Charmonium production off nuclei: from SPS to RHIC

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Heidelberg

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from SPS to RHIC

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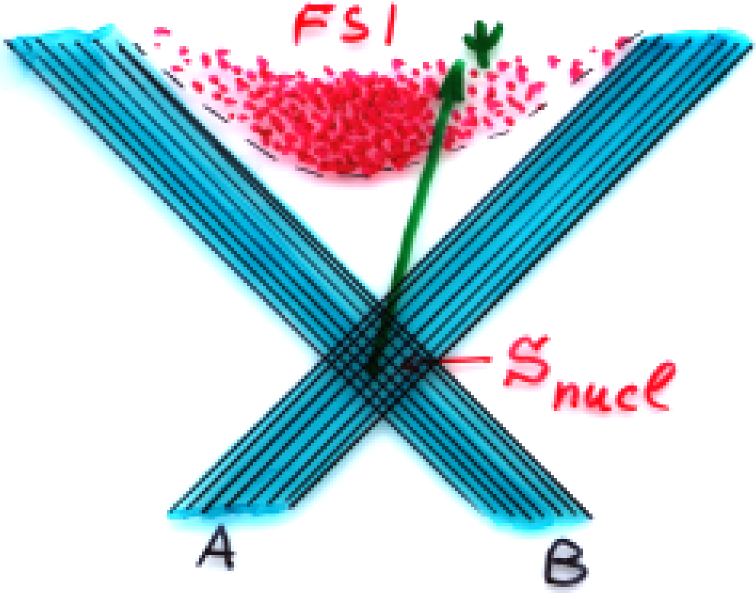
Charmonium suppression as a probe for QGP



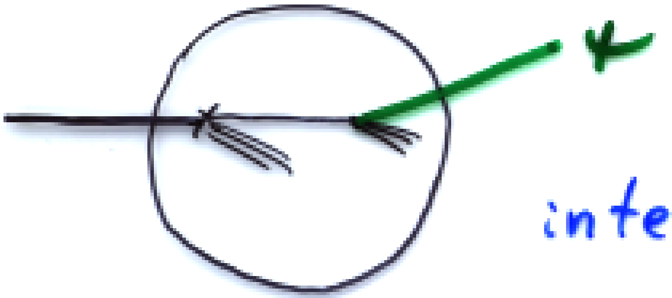
$$S^{\psi}_{AB} = \underset{\substack{\Uparrow\\ \text{The base line}}}{S_{nucl}} \times \underset{\substack{\Uparrow\\ \text{The probe}}}{S_{FSI}}$$

S_{nucl} is still the main source of suppression, one desperately needs to understand it.

First of all, in pA collisions

Nuclear effects at SPS

1. Absorption



Initial state interaction is assumed to have no effect

$$S_{pA}^{\psi} = \frac{\sigma_{pA}^{\psi}}{A\,\sigma_{pN}^{\psi}} = \int d^2b \int_{-\infty}^{\infty} dz\, \rho_A(b,z)\, e^{-\sigma_{abs}^{\psi N} \int_{z}^{\infty} dz'\, \rho_A(b,z')}$$

$$S_{pA}^{\psi} < 1$$

Does this simple model which misses many important effects, indeed describes data for ψ suppression in pA collisions?

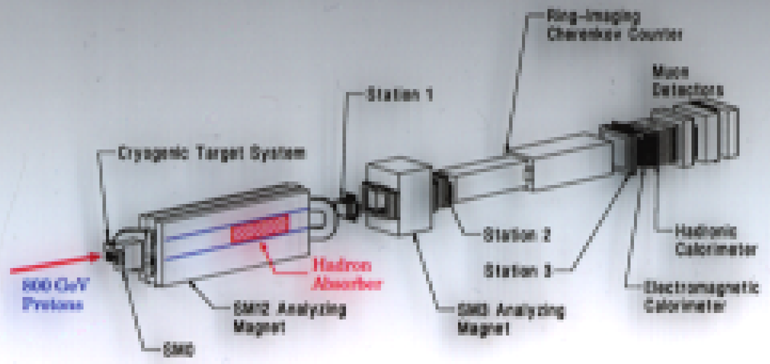
Certainly not!

No x_F-dependence is predicted in a strict contradiction with data.

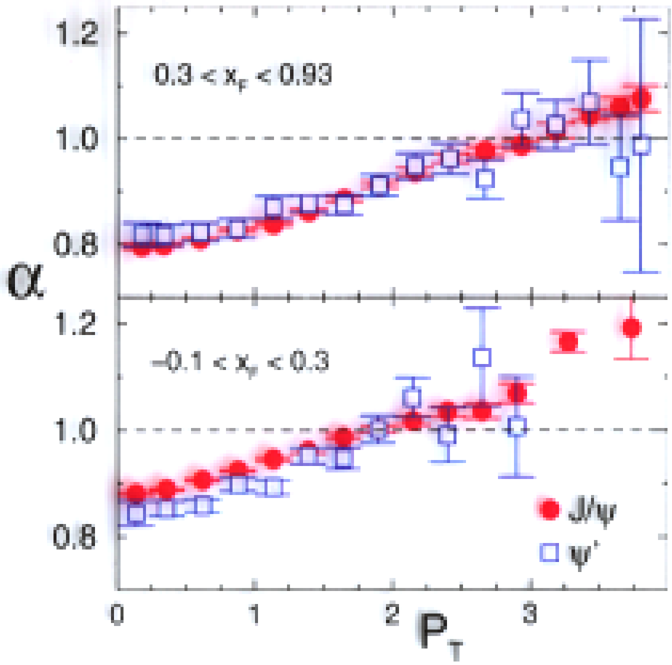
Nuclear Dependence of J/ψ and ψ' Production in 800 GeV/c p-A Collisions

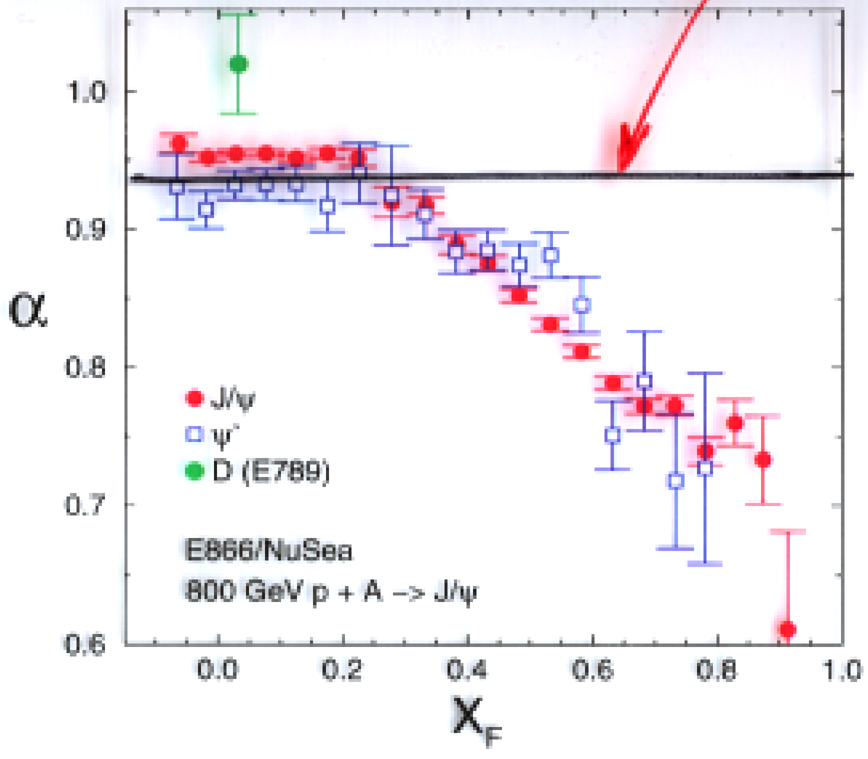
FNAL E866/NuSea

ACU, ANL, FNAL, GSU, IIT, LANL, LSU,
NMSU, UNM, ORNL, TAMU, Valpo.



$$\sigma_A = \sigma_p * A^\alpha$$

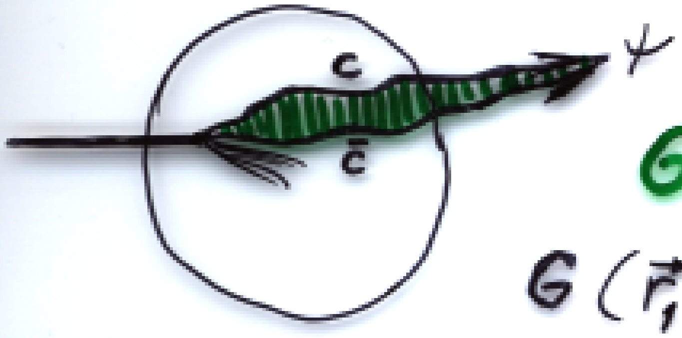




absorption model

2. Formation time effects

B. K.,
B. Zakharov
PRD44 (1991) 3466



Green function

$$G(\vec{r}_1, z_1; \vec{r}_2, z_2)$$

Describes the propagation of a $c\bar{c}$ pair with initial separation $\vec{r}_1$ at the longitudinal coordinate z_1 up to the final $\vec{r}_2$ at z_2.

at fixed energy of ψ the absorption cross section (effective) varies between

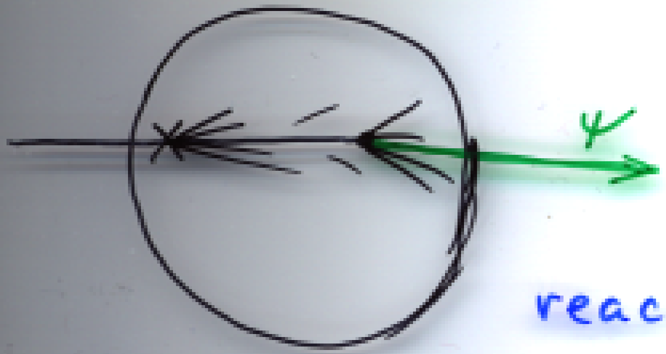
$$\sigma_{eff} = \frac{\langle \sigma^2_{q\bar{q}}(r) \rangle}{\langle \sigma_{q\bar{q}}(r) \rangle} \approx 3.5 \text{ mb}$$

for light nuclei, up to

$$\sigma_{eff} \simeq 5.8 \text{ mb}$$

for very large nuclei (corrected for ψ' and χ decays).

3. Energy loss



Similar to Drell-Yan reaction, initial state interactions lead to energy loss by the incident partons precedin production of Ψ. It results in an extra suppression of the Ψ production rate, especially at large x_F.

The recent analysis of the E772/866 data gives the rate of energy loss

★ $$-\frac{dE}{dz} = 2.3 \pm 0.52 \pm 0.5 \ \frac{\mathrm{GeV}}{\mathrm{fm}}$$

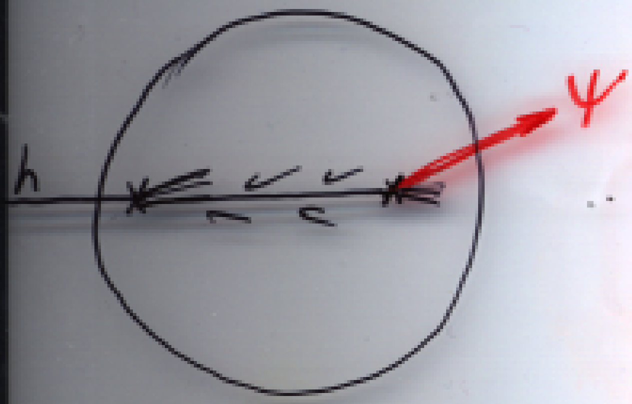
M. Johnson
et al.
hep-ex/0010051

Manifestations of energy loss

- Charmonium (Drell-Yan pair) production off nuclei:

The pojectile hadron interacts inelastically on the nuclear surface, and this is a start for hadronization.

B.K. &
F. Niedermayer
1984



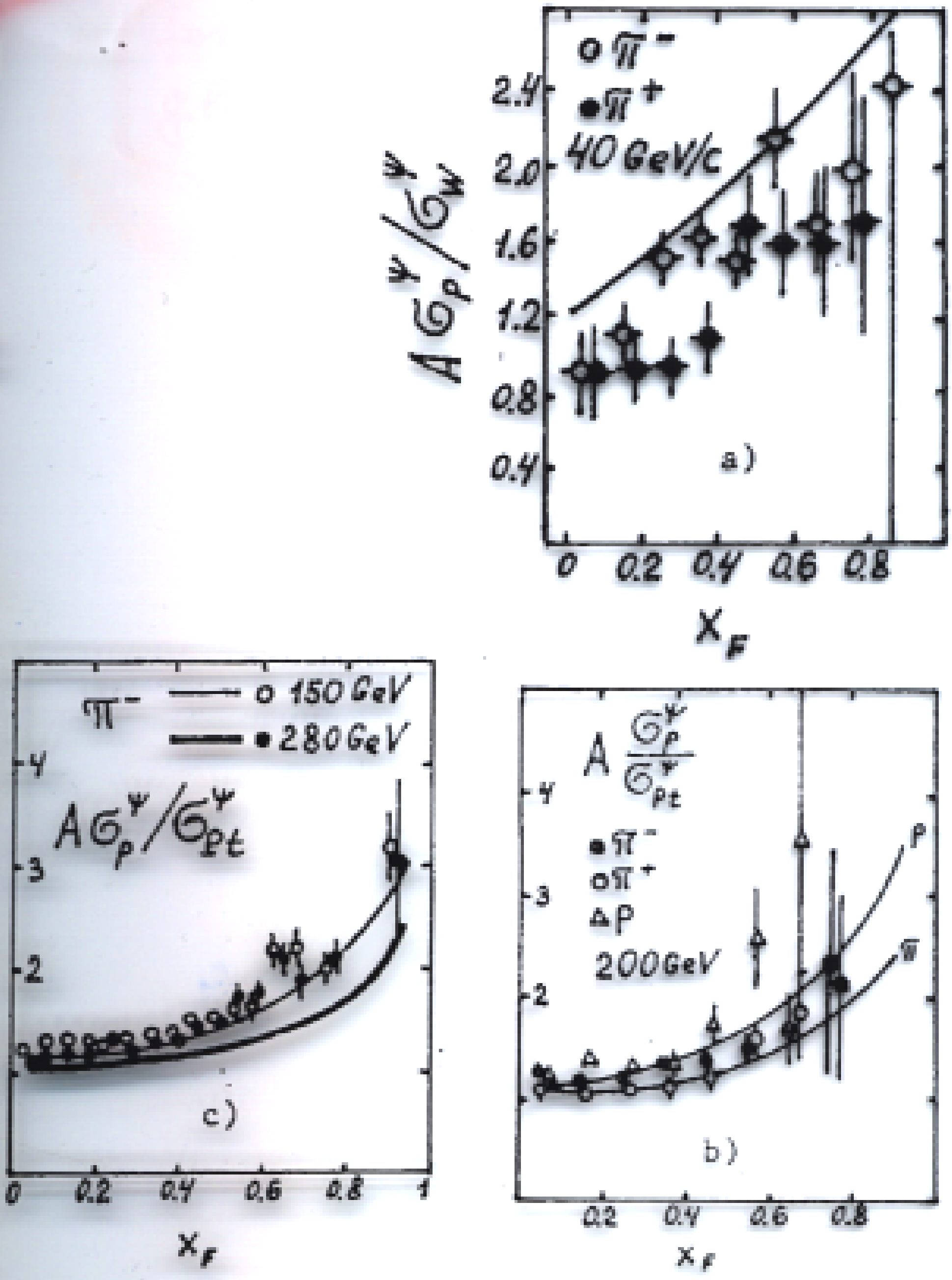
$$\frac{dE}{dz} = -3\ \text{GeV/fm}$$

$$\tilde{E} = E - \varkappa \Delta Z$$

$$\Delta X_1 = -\frac{\varkappa \Delta Z}{E}$$

[illegible] E772 data for DY at 800 GeV

$\varkappa \sim 1 \pm 1\ \frac{\text{GeV}}{\text{fm}}$



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E537

S. Katsanevas e.a.

PRL 60(1988)2121

B.K.
F. Niedermayer
1984

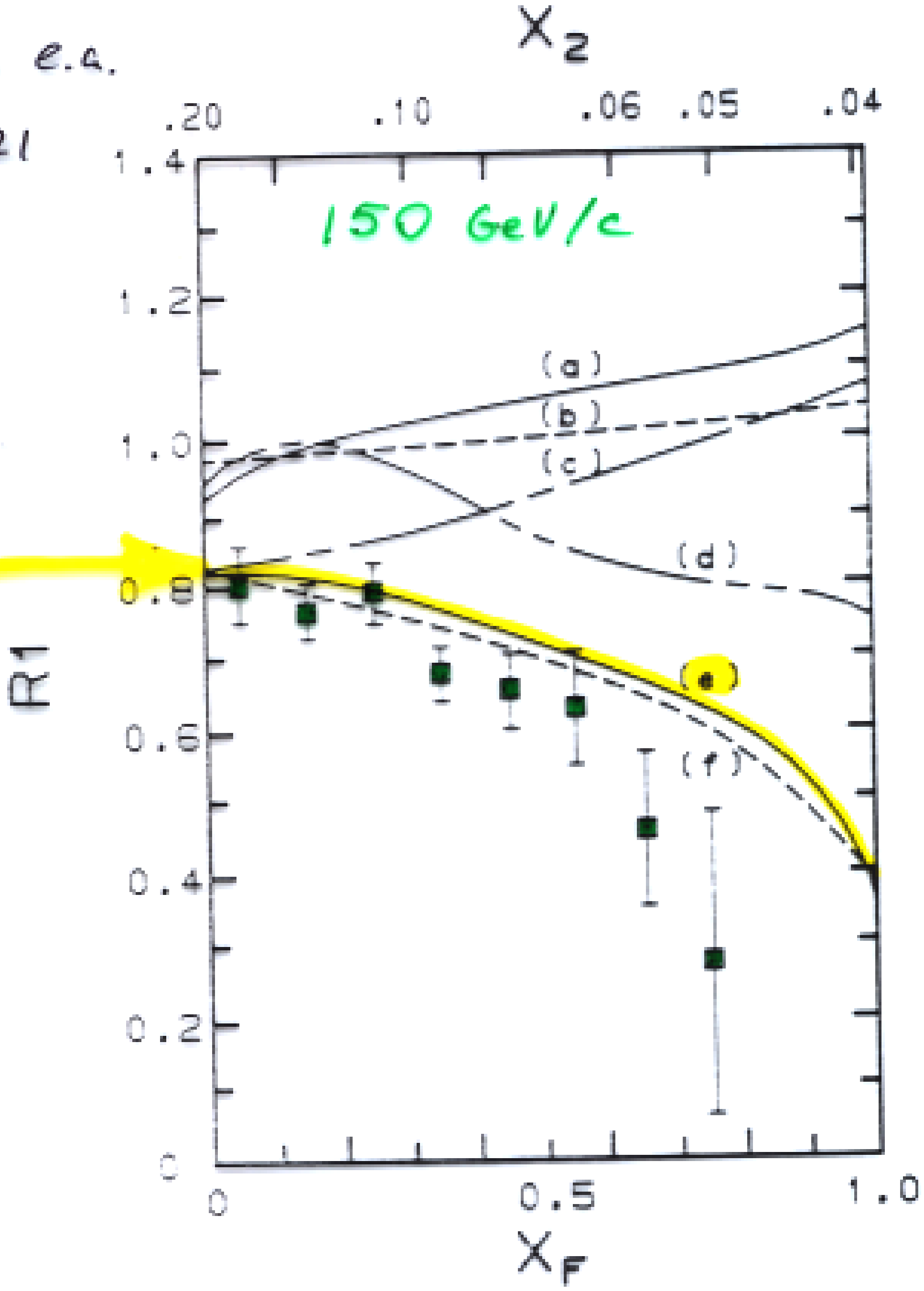

FIG. 5. Comparison of the ratio $(A^{-1}d\sigma/dx_F)$ for π^-W to π^-Be to various models: curve *a*, soft-π model; curve *b*, rescaling model; curve *c*, six-quark model; curve *d*, shadowing model; curve *e*, rescattering model; and curve *f*, three-gluon-fusion model without $q\bar{q}$ contributions.

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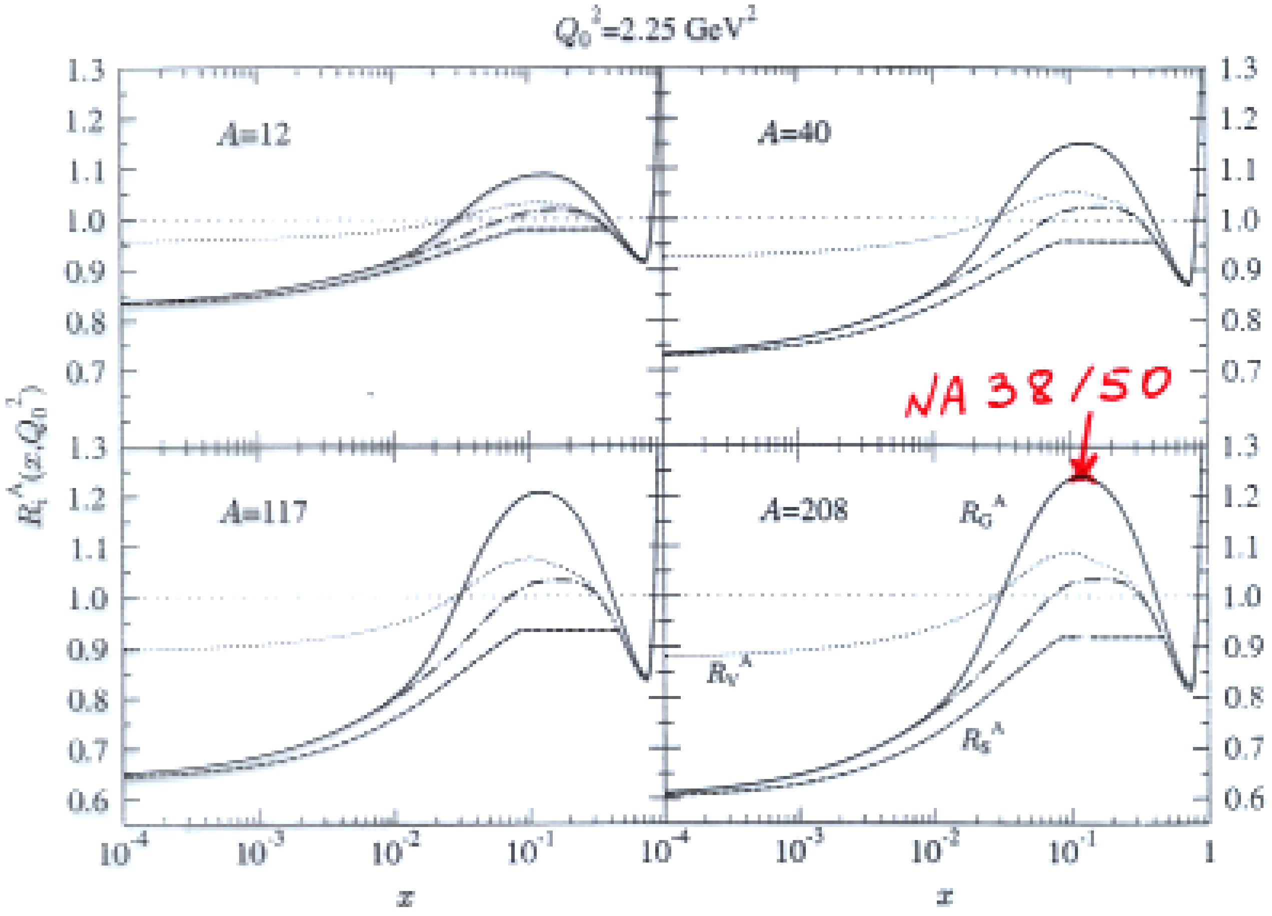
4. Gluon antishadowing at large x_2

$$\frac{\sigma^{\psi}_{pA}}{\sigma^{\psi}_{pN}} \propto \frac{G_A(x_2)}{G_N(x_2)}$$

$$x_2 \approx \frac{M_{\psi}^2}{s x_1} = \frac{M_{\psi}^2}{2 m_N E_{\psi}} \approx \boxed{0.1}$$

Gluons are expected to be enhanced by 10-20% in heavy nucley

K. Eskola
V. Kolhinen
P. Ruuskanen



NA 38/50

Figure 2: The initial nuclear ratios $R_G^A(x,Q_0^2)$ (solid line), $R_V^A(x,Q_0^2)$ (dotted) and $R_S^A(x,Q_0^2)$ (dashed) for isoscalar nuclei at $Q_0^2 = 2.25$ GeV^2. The ratio $R_{F_2}^A(x,Q_0^2)$ (dotted-dashed) is also shown.

L. Frankfurt
M. Strikman
Eur. Ph. J. A5 (1999) 293

NA38/50

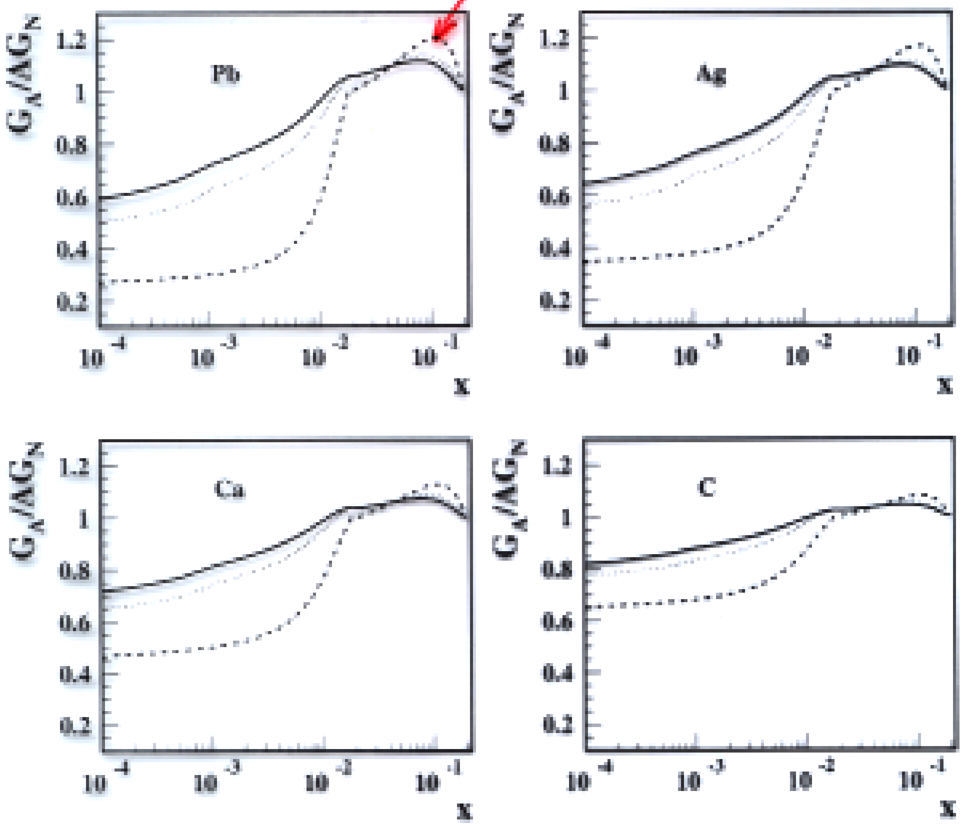


FIG. 4. Dependence of G_A/AG_N on x for Q=2,5,10 GeV (dashed, dotted, solid curves) calculated in the quasieikonal model.

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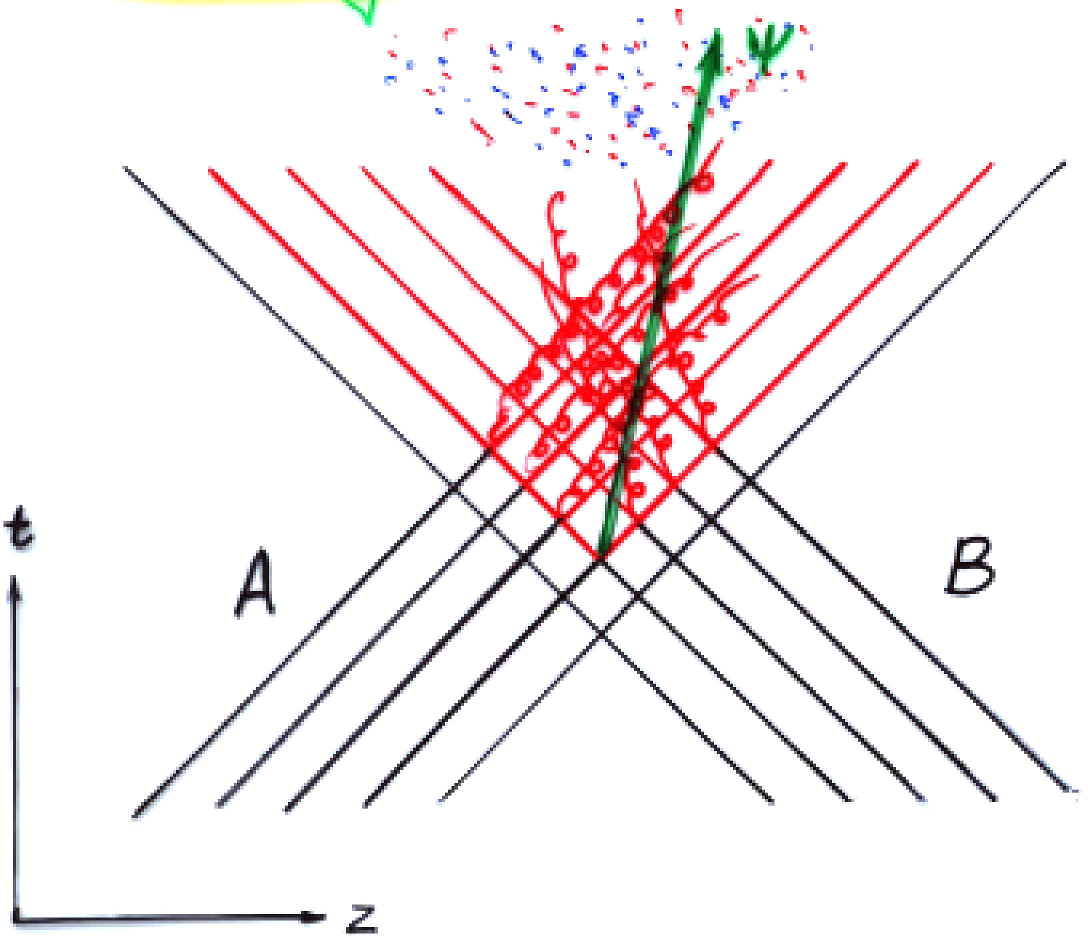
5. Excitation of nuclear matter in heavy ion collisions



J. Hüfner & B.K.

J. Hüfner
B.K.
& A. Polleri

Each nucleon crossing the Ψ trajectory has already interacted and is colored.

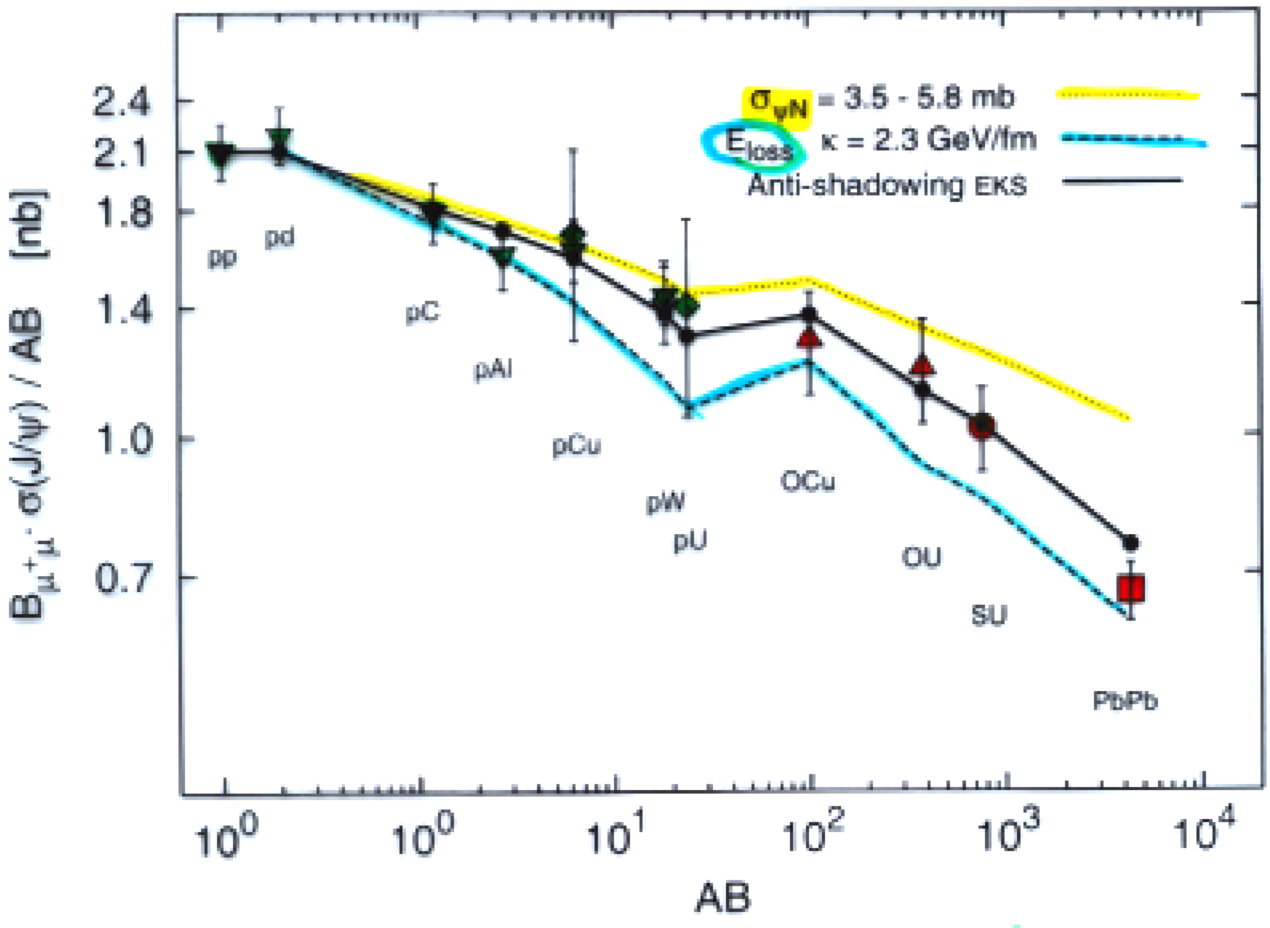
In addition the radiated gluons (those who lost coherence with the source) also contribute t the break up of the Ψ.

This is a very nonlinear effect.
It is practically absent for pA or light nuclei

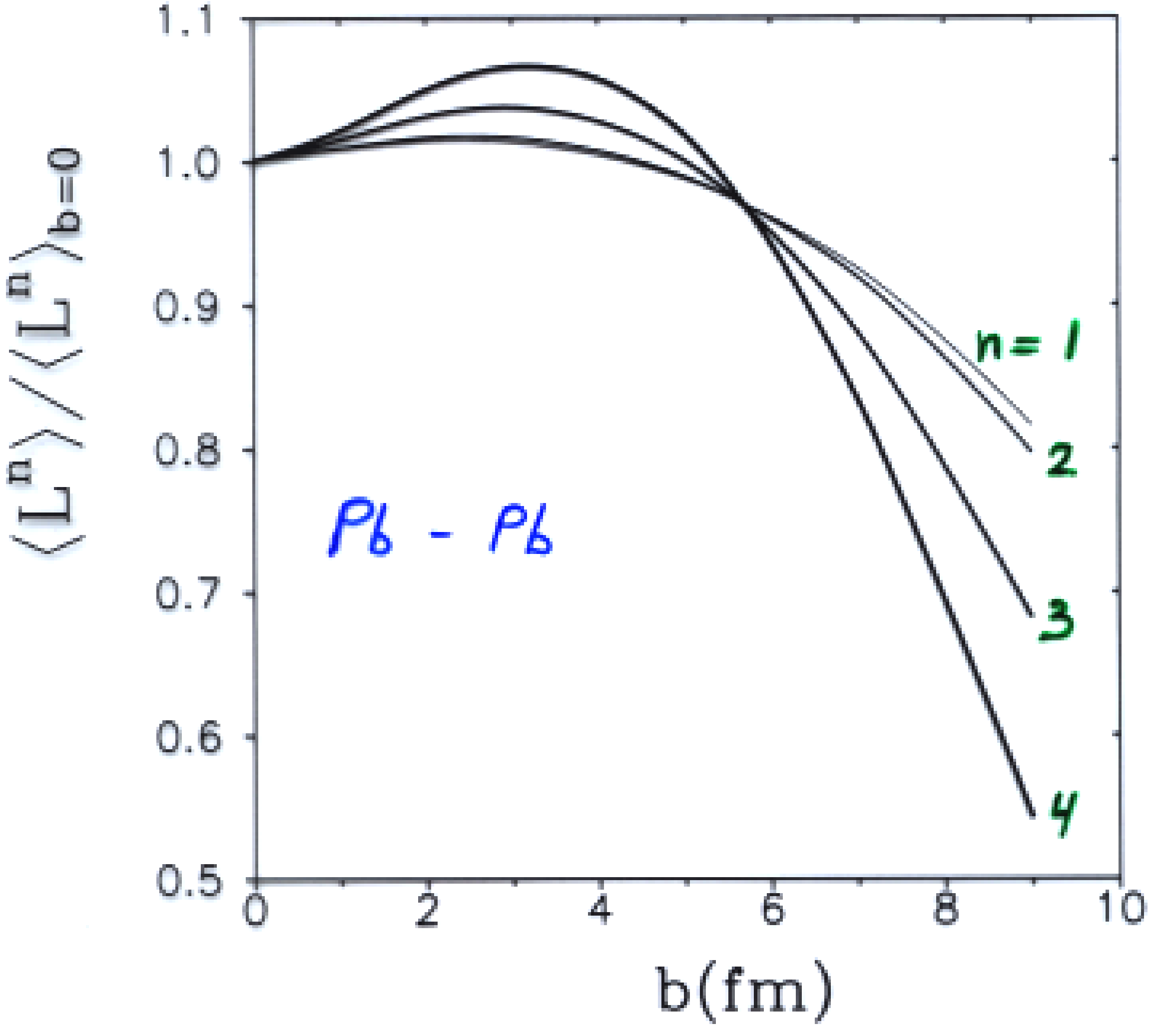
Presence of all these effects is undisputable. However, the amount of theoretical uncertainty varies and more work is needed.

Most of the effects are nonlinear and grossly enhanced for heavy nuclei:

J. Hüfner
B. K.
A. Polleri:

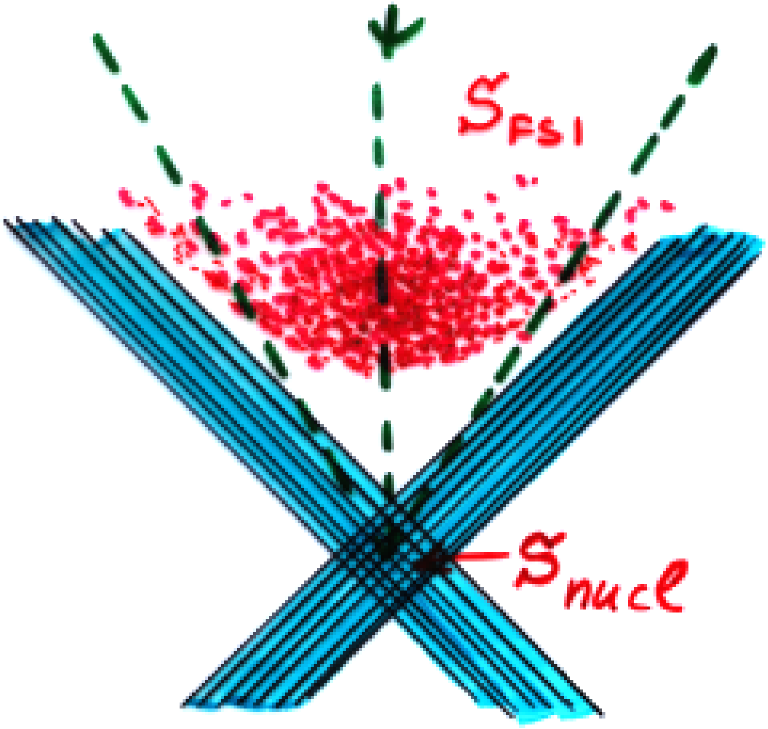


The above effects depend only on the nuclear thickness function and can provide only a flat or even rising E_T-dependence for central collisions.



The falling E_T dependence of Ψ suppression signals about interaction with the produced matter, comoving hadrons, QGP ...

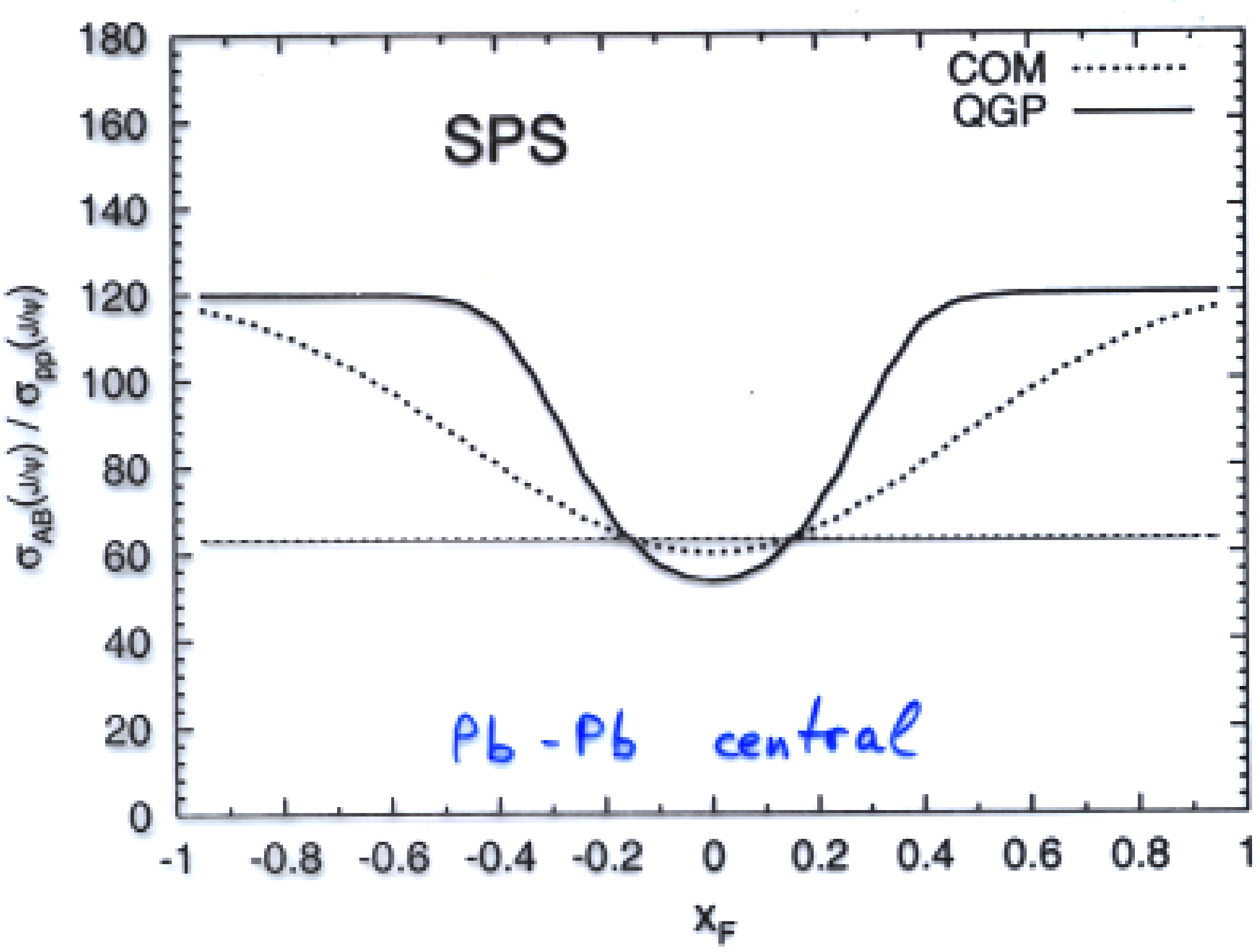
Scanning the QGP

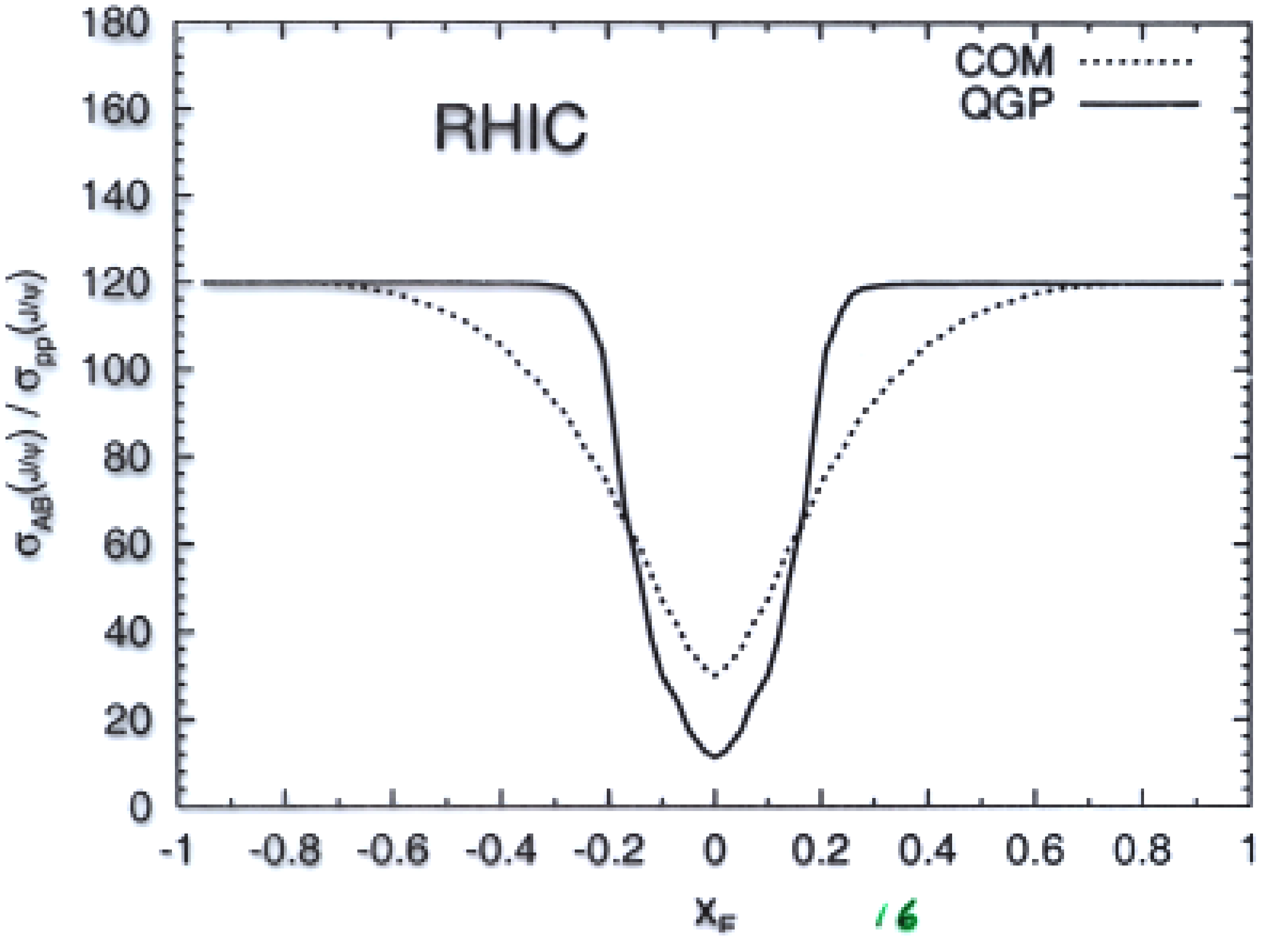


$$S_{AB}^{\psi} = S_{nucl} \times \boxed{S_{FSI}}$$

Varying x_F one scans different areas of the produced medium which is expected to be most dense at $x_F = 0$

J. Hüfner
B.K.
A. Polleri:





RHIC

J. Hüfner
B. K.
A. Tarasov

Many of the effects under discussion are gone (energy loss, formaton time effects, promt gluons)

a new phenomenon becomes the main source of nuclear suppression of Ψ, **shadowing**.

Shadowing for quarks and gluons.
Partonic interpetation is not Lorentz invariant, only observables are.

Parton model
(fusion)

Light-cone (Gribov's) formulation
(multipe interaction of Fock states)

quark shadowing gluon shadowing

(A. Mueller)

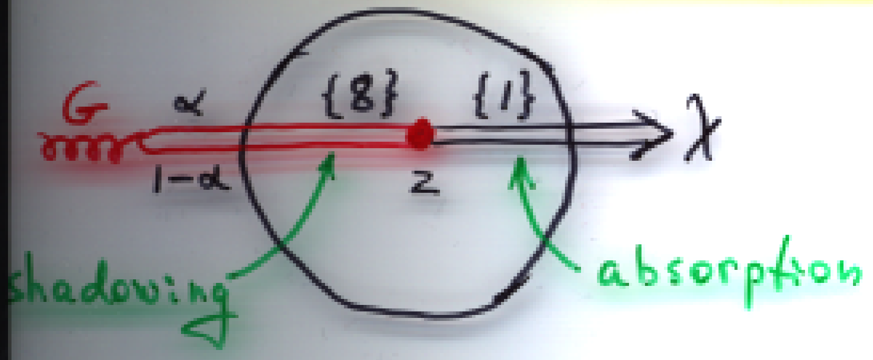
★ Hadroproduction of charmonia

still ambiguous

How to calculate shadowing ?

① $l_c = \frac{2E_\chi}{M_\chi^2} \gg R_A$

J. Hüfner
B.K.
A. Tarasov



B.K.
Al. Zamolodchikov
1980

$$\sigma(GA\to\chi X) = \int d^2b \int_{-\infty}^{\infty} dz\, \rho_A(b,z)\, |A(b,z)|^2$$

$$A(b,z) = \int_0^1 d\alpha \int d^2r_T\, \underset{?}{\Phi^*_\chi(r_T,\alpha)}\, \hat{A}(b,z,\vec{r}_T,\alpha)\, \underset{?}{\Phi_G(\vec{r}_T,\alpha)}$$

$$\hat{A}(b,z,r_T,\alpha) = \exp\left[-\tfrac{1}{2}\overset{?}{\sigma_{abs}(\vec{r}_T)}\, T_+(b,z)\right] (\vec{e}_T\cdot\vec{d})$$

$$\times \exp\left[-\tfrac{1}{2}\underset{?}{\sigma_{shad}(r_T,\alpha)}\, T_-(b,z)\right]$$

$\sigma_{abs}(r_T) = \sigma^N_{q\bar{q}}(r_T, s)$ - the universal dipole cross section

$\propto r_T^2 \; (r_T \to 0)$

Well fixed by DIS data $\sigma^N_{q\bar{q}} = \sigma_0(s)\left(1 - e^{-\frac{r_T^2}{r_0^2(s)}}\right)$

G-B&W

KST

$\sigma_{shad}(r_T, \alpha) = ?$

What is the cross of $c\bar{c}$ production by a gluon ?

The gluon has two Fock components

$$|G\rangle = |G\rangle_0 + |\bar{c}c\rangle$$

$\bar{c}c$ can be produced only due to difference between the amplitudes for $|G\rangle_0$ and $|c\bar{c}\rangle$

$\sigma^{G\to\bar{c}c}(r_T, \alpha) = \Big|$  $\Big|^2 =$

$= \sum$  $= \sigma^N_{q\bar{q}G}(r_T, \alpha)$

$\sigma_{shad}(r_T, \alpha) = \sigma^N_{q\bar{q}G}(r_T, \alpha) = \frac{9}{8}\left[\sigma^N_{q\bar{q}}(\alpha r_T) + \sigma^N_{q\bar{q}}((1-\alpha) r_T)\right] - \frac{1}{8}\sigma^N_{q\bar{q}}(r_T$

$\simeq \frac{7}{16}\,\sigma(r_T)$

$\Phi_G(\vec r_T,\alpha)$ is different from the photon wave function only by a factor

$$\Phi_G^{\bar\mu\mu}(r_T,\alpha) = \frac{\sqrt{2\alpha_s}}{4\pi}\,\xi_c^{\mu\dagger}\,\hat O\,\tilde\xi_{\bar c}^{\bar\mu}\,K_0(m_c r_T)$$

$$\hat O = m_c\vec\sigma\cdot\vec e + i(1-2\alpha)(\vec\sigma\cdot\vec n)(\vec e\,\vec\nabla_T) + (\vec e\times\vec n)\vec\nabla_T$$

$\Phi_\chi(\vec r_T,\alpha)$ is related by the Lorentz boost to the χ wave function in the rest frame

J. Hüfner
Yu. Ivanov
B.K.
A. Tarasov
PRD
62(2000)094022

$$\Phi_\chi^{\mu\bar\mu}(p_T,\alpha) = \sqrt{\frac{\partial p_L(p_T,\alpha)}{\partial\alpha}}\;\Psi_\chi^{\mu\bar\mu}(\vec p=\vec p_T+p_L\vec n)$$

LC wave function rest frame

$$p_L = (\alpha-\tfrac{1}{2})\,M_{c\bar c}(p_T,\alpha)\,;\qquad M_{c\bar c}^2 = \frac{m_c^2+p_T^2}{\alpha(1-\alpha)}$$

Important is the Melosh spin rotation

The spin part: $S_{1,m}^{\mu\bar\mu} = \frac{1}{\sqrt2}\,\xi_c^{\mu\dagger}\,\vec\sigma\cdot\vec e_m\,\tilde\xi_{\bar c}^{\bar\mu}$

LC

$$\xi_c^{\mu} = \hat R(\vec p_T,\alpha)\,\eta_c^{\mu}$$

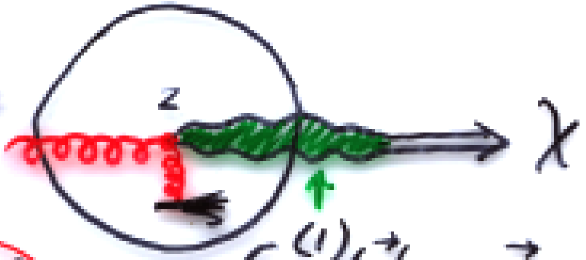
rest frame

$$\xi_{\bar c}^{\bar\mu} = \hat R(-\vec p_T,1-\alpha)\,\eta_{\bar c}^{\bar\mu}$$

$$\hat R(\vec p_T,\alpha) = \frac{m_c+\alpha M_{c\bar c}-i\vec\sigma\cdot(\vec n+\vec p_T)}{\sqrt{(m_c+\alpha M_{c\bar c})^2+p_T^2}}$$

General case, no restrictions for ℓ_i, ℓ_f

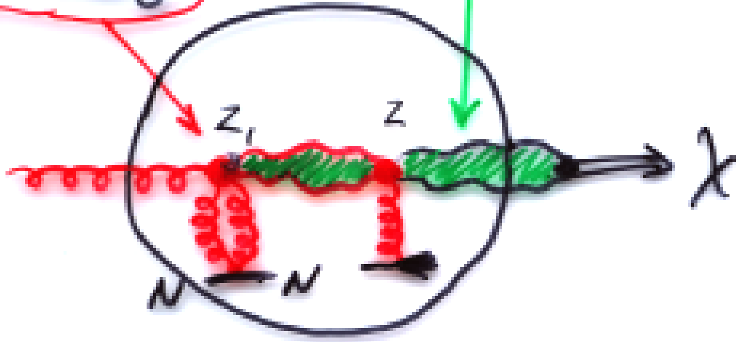
$A(GA\to\chi X) =$



$G^{(1)}(\vec r_T{}', z; \vec r_T, z_+)$

$$q_L \approx \frac{m_\chi^2}{2E_G}$$

$-$



$G^{(8)}(\vec r_T{}'', z_1; \vec r_T{}', z)$

$$i\frac{d}{dz} G^{(k)}(\vec r_T, z; \vec r_T{}', z') = \left[\frac{-\Delta_T + m_c^2}{2p_G\,\alpha(1-\alpha)} + V^{(k)}(\vec r_T,\alpha)\right] \times G^{(k)}(\vec r_T, z; \vec r_T{}', z')$$

$$\mathrm{Im}\, V^{(k)}(\vec r_T,\alpha) = -\frac{1}{2}\,\sigma^{(k)}(r_T,\alpha)\,\rho_A(b,z)$$

$$\begin{cases} \sigma^{(1)}(r_T,\alpha) = \sigma_{abs}(r_T,\alpha) \\ \sigma^{(8)}(r_T,\alpha) = \sigma_{shad}(r_T,\alpha) \end{cases}$$

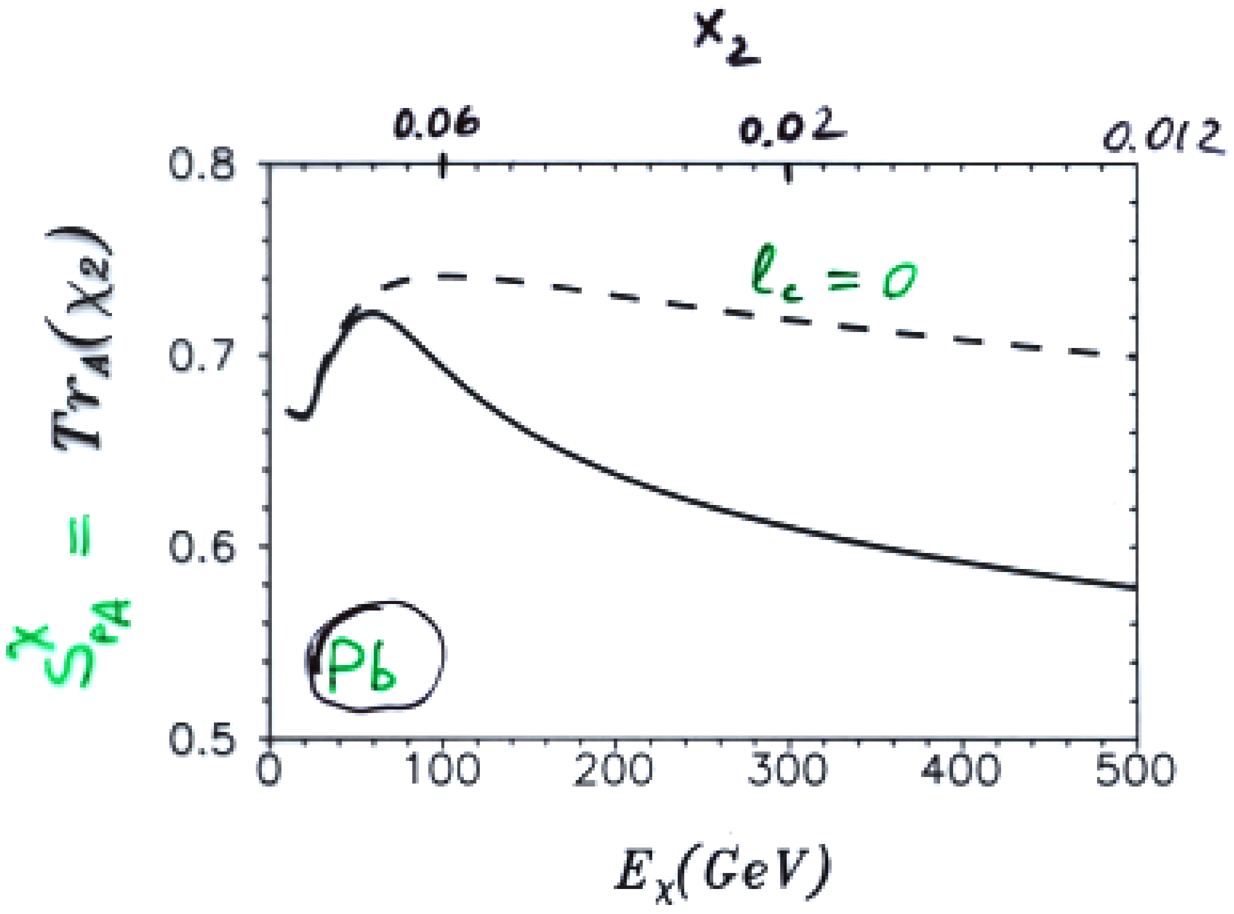
$$\mathrm{Re}\, V^{(8)} = 0; \quad \underbrace{\mathrm{Re}\, V^{(1)} = \frac{a^4(\alpha)\, r_T^2}{2p_G\,\alpha(1-\alpha)}}$$

$$a^2(\alpha) = 4\alpha(1-\alpha)\,\omega\,\frac{m_c}{2}$$

Both shadowing and absorption depend only on the energy of χ

$$E_\chi = x_1 E_p = \frac{M_\chi^2}{2m_N x_2}$$

x_2 scaling



One cannot borrow quark shadowing from DIS ($F_2^A(x)/F_2^N(x)$).

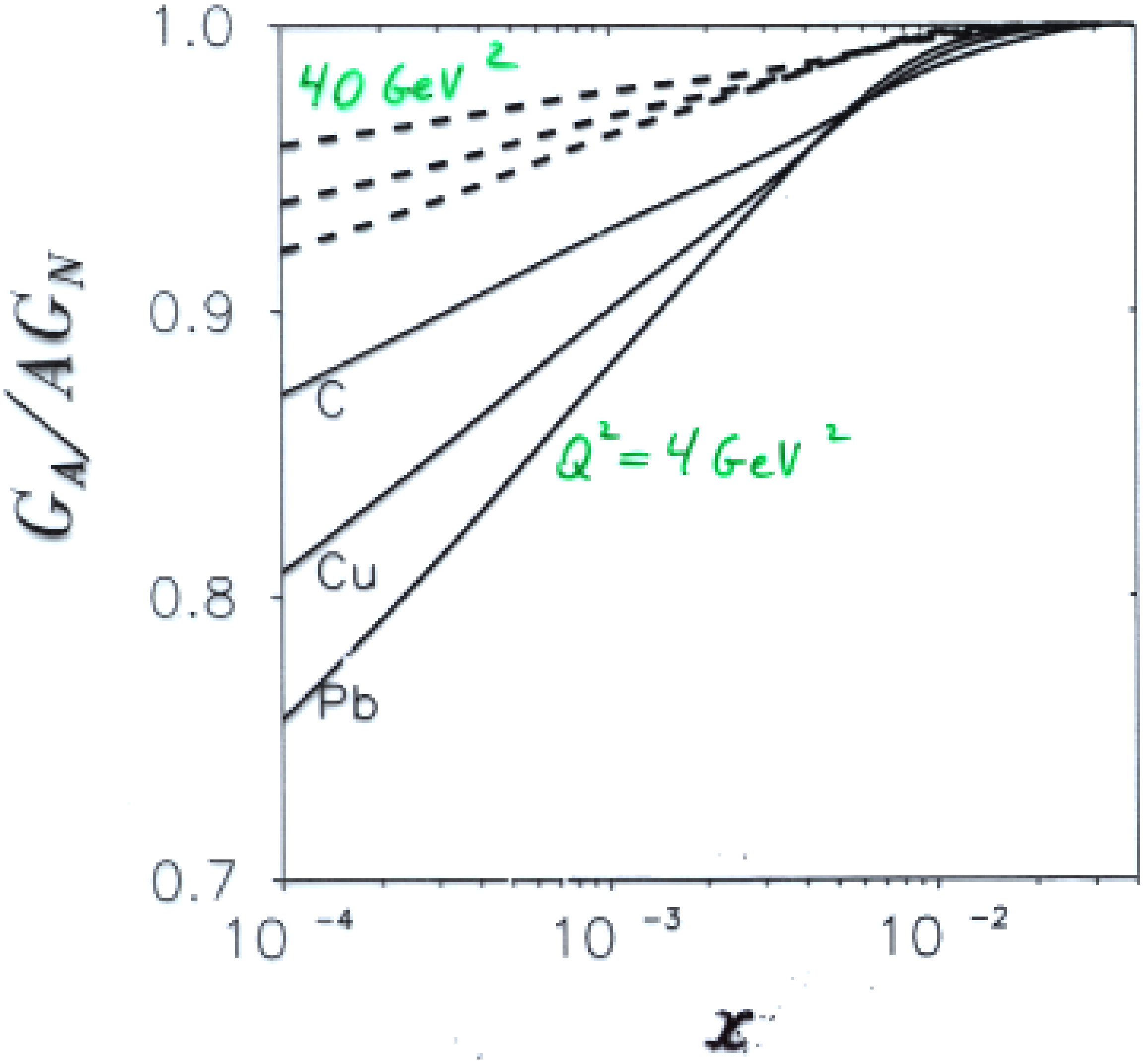
No QCD factorization for production of colorless states.

Gluon shadowing

B. K.
A. Schäfer
A. Tarasov

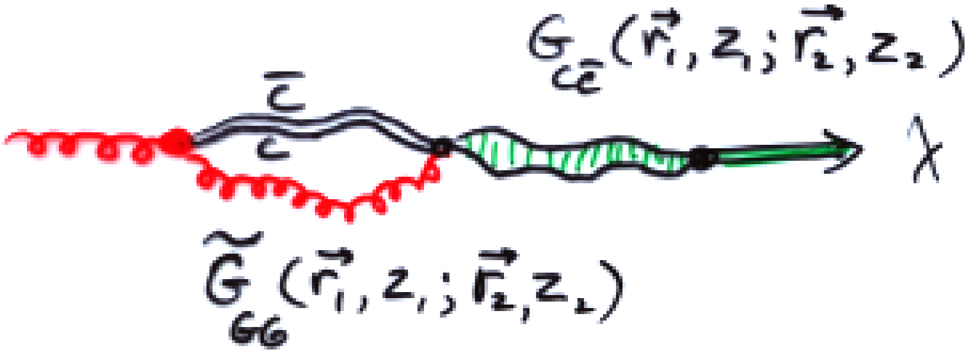
DIS :

The strong nonperturbative interaction between $(q\bar{q})_8$ and G squeezes the wave packet down to the size $r_0 \sim 0.3$ fm



Rather weak gluon shadowing in DIS

No nonperturbative gluon interaction contributes if a colorless state is produced.



The modified Green function: $\mathrm{Re}\, V = 0$

The effective shadowing cross section

$$\sigma_{shad} \approx 7\,mb \quad \Rightarrow \quad \sigma_{shad} \approx 50\,mb$$

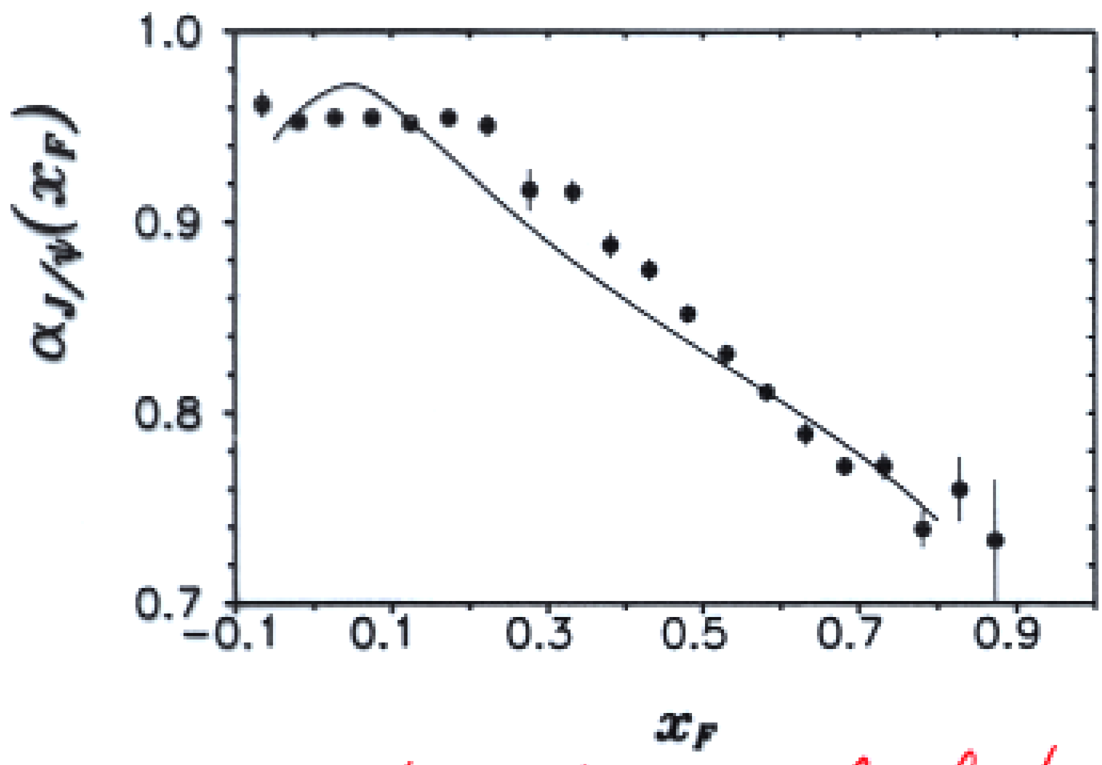
DIS   Charmonium production

Dramatic violation of the QCD scaling!

The onset of shadowing has been observed by the E772/E866 experiments at Fermilab.

Effects involved:

- shadowing, both quark and gluon
- gluon antishadowing at large x_2 (EKS)
- energy loss
- formation time effects
- energy dependence of $\sigma_{tot}^{\chi N}(s)$
- decay $\chi \rightarrow J/\psi + \gamma$



a parameter free calculation

Again, scales in x_2

at low energies x_2 scaling is broken by energy loss.

Conclusions

- The oversimplified absorption model used at the SPS energies misses many important nonlinear effects.
- A complementary study of the x_F-dependence of charmonium suppression should provide new important information about the properties of the produced medium.
- A light cone QCD approach is developed which incorporates the effects of absorption and shadowing
- Shadowing becomes a dominant effect at RHIC increasing nuclear suppression by a factor of few. x_2 scaling is predicted