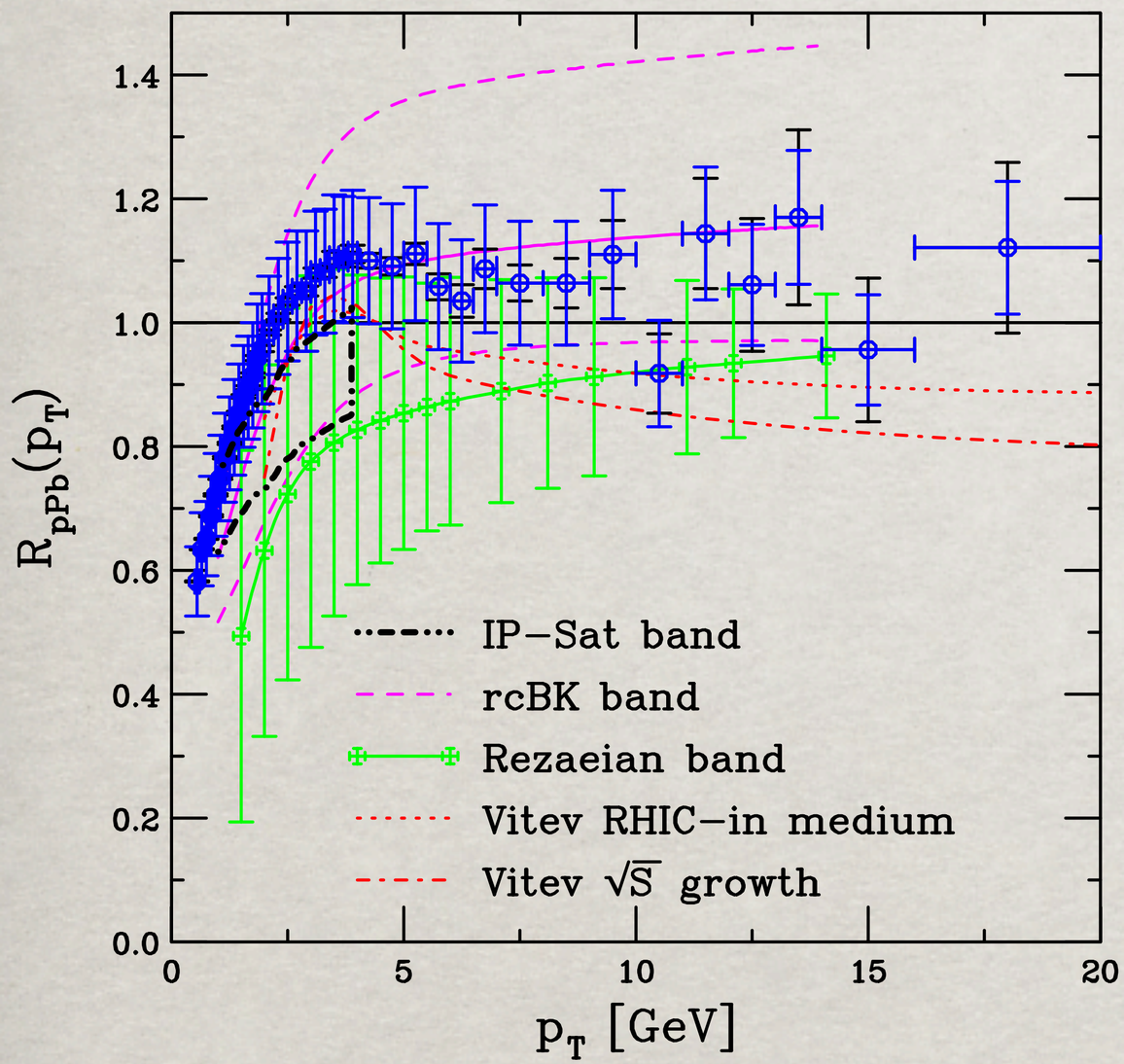


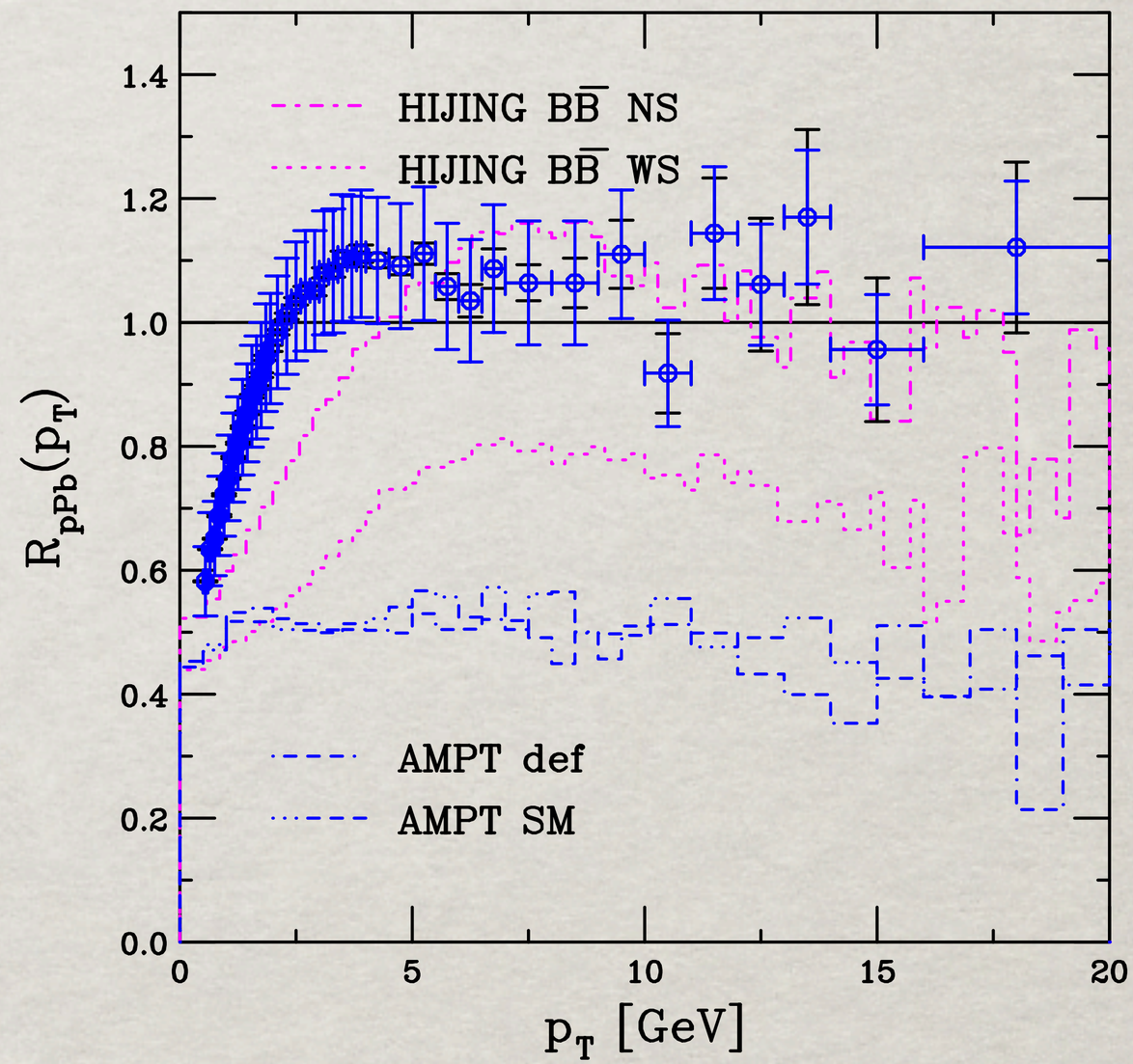
The first successful prediction

B.K., J.Nemchik, A.Schafer, A.Tarasov (2002)



Predicted vs measured

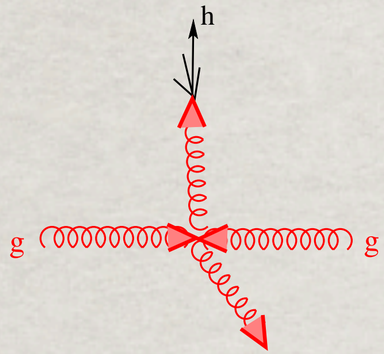


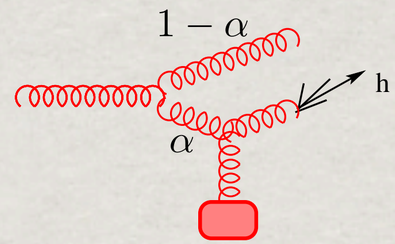


Not successful either

Details

parton model





dipole description

$$\frac{\mathbf{d}\sigma^{\mathbf{N(A)}}_{\mathbf{g\to 2g}}(\alpha,\mathbf{x_2})}{\mathbf{d^2k_T\,dy}} = \int \mathbf{d^2r d^2r'\, e^{ik_T(r-r')}} \left\langle \mathbf{\Psi^\dagger_{gg}(r,\alpha)\Psi_{gg}(r',\alpha)} \right\rangle \mathbf{\Sigma^{N(A)}_{3g}(r,r',\alpha,x_2)}$$

$$\Sigma^{N(A)}_{3g}(\vec{r},\vec{r}\,',\alpha,x_2) = \begin{cases} \sigma^N_{3g}(r,\alpha)+\sigma^N_{3g}(r',\alpha)-\sigma^N_{3g}(\vec{r}-\vec{r}\,',\alpha); & \textbf{(pp)} \\ 2\int d^2b\left[1-e^{-\frac{1}{2}\sigma^N_{3g}(r,\alpha)T_A(b)}e^{-\frac{1}{2}\sigma^N_{3g}(r',\alpha)T_A(b)}+e^{-\frac{1}{2}\sigma^N_{3g}(\vec{r}-\vec{r}\,',\alpha)T_A(b)}\right] & \textbf{(pA)} \end{cases}$$

$$\sigma^N_{3g}(r,\alpha) = \frac{9}{8}\Big\{\sigma_{\bar{q}q}(r)+\sigma_{\bar{q}q}(\alpha r)+\sigma_{\bar{q}q}[(1-\alpha)r]\Big\}$$

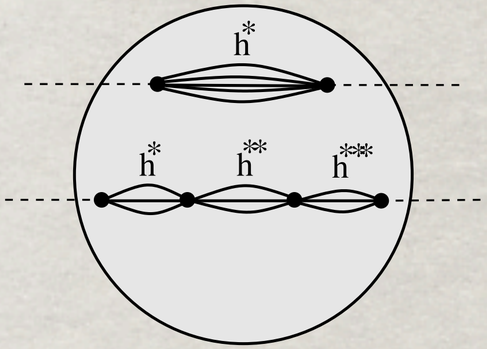
$$\Psi_{gg}(\vec{r},\alpha) = \frac{\sqrt{8\alpha_s}}{\pi\, r^2}\exp\left[-\frac{r^2}{2\,r_0^2}\right]\left[\alpha(\vec{e}^{\,*}_1\cdot\vec{e})(\vec{e}^{\,*}_2\cdot\vec{r})(1-\alpha)(\vec{e}^{\,*}_2\cdot\vec{e})(\vec{e}^{\,*}_1\cdot\vec{r})-\alpha(1-\alpha)(\vec{e}^{\,*}_1\cdot\vec{e}^{\,*}_2)(\vec{e}\cdot\vec{r})\right]$$

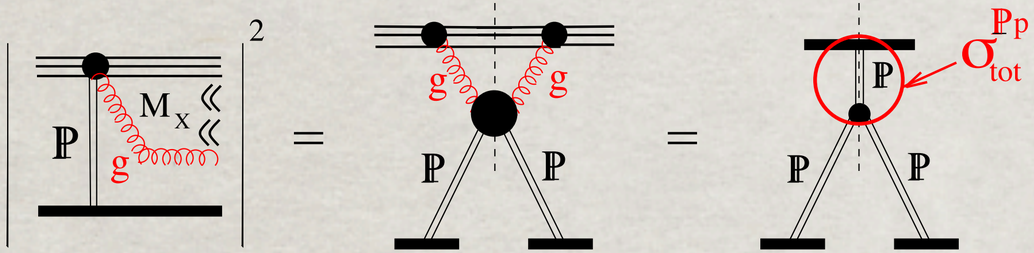
$\mathbf{r_0 \approx 0.3fm}$

$$\left\langle \Psi^\dagger_{gg}(\vec{r})\Psi_{gg}(\vec{r}\,') \right\rangle = \frac{4\alpha_s}{\pi^2}\,\frac{\vec{r}\cdot\vec{r}\,'}{r^2\,r'^2}\exp\left[-\frac{r^2+r'^2}{2\,r_0^2}\right]\left[1+\alpha^4+(1-\alpha)^4\right]$$

Weakness of gluon shadowing

Gluon shadowing is a part of the Gribov inelastic corrections related to the triple-Pomeron term in diffraction.





expected: $\sigma_{\mathbf{tot}}^{\mathbf{Pp}} \sim 50\,\mathrm{mb}$

measured: $\sigma_{\mathbf{tot}}^{\mathbf{Pp}} \lesssim 2\,\mathrm{mb}\,!!!$

Smallness of the diffractive cross section means weakness of gluon shadowing.

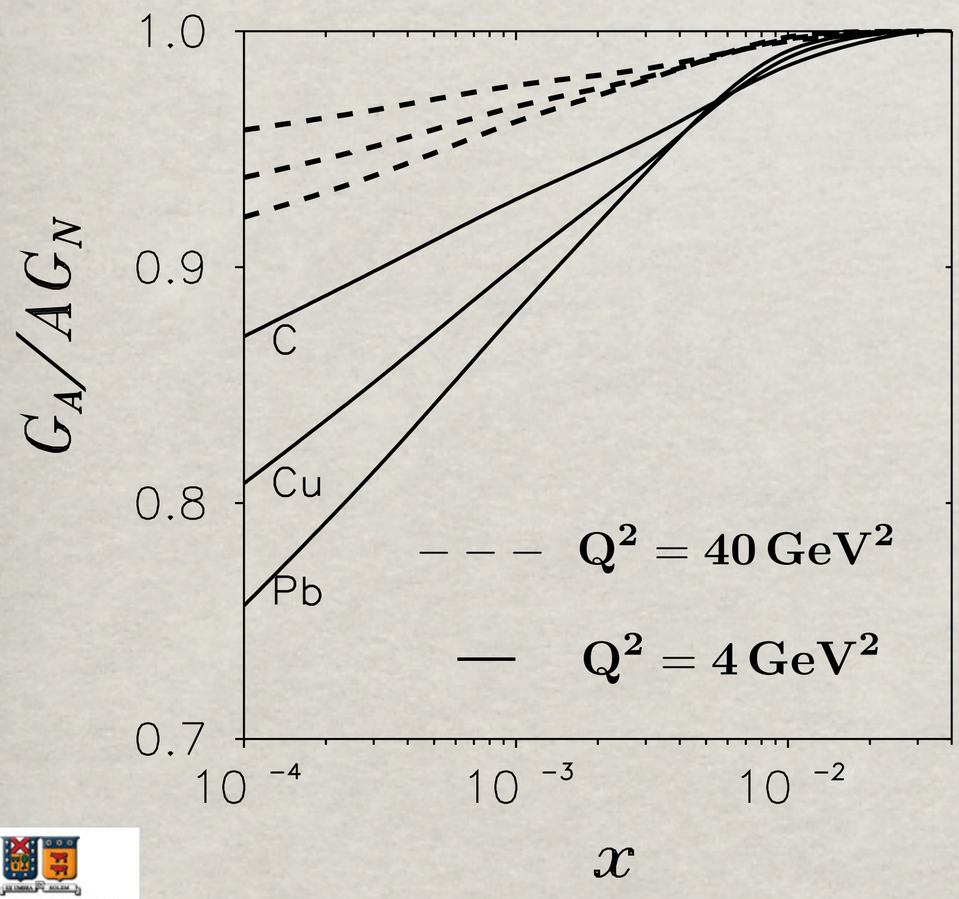
In terms of pQCD this shows a suppression of diffractive gluon radiation, which can only be related to smallness of gluonic dipoles.

Gluon shadowing from DIS

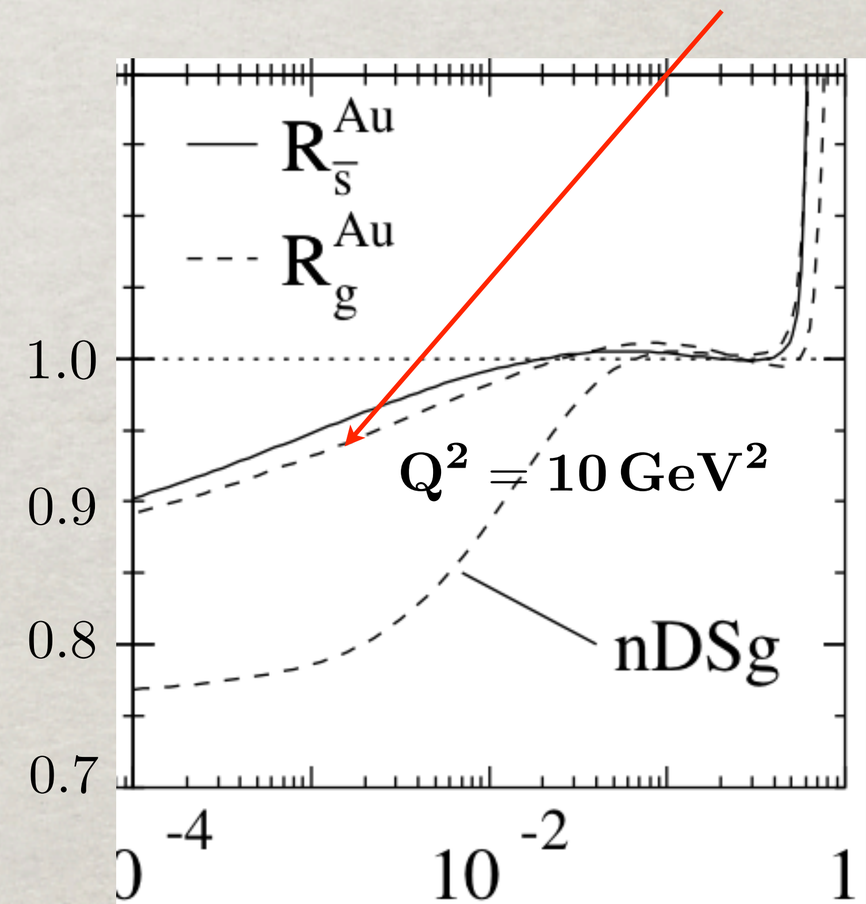
Gluon shadowing in DIS correspond to inclusion of the higher Fock components of the photon, $\gamma^* \to \bar{q}q + g$, B.K., A.Schaefer, A.Tarasov,1999 .

Gluon PDFs in DIS are probed via the DGLAP evolution from the Q^2 dependence of $F_2(x, Q^2)$
So far only the NMC experiment managed to detect a variation of the nuclear PDF with Q^2

B.K., A.Schaefer, A.Tarasov,1999 (KST)

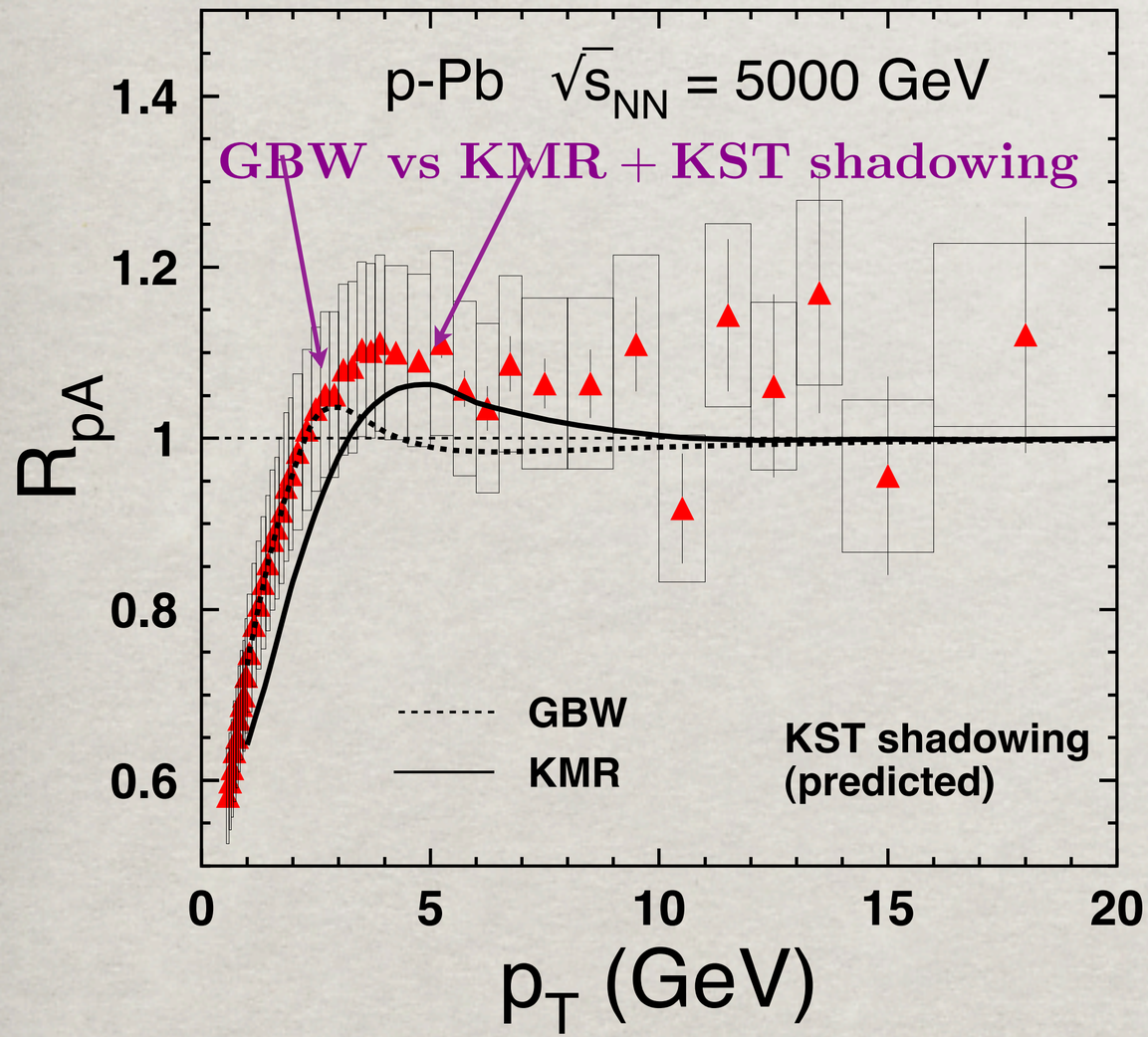


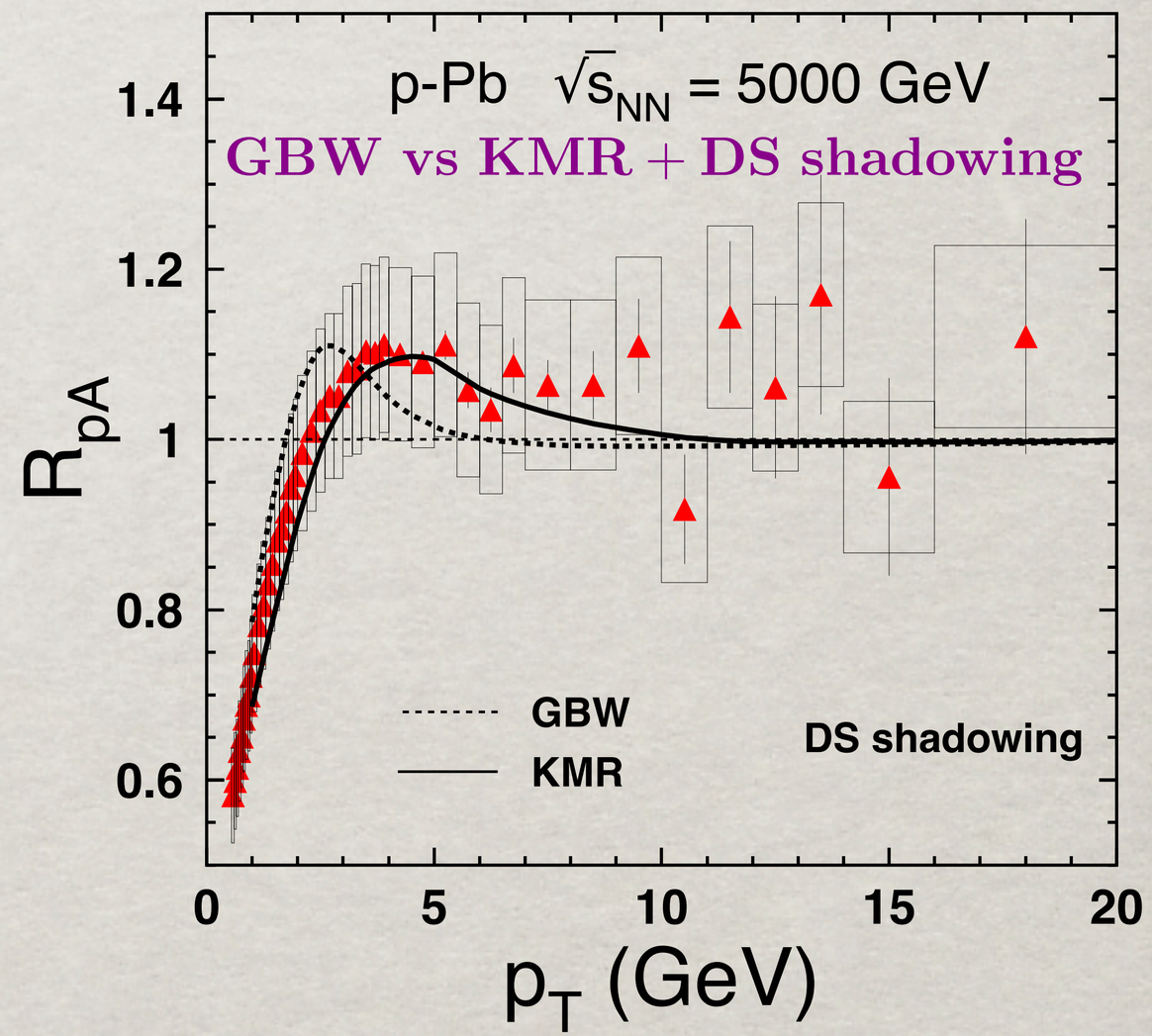
D.de Florian, R.Sassot, 2004 (DS)



Improved predictions

With the same 2002 computer code, but using a contemporary versions of the unintegrated gluon distribution (KMR) one can improve the shape of pT-dependence.





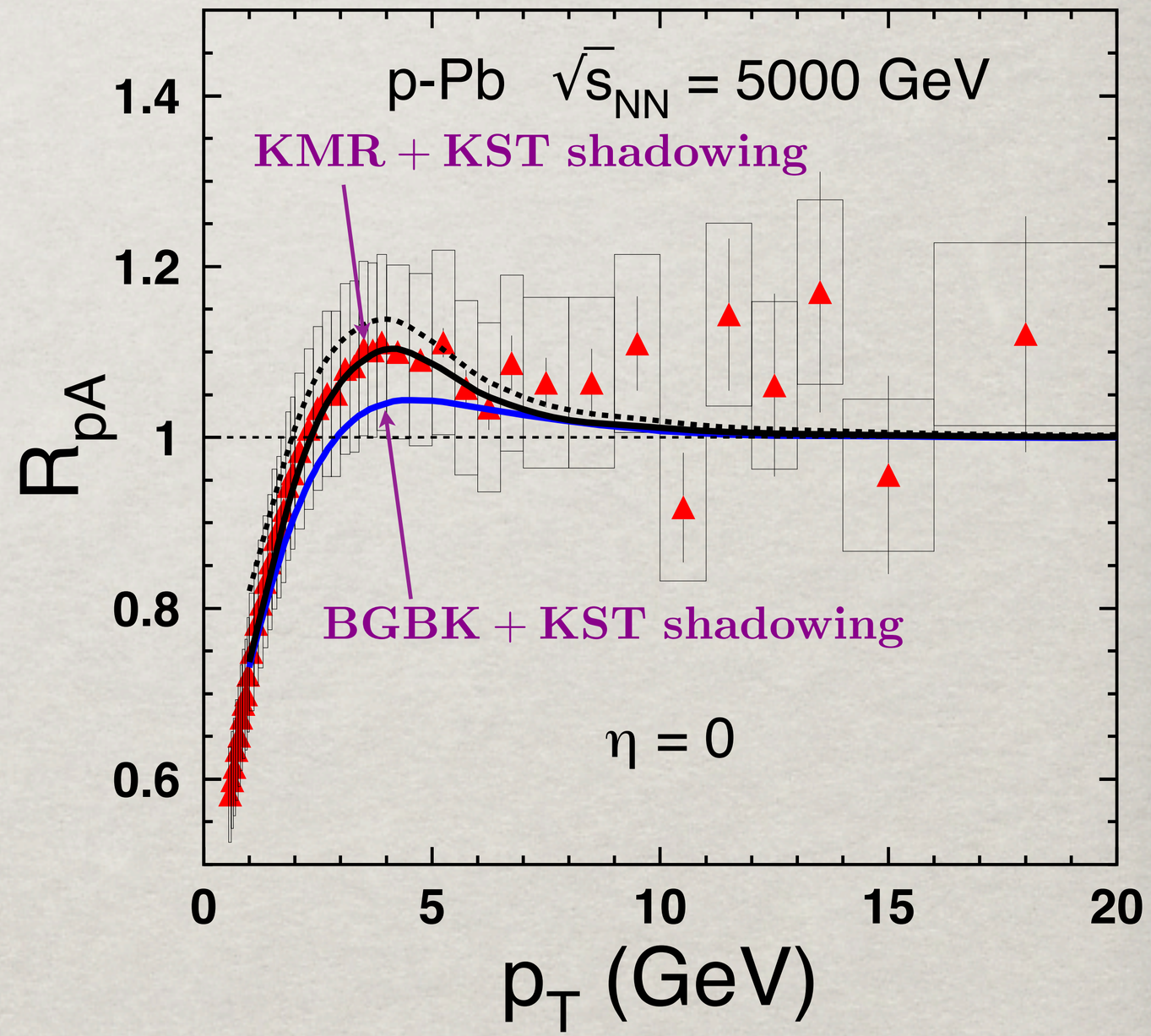
POSTDICTIONS: Further improvements

- A better choice of the scale for gluon shadowung.

$$Q^2 = \frac{4}{xg(x, k_T^2)} \int dq^2 \, \mathcal{F}_g(x, q, k_T^2)$$

- Alternative parametrizations for the dipole cross section:

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



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.

- Production time of a high-p_T dipole is short and does not rise with p_T. It is even shorter for heavy-light dipoles. 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.

Summary

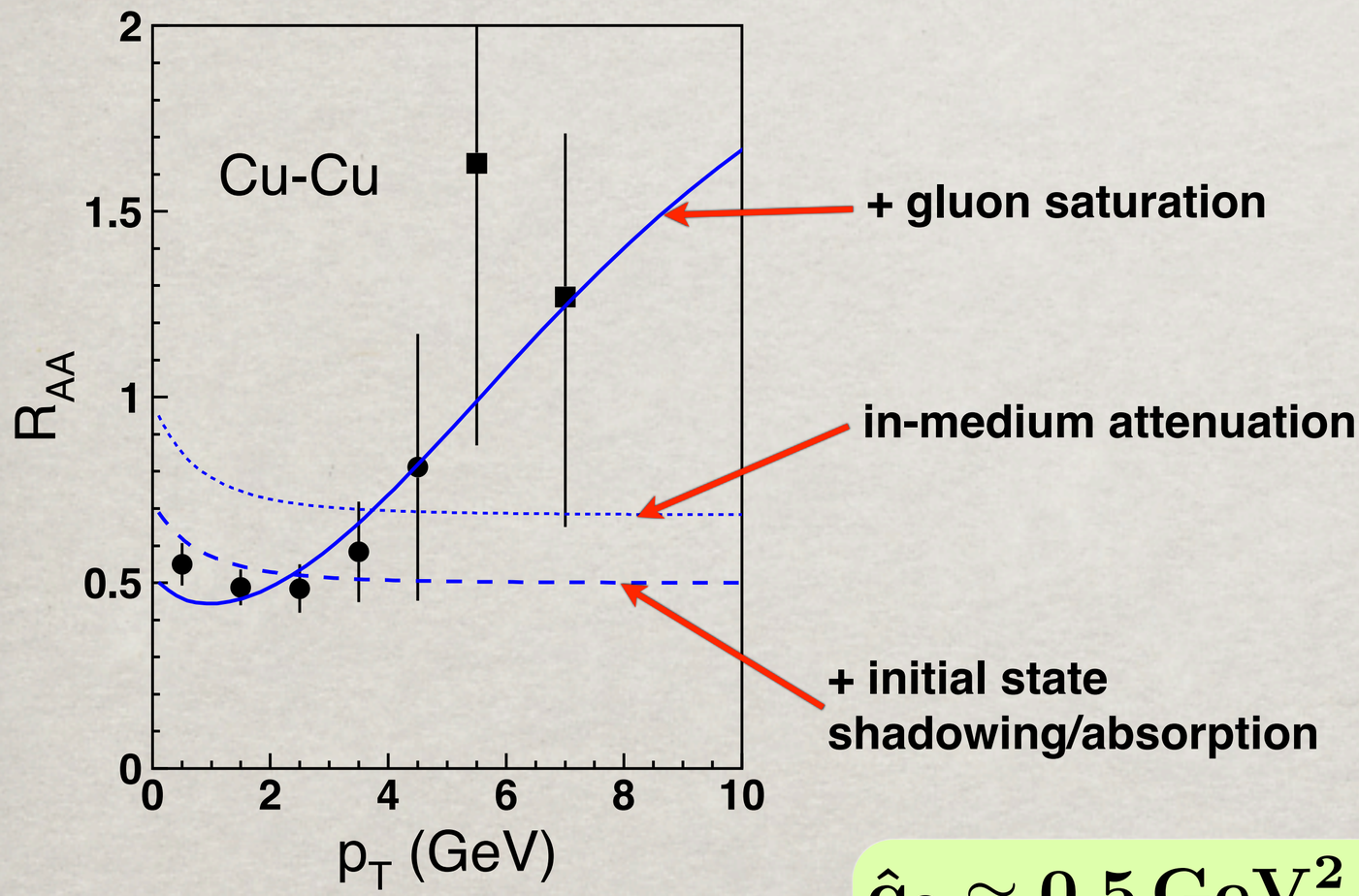
- Energy deficit at large x_L and x_T due to initial state energy loss (proportional to the collision energy) in pA and AA collisions cause a suppression, observed in data.

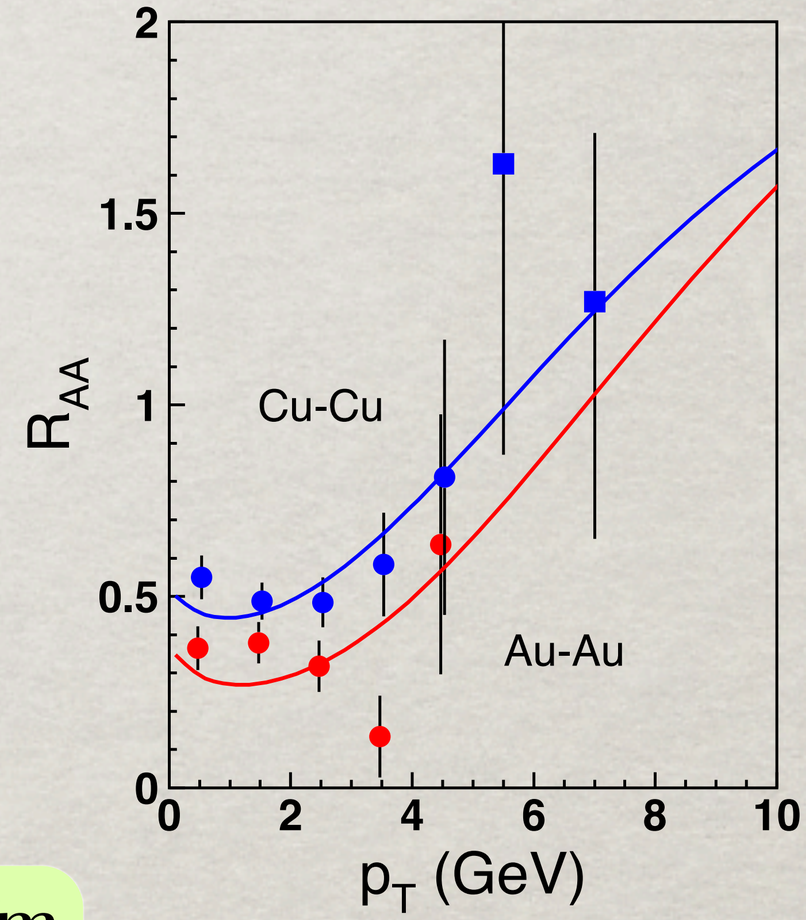
- The energy loss model is essentially based on the unjustified assumption that hadronization is lasting long time and ceases outside the medium.

- Such a model does not pass the test with data on nuclear suppression of inclusive hadrons produced in DIS at large z_h, while the model based the proper treatment of the production length successfully predicted the nuclear effects.

BACKUPS Alternative probe: J/Ψ suppression

B.K., I.Potashnikova, I.Schmidt, Phys.Rev. C82(2010)024901





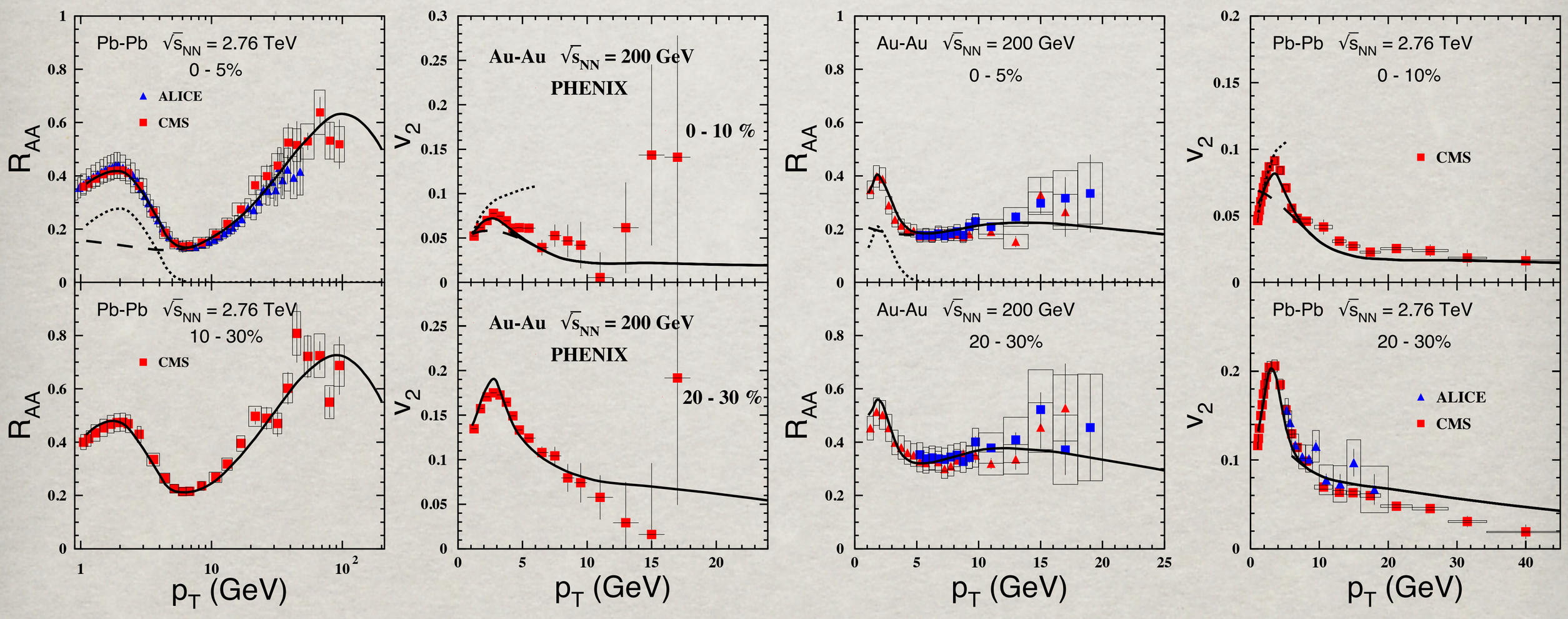
$$\hat{q}_0 \approx 0.5\,\mathrm{GeV}^2/\mathrm{fm}$$

is somewhat smaller than was found from hadron suppression.

J/Psi data are at small $p_T \lesssim 4\,\mathrm{GeV}$

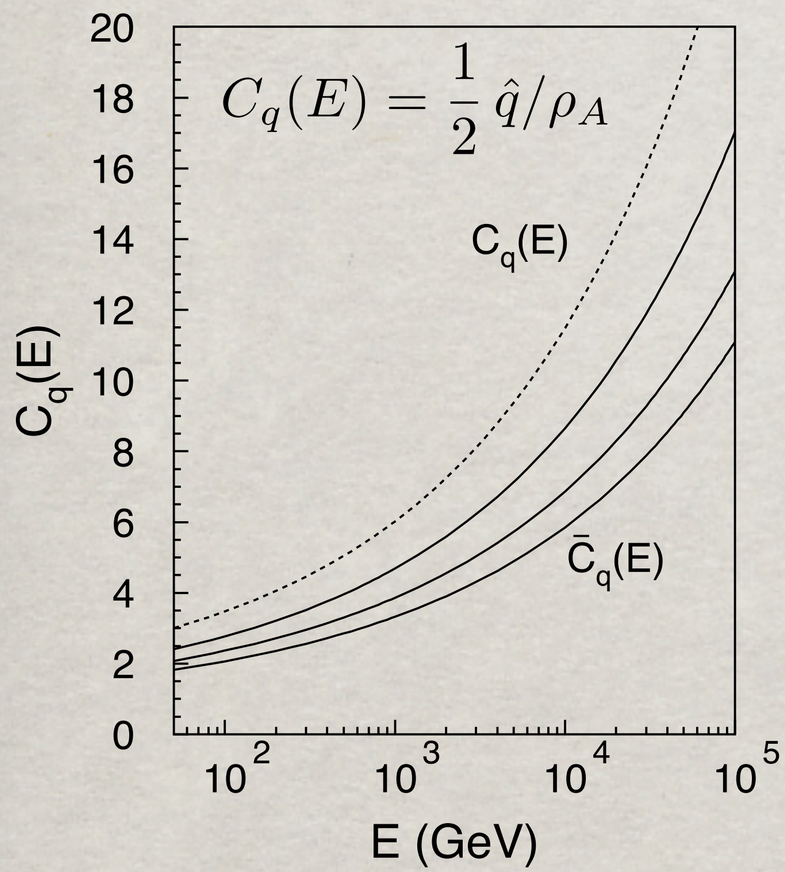
BACKUPS

Merging pQCD and hydrodynamics



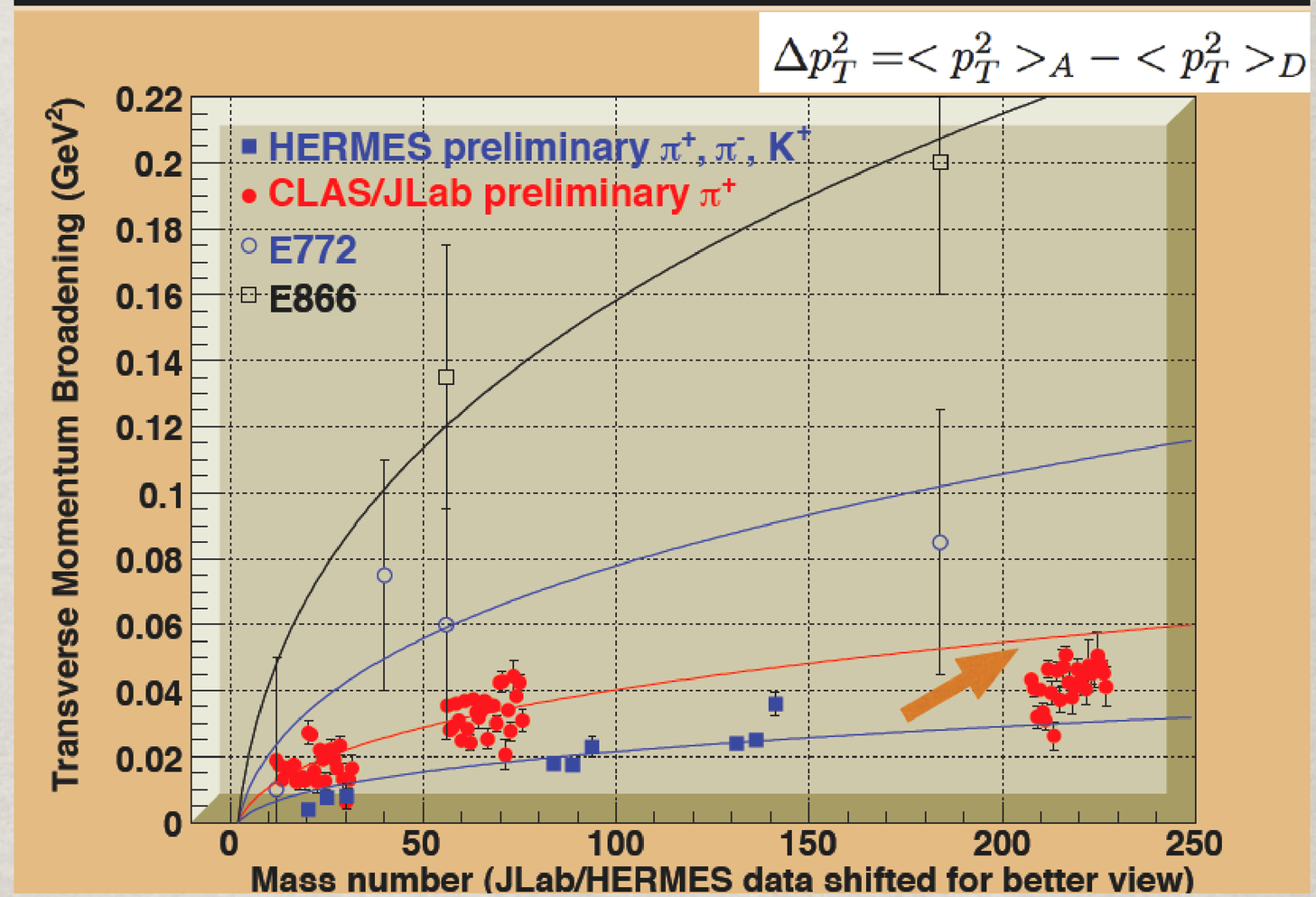
BACKUPS Rising p_T -dependence of $\hat{q}$

$\hat{q}$ in cold nuclear matter rises with energy.



B.K., I.Potashnikova & I.Schmidt
Phys.Rev. C81(2010)035204

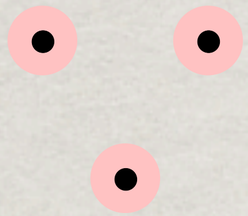
Comparison of p_T broadening data - Drell-Yan and DIS

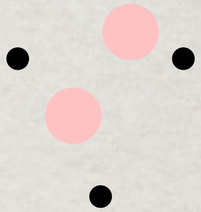


Collection of Will Brooks

BACKUPS

Two-scale hadronic structure





B.K., A.Schafer, A.Tarasov(1999):
the valence quarks carry small size gluon clouds, $r_0 \approx 0.3\mathrm{fm}$

Shuryak & Zakhed (2004):
gluonic spots of small size, $r_0 \approx 0.3\mathrm{fm}$ are floating in the proton.

Small gluonic spots ==> weak gluon shadowing:

$$\left.\frac{G_A(x)}{AG_N(x)}\right|_{x\ll 1} = \frac{2}{\langle\sigma_{GG}(r)\rangle}\int d^2b\left[1-\left\langle e^{-\frac{1}{2}\sigma_{GG}(r)T_A(b)}\right\rangle\right] = 1-\frac{3C}{8}\,r_0^2\,\rho_A R_A + \ldots \approx 0.8$$

Even if small-x gluons overlap in the longitudinal direction, they can miss each other in transverse plane, if they are located within small spots. Indeed, for a heavy nucleus (lead) the mean number of gluonic spots overlapping with a given one is,

$$\langle n\rangle = \frac{3\pi}{4}\,r_0^2\,\langle T_A\rangle = \pi\,r_0^2\,\rho_A\,R_A = 0.3$$

String model

A quark initiating a jet is decelerated by a string with a constant rate of energy loss equal to the string tension

$$-\frac{\mathbf{dE}}{\mathbf{dl}} = \kappa = \mathbf{1\,GeV/fm}$$

In order to respect energy conservation the last string break must happen sufficiently early, otherwise the quark energy will drop below the energy of the final hadron $\mathbf{E_h = z_h E}$

$$\mathbf{l_p \leq \frac{E}{\kappa}(1 - z_h)}$$

B.K., F.Niedermayer, 1983

A.Bialas, M.Gyulassy, 1987

E.g. for $\mathbf{E = 10\,GeV}$ and $\mathbf{z_h = 0.8}$ hadronization ceases at $\mathbf{l_p \leq 2\,fm}$

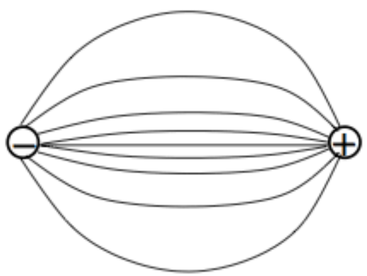
The nonperturbative static string model is too oversimplified to be a realistic description for hard reactions.
Perturbative effects are essential.

Energy loss in vacuum

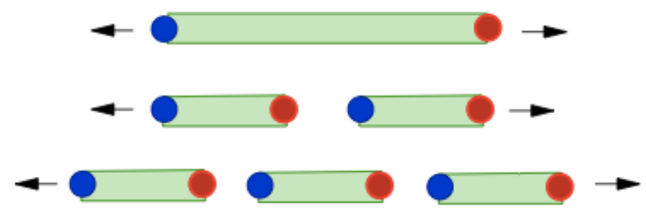
A long production time for a leading hadron carrying a large fractional momentum z_h may get in conflict with energy conservation, which constraints the magnitude of l_p.

Example of constraints on l_p: string model.

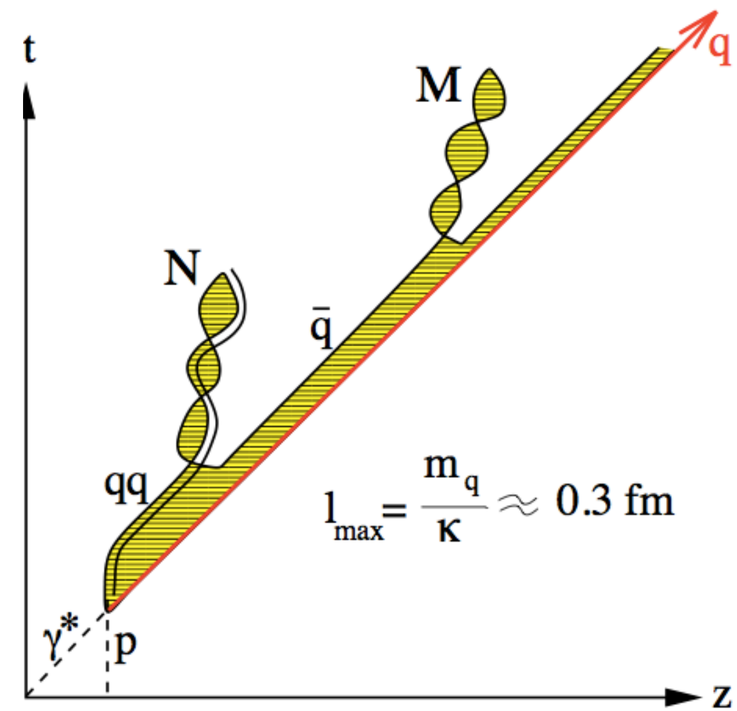
$V(r) = \frac{\alpha}{r}$ QED



QCD $V(r) = \kappa\, r$



Schwinger phenomenon
quark tunnelling from vacuum



Energy of the string per unit of length, string tension

$$\kappa = \frac{1}{2\pi\alpha'_R} \approx 1\ \mathrm{GeV/fm}$$