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Forward Physics in Proton-Nucleus and Nucleus-Nucleus Collisions.

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Forward Physics in Proton-Nucleus and Nucleus-Nucleus Collisions

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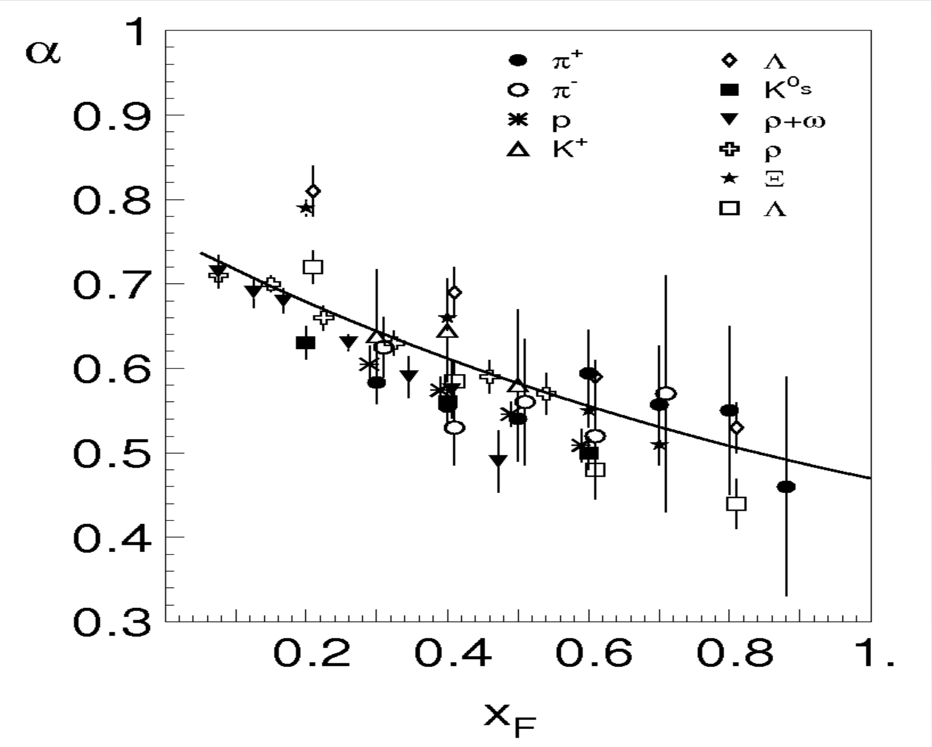
OUTLINE

- Energy sharing effects at the kinematic limit and breakdown of QCD factorization
- Discussion of nuclear effects in:
  - —— soft hadron production
  - —— hadron production at large η in p(d)-A collisions
  - —— NA49 data
  - —— direct photon production in A-B collisions
  - —— inclusive hadron production at $\eta = 0$
  - —— Drell-Yan reaction
- Summary & Outlook

Reactions at large x_F

PRODUCTION OF LEADING HADRONS WITH SMALL p_T



Exponent describing the A dependence $(\propto A^{\alpha})$ of the nucleus-to-proton ratio for production of different hadrons as a function of x_F

Reactions at large x_F

PRODUCTION OF LEADING HADRONS WITH SMALL p_T

— data for production of different hadrons in pA collisions

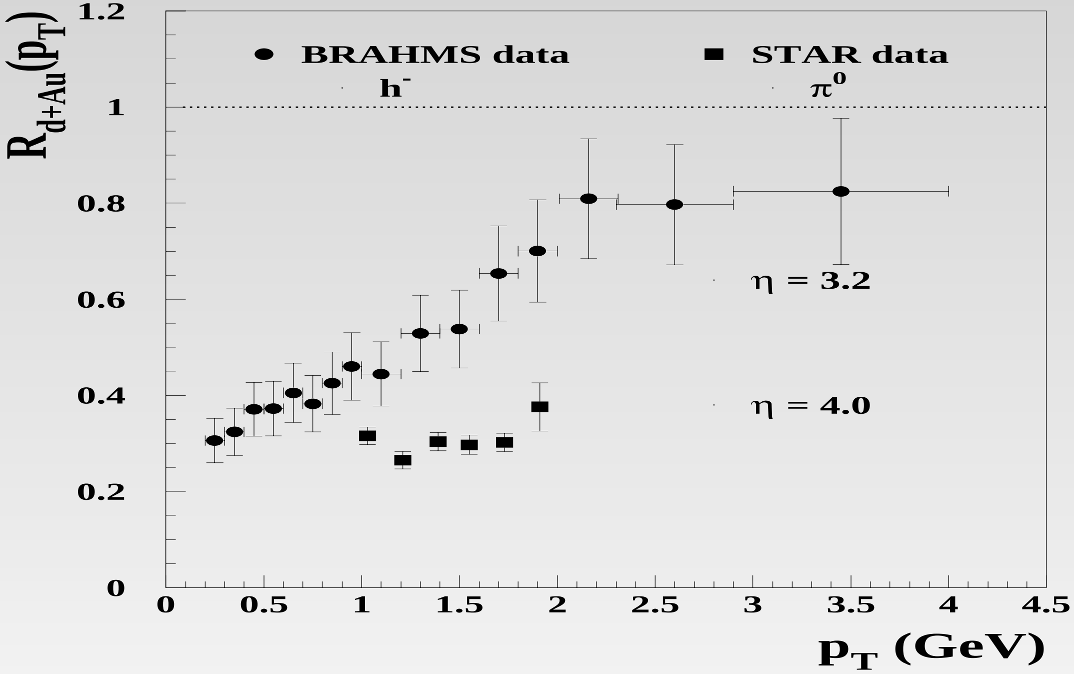
*** exhibit quite strong and universal nuclear suppression at large x_F

*** data covering the laboratory energy range from $\mathbf{70}$ to $\mathbf{400\,GeV}$ demonstrate x_F- scaling

Reactions at large x_F

HADRON PRODUCTION AT LARGE η

— nuclei are known to suppress reactions at large x_F



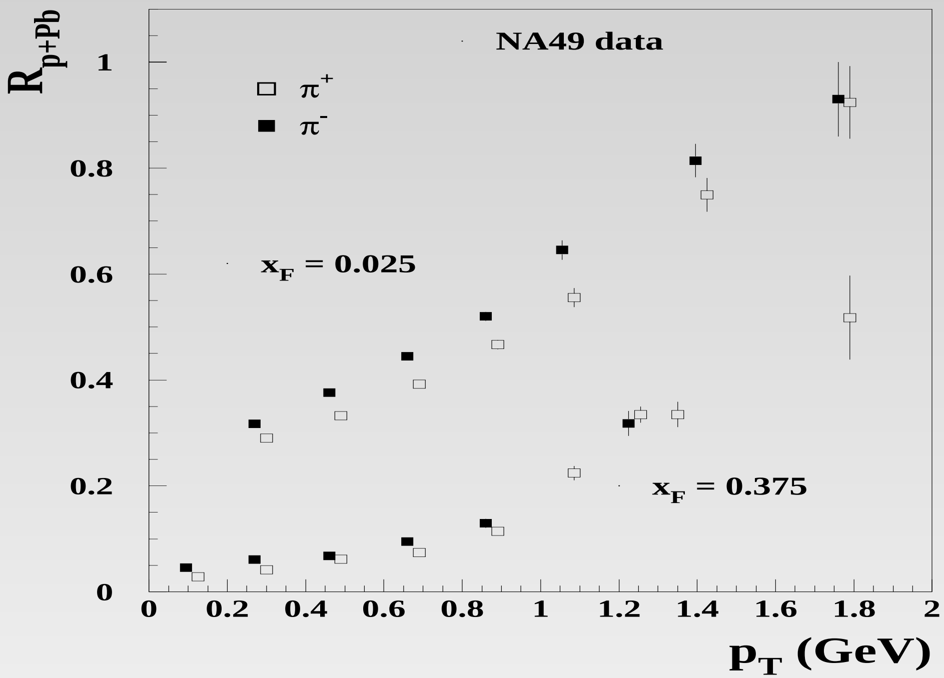
Nuclear modification factor for hadrons in $d + Au$ collisions

— at $\eta = \mathbf{3.2}$ - $\mathbf{4.0}$ the data reach large x_F region

$$x_F \sim \frac{p_T}{\sqrt{s}} e^{\eta} \sim 0.5 - 0.6$$

Reactions at large x_F

NA49 data



Nuclear modification factor for pions in $p + Pb$ collisions as a function of p_T for two different fixed values of x_F

— corresponding values of rapidity are different for each p_T- bin

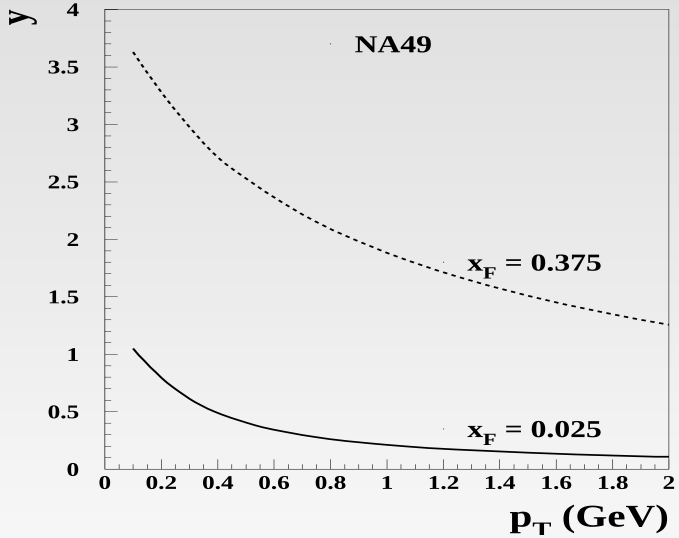
Reactions at large x_F

NA49 data

— at fixed x_F the rapidity varies with p_T : $y = \frac{1}{2} ln \frac{E+P_L}{E-p_L}$

— where longitudinal hadron momentum $p_L = x_F \frac{\sqrt{s}}{2}$

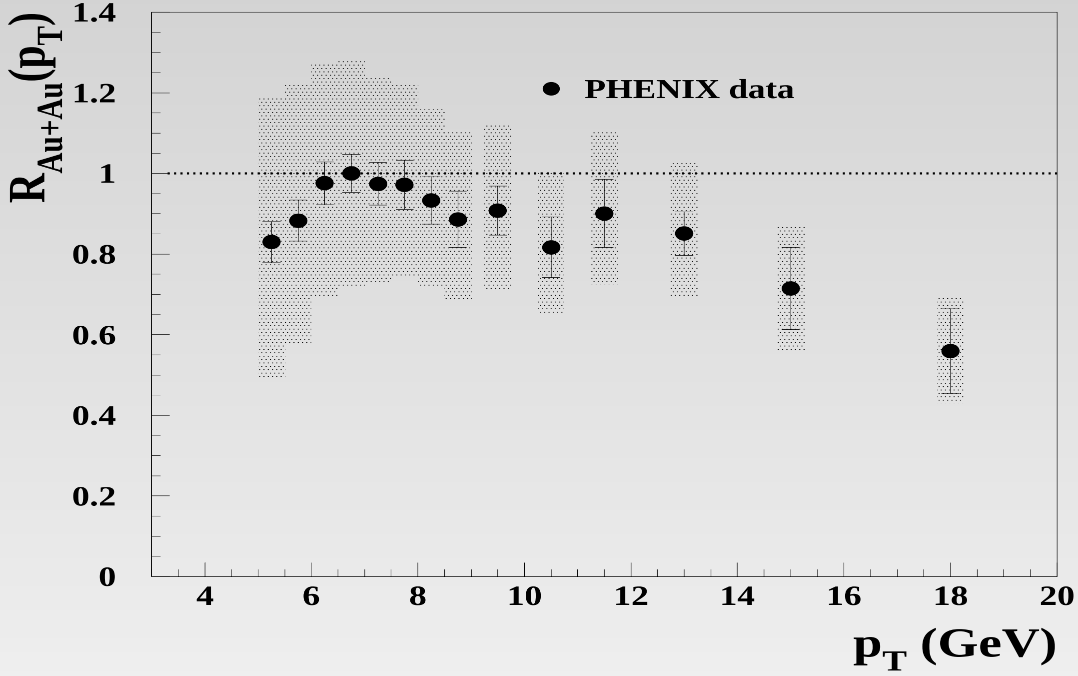
— and the corresponding energy $E = \sqrt{p_T^2 + p_L^2 + m_h^2}$



Rapidity as a function of p_T for two different fixed values of x_F

Reactions at large x_F

DIRECT PHOTON PRODUCTION IN A-B COLLISIONS

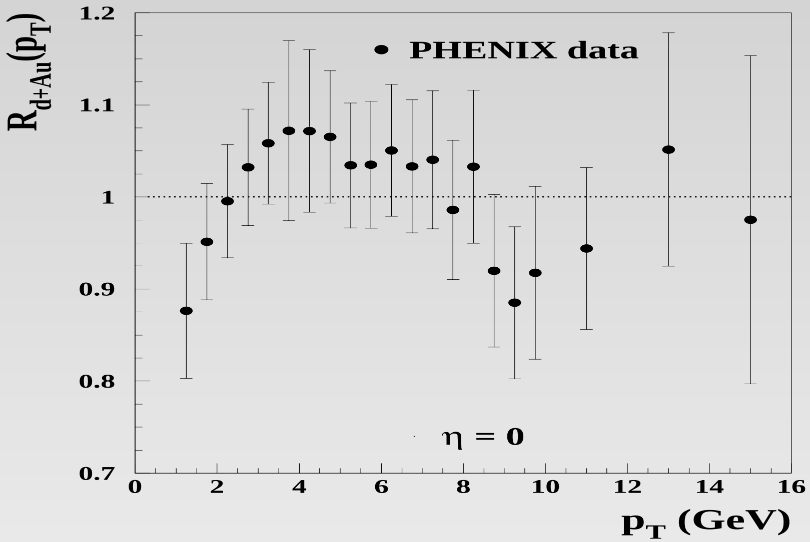


Nuclear modification factor for direct photon production in $Au + Au$ collisions as a function of p_T

— strong nuclear suppression at large $p_T > 14\,\mathrm{GeV}$

Reactions at large x_F

LARGE p_T HADRON PRODUCTION AT $\eta = 0$



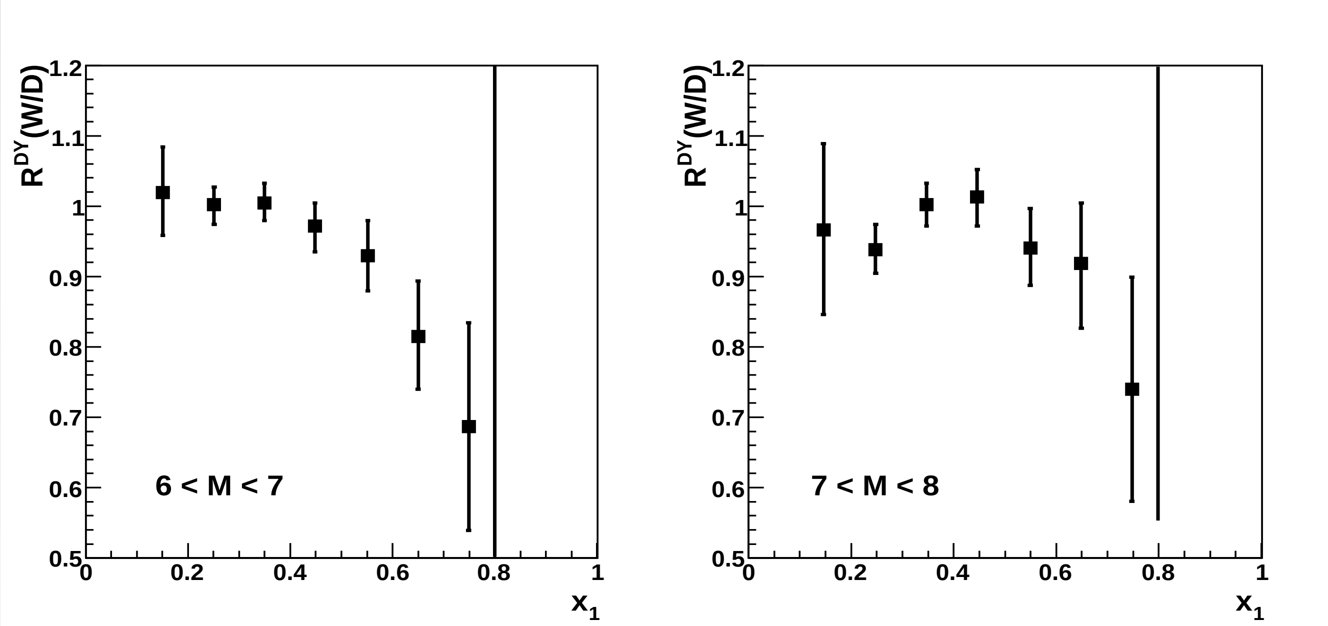
Nuclear modification factor for large-$\boldsymbol{p_T}$ neutral pion production in $\boldsymbol{d + Au}$ collisions as a function of $\boldsymbol{p_T}$

— data show an evidence for nuclear suppression at large $\boldsymbol{p_T}$ - large error bars

— it is in accord with $\boldsymbol{x_F}$ scaling of nuclear suppression

Reactions at large x_F

NUCLEAR SUPPRESSION OF DILEPTONS



Ratio of DY cross section on W and D as a function of x_1, at large dilepton masses to eliminate nuclear shadowing

— In 1990 the E772 experiment at Fermilab first observed that the DY process is suppressed at large x_F.

Reactions at large x_F

NUCLEAR SUPPRESSION OF DILEPTONS

— in the target rest frame, the DY process looks like fragmentation of a projectile quark into a dilepton via bremsstrahlung of a heavy photon.

— standard kinematic variables :

$$x_1 = \frac{2\,P_2 \cdot q}{s} \qquad\qquad x_2 = \frac{2\,P_1 \cdot q}{s}$$

— with Feynman variable $x_F = x_1 - x_2 = 2\,p_L/\sqrt{s}$, where p_L is the longitudinal momentum of the photon in the hadron-hadron center of mass frame, $s = (P_1 + P_2)^2$ is the center of mass energy squared of the colliding protons.

— variables P_1, P_2 and q are the four-momenta of the beam, target and the real photon, respectively and p_T is the transverse momentum of the real photon

Reactions at large x_F

NUCLEAR SUPPRESSION OF DILEPTONS

— in the target rest frame, x_1 represents the momentum fraction of the proton taken away by the photon

— using following definition

$$\tau = x_1\, x_2 = \frac{p_T^2 + M^2}{s}$$

— one can obtain useful expressions for the kinematic variables x_1 and x_2:

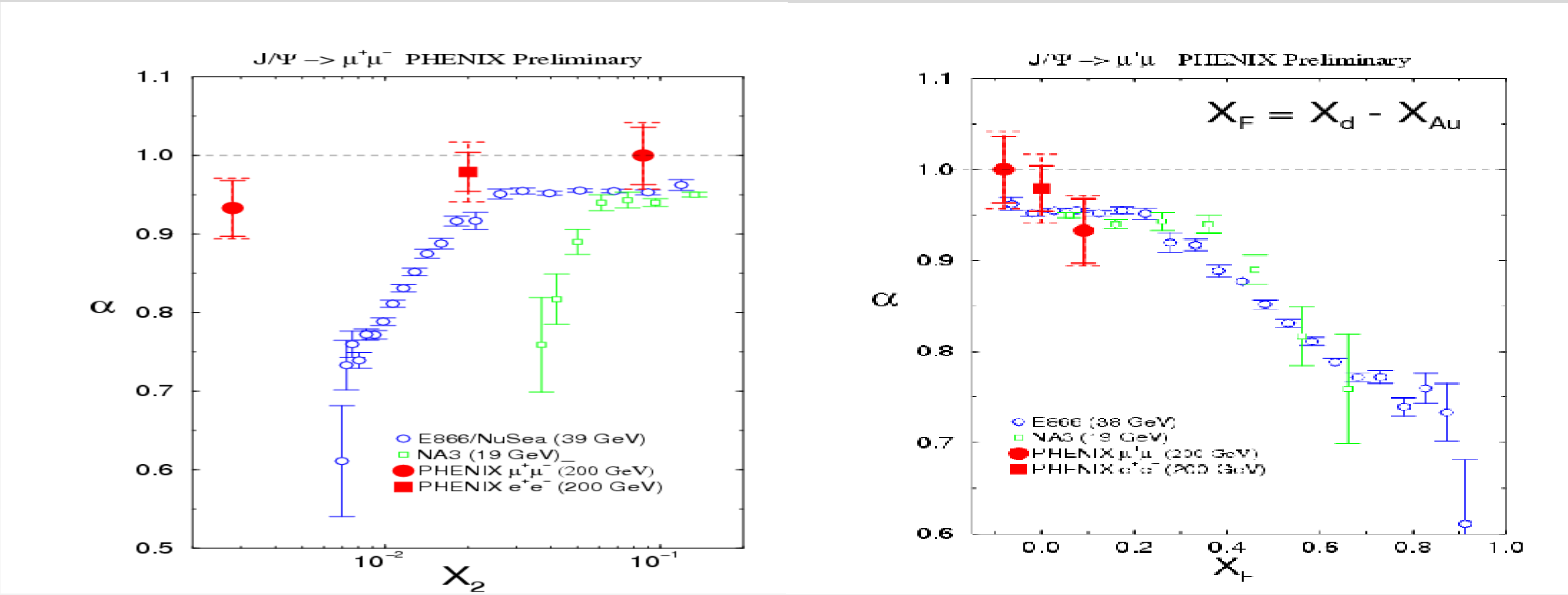
$$x_1 = \frac{1}{2}\left(\sqrt{x_F^2 + 4\,\tau} + x_F\right) \qquad x_2 = \frac{1}{2}\left(\sqrt{x_F^2 + 4\,\tau} - x_F\right)$$

— at fixed p_T, x_1 rises with x_F

Reactions at large x_F

J/Ψ PRODUCTION

Unexpected results from d-Au collisions



x_2 resp. x_F behavior of the exponent α describing the A dependence ($\propto A^\alpha$) of the nucleus-to-proton ratio

— a clear demonstration of x_1-, rather than x_2- scaling

Questions

- Why do we observe a common feature of all known reactions on nuclear targets - a significant suppression at large x_F (x_1) ?
- Why do we observe x_F (x_1) scaling ?
- Why the soft hadron production is flavor independent ?

Interpretations of suppression

In terms of the Fock-state decomposition of the nucleus

— Fock states in a quark

$$|q\rangle_{phys} = a_0\,|q\rangle_0 + a_1\,|qG\rangle + a_2\,|qGG\rangle + ...$$

— the amplitudes a_i depend on resolution -

— SOFT PROCESS - the lowest component dominates **(poor resolution)**

— HARD REACTION - higher Fock states are important **(better resolution)** $\rightarrow$ INTENSIVE GLUON BREMSSTRAHLUNG

Interpretations of suppression

— the dominant Fock components are determined by the resolution of the interaction

— a nucleus can resolve more Fock states than a proton since the saturation scale Q_s rises with the mass number of the target A.

— the leading parton distribution involves higher multiparton Fock states in a nucleus and must fall more steeply towards

$x_F \longrightarrow 1$

as suggested by the Blankenbecler-Brodsky counting rule
PR, D10, 2973 (1974)

Interpretations of suppression

— if one parton in a multiparton Fock state takes the main part of the momentum, $x_1 \longrightarrow 1$

— the rest partons are pushed into a small phase space cell $\sim 1 - x_1$

— the more partons are in the Fock state, the less is the probability to find them in the small phase space $\sim (1 - x_1)^n$

Brodsky-Farrar counting rule

PRL, 31, 1153 (1973)

Interpretations of suppression

In terms of energy loss

— the involvement of higher Fock states $\longrightarrow$ **gluon bremsstrahlung is more intense in the interaction on a nucleus than on a proton target**

— it leads to a larger energy loss

— the large x_F suppression may be envisioned to be a consequence of induced energy loss proportional to energy

— such an induced energy loss proportional to energy results in x_F scaling of nuclear suppression.

Conclusions

— the projectile parton distribution at $x_1 \to 1$ depends on the target **!**
(another source of factorization breakdown)

— the number of the projectile partons and Fock state decomposition depend on resolution of the interaction

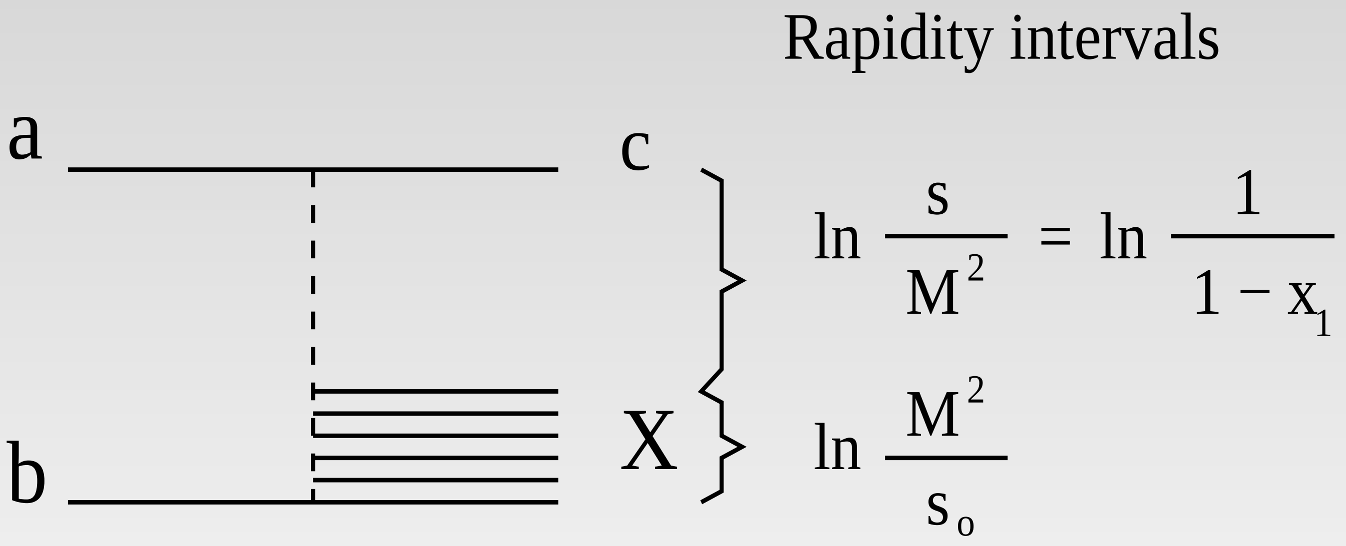
— the resolution of a nuclear target is controlled by the SATURATION SCALE Q_s, which rises with the mass number of nuclear target A

— the more partons is resolved by the nuclear target, the steeper is behavior of the single-parton distribution at $x_1 \to 1$

$$f_q(x_1) \propto (1 - x_1)^{n(A)}$$

Alternative interpretations of suppression

— any reaction, $a + b \to c + X$, where $c = h, \bar{l}l, J/\Psi, \ldots$ in a large rapidity gap (LRG) process at $x_1(x_F) \to 1$



— the probability to radiate no gluons in the rapidity interval $\Delta y = ln\, \frac{1}{1-x_1}$ is suppressed by the SUDAKOV'S FORM FACTOR $S(\Delta y)$, which violates QCD factorization

Alternative interpretations of suppression

CFRJS

* assuming as usual an uncorrelated Poisson distribution for gluons, Sudakov suppression factor, i.e. the probability to have a rapidity gap Δy, becomes

$$S(\Delta y) = e^{-\langle n_G(\Delta y)\rangle}$$

* the mean number of gluons radiated in the rapidity interval Δy is related to the height of the plateau in the gluon spectrum

$$\langle n_G(\Delta y)\rangle = \Delta y \, \frac{d\, n_G}{dy},$$

where dn_G/dy is constant

* correspondingly

$$S(\Delta y) = (1 - x_1)^{\frac{dn_G}{dy}}$$

Alternative interpretations of suppression

— the height of the gluon plateau was estimated by Gunion and Bertsch, PR D25, 746 (1982) as

$$\frac{dn_G}{dy} = \frac{3\,\alpha_S}{\pi}\, ln \left[\frac{m_\rho^2}{\Lambda_{QCD}^2}\right] \approx 1$$

— thus the Sudakov form factor

$$S(x_1) = (1 - x_1)$$

— this coincides with the suppression factor applied to every additional Pomeron exchange in the quark-gluon string and dual parton models based on the Regge approach
A.B. Kaidalov, JETP Lett. 32, 474 (1980), PL B116, 459 (1982)
A. Capella et al., Phys. Rep.. 236, 226 (1994)

Alternative interpretations of suppression

— alternative formulation of this suppression at $x_1 \longrightarrow 1$ - as a survival probability of the LRG in multiple interactions with the nucleus

— every additional inelastic interaction contributes an extra suppression factor $S(x_1)$

— the probability of an n-fold inelastic collision is related to the Glauber model coefficients via the Abramovsky-Gribov-Kancheli (AGK) cutting rules

— the survival probability at impact parameter $\vec{b}$ reads

$$W^{hA}_{LRG}(b) = \exp[-\sigma^{hN}_{in} T_A(b)] \sum_{n=1}^{A} \frac{1}{n!} \left[\sigma^{hN}_{in} T_A(b)\right]^n S(x_1)^{n-1}$$

Alternative interpretations of suppression

— in this expression particles (gluons) are assumed to be produced independently in multiple rescatterings, i.e. in Bethe-Heitler regime

— the same $W^{hA}_{LRG}(b)$ is employed in the dual parton model

— at $x_F \to 1$ energy conservation allows only radiation of low-energy gluons having short coherence time. Therefore, particles are produced incoherently in multiple interactions.

— at $x_F \to 1$ only the first term survives and

$$\sigma^A_{LRG}(x_F \to 1) = \int d^2\, b W^{hA}_{LRG}(b) \sim A^{1/3}$$

like data suggest

Diffraction excitation of the nuclear target

— represents another example of LRG reaction on nuclei

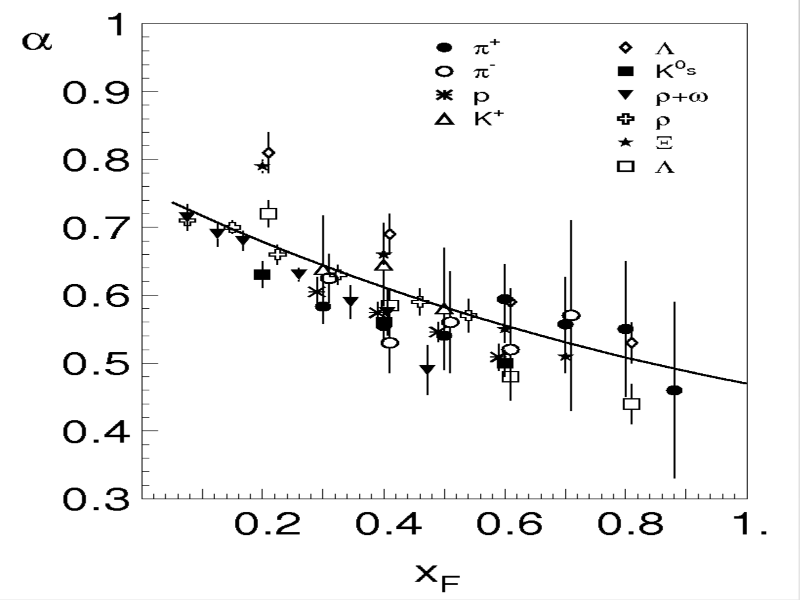
$$\sigma^{pA}_{diff} = \int\limits_{0.925}^{1} dx_F \, \frac{d\sigma(pA \to pX)}{dx_F} = \sigma_0 \, A^{\alpha},$$

with $\alpha = 0.34 \pm 0.02$, and $\sigma_0 = 3.84 \pm 0.94$ mb, following from HELIOS experiment at energy 450 GeV

— it consistent with the above expectation

— only the nuclear periphery contributes

Leading hadrons with small p_T



Exponent describing the A dependence $(\propto A^{\alpha})$ of the nucleus-to-proton ratio for production of different hadrons as a function of x_F

— quite strong and universal nuclear suppression at large x_F

— data spanning the lab. energy range from 70 to 400 GeV demonstrate that nuclear effects scale in x_F

Leading hadrons with small p_T

— one can relate the observed suppression to the dynamics discussed above via survival probability of LRG, which is close to the description of soft inclusive reaction with quark-gluon string [A.B. Kaidalov, PL B116, 459 (1982)], or dual parton [A. Capella et al., Phys.Rep. 236, 225 (1994)] models

— Nuclear effect can be calculated summing over n and integrating over impact parameter in the relation for survival probability of LRG:

$$R_{A/N}(x_F) = \frac{1}{(1-x_F)\,\sigma_{eff}\,A} \int d^2b\; \exp[-\sigma_{eff}\,T_A(b)] \times \Big\{ \exp[(1-x_F)\sigma_{eff} T_A(b)] - 1 \Big\}$$

Leading hadrons with small p_T

— within the Glauber model $\sigma_{eff} = \sigma_{in}^{hN}$

— however Gribov's corrections make medium more transparent and substantially reduce σ_{eff}. For $A = 40$, $\sigma_{eff} = 20$ mb.

— above simple expression explains the observed x_F scaling a describes rather well the data

— $\alpha(x_F)$ does not reach values as small as 1/3. This exponent varies with A and simple geometrical considerations may be accurate only for heavy nuclei.

High-p_T hadrons at large η

CFRJS

Leading order kinematics

— light-front momentum fraction variables in projectile and target:

$$x_1 = \frac{M_T}{\sqrt{s}} Exp(y) \qquad x_2 = \frac{M_T}{\sqrt{s}} Exp(-y)$$

— where y is the rapidity of the $(x_F, \vec{k_T})$ system

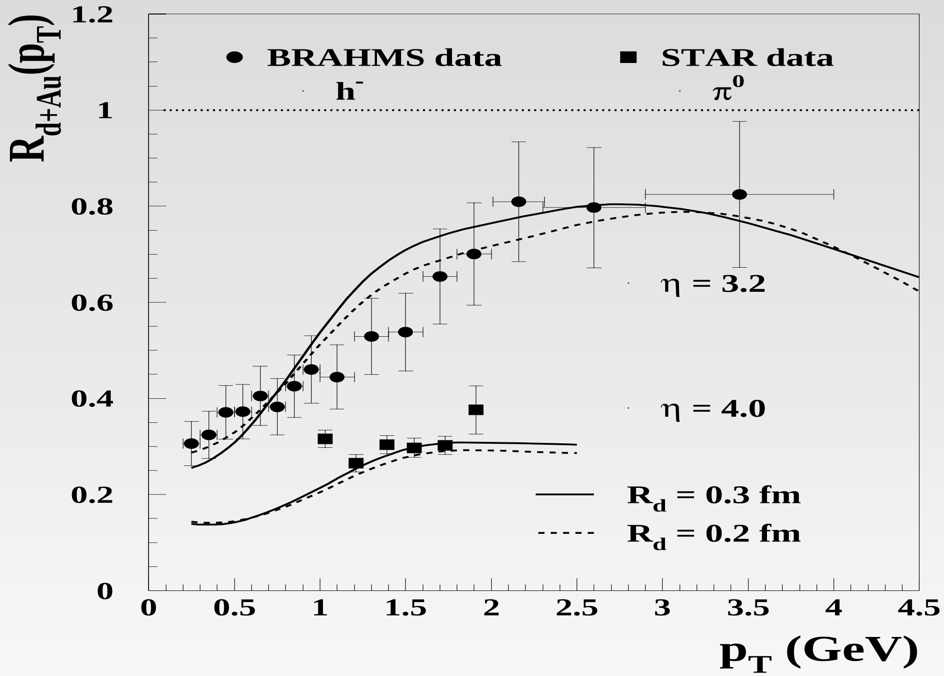
— Feyman variable $x_F = x_1 - x_2 = \frac{2\, M_T}{\sqrt{s}} sinh(y)$

— at forward rapidity - PROJECTILE - $x_1 \sim 0.5 - 1$
mostly valence quarks contribute

— at forward rapidity - TARGET - $x_2 < 0.01$
mainly gluons dominate

High-p_T hadrons at large η

— forward rapidities $\longleftrightarrow$ the beam fragmentation region at large Feynman variables - means small $\boldsymbol{x_2}$ values - one can access the strongest coherence effects - associated with shadowing or the color glass condensate



Nuclear modification factor for hadrons in $d + Au$ collisions

High-p_T hadrons at large η

— the simple sum rule for valence quark production

$$\frac{\int d^2p_T \frac{d\sigma^{pA}}{dp_T^2}}{A \int d^2p_T \frac{d\sigma^{pp}}{dp_T^2}} = \frac{\sigma_{in}^{pA}}{A\,\sigma_{in}^{pp}} \propto A^{-1/3}$$

explains the strong nuclear suppression at small p_T

— suppression at small p_T at $\eta = 3.2$ is > than at $\eta = 0$

— at $\eta = 0$, nuclei modify the q_T distribution of radiated gluons - an effect known as the CGC or Cronin effect - gluons are suppressed at small p_T, enhanced at medium p_T, and unchanged at large p_T

— GS, or the Landau-Pomeranchuk effect is a part of the CGC and reduces the total number of radiated gluons more strongly at small than at large p_T - strong suppression of small-p_T particle production at midrapidities is a manifestation of CGC

High-p_T hadrons at large η

— interpretation of data in terms of CGC should be careful - CGC is supposed to be a result of coherence between different parts of the nucleus

— nuclear modifications of the T-momentum distribution occur in both the coherent and incoherent regimes. Only the coherent regime can be an effect of the CGC.

— the RHIC data at midrapidities are in the transition region - particles are produced coherently on the nucleus at small $p_T < 1\,\text{GeV}$, but incoherently at larger p_T

High-p_T hadrons at large η

— the cross section of hadron production in $dA(pp)$ collisions is given by a convolution of the distribution function for the projectile valence quark with the quark scattering cross section and the fragmentation function

$$\frac{d^2\sigma}{d^2p_T\, d\eta} = \sum_q \int_{z_{min}}^{1} dz\, f_{q/d(p)}(x_1, q_T^2)\, \frac{d^2\sigma[qA(p)]}{d^2q_T\, d\eta}\bigg|_{\vec{q}_T=\vec{p}_T/z} D_{h/q}(z)$$

where

$$x_1 = \frac{q_T}{\sqrt{s}}\, e^{\eta}\,.$$

— interaction with a nuclear target does not obey factorization, since the effective projectile quark distribution correlates with the target

High-p_T hadrons at large η

— the main source of suppression at large p_T concerns to multiple soft rescatterings of the quark in nuclear matter

— summed over multiple interactions, the quark distribution in the nucleus reads,

$$f^{(A)}_{q/N}(x_1, q_T^2) = C\, f_{q/N}(x_1, q_T^2)\, \frac{\int d^2b\, \left[e^{-x_1 \sigma_{eff} T_A(b)} - e^{-\sigma_{eff} T_A(b)}\right]}{(1 - x_1) \int d^2b\, \left[1 - e^{-\sigma_{eff} T_A(b)}\right]}$$

— the normalization factor C is fixed by the Gottfried sum rule

— the cross section of quark scattering on the target in is calculated in the light-cone dipole approach [M.B. Johnson, B.Z. Kopeliovich and A.V. Tarasov, PR C63, 035203 (2001)], which provides an easy way to incorporate multiple interactions

High-p_T hadrons at large η

— the Cronin effect is an interplay of the quark primordial $\boldsymbol{k_T}$ and the momentum $\boldsymbol{q_T}$ gained via the interaction

— the larger is $\boldsymbol{k_T}$ and the smaller is $\boldsymbol{q_T}$, the weaker is the Cronin effect. And VICE VERSA

— this confirms an importance of the nucleon quark structure. We include three mechanisms of high-$\boldsymbol{p_T}$ valence quarks production characterized by different initial transverse momenta

— particularly as a demonstration of different primordial momenta for quark and gluon one can observe weaker Cronin effect at larger energies

Nuclear broadening of p_T

M.Johnson, BK, A.Tarasov
PR C63(2001)035203

$$\frac{dN_q}{d^2k_T} = \int d^2r_1\, d^2r_2\, e^{i\,\vec{k}_T\,(\vec{r}_1-\vec{r}_2)}\,\Omega^q_{in}(\vec{r}_1,\vec{r}_2)\, e^{-\frac{1}{2}\,\sigma(\vec{r}_1-\vec{r}_2,x)\,T_A(b)}$$

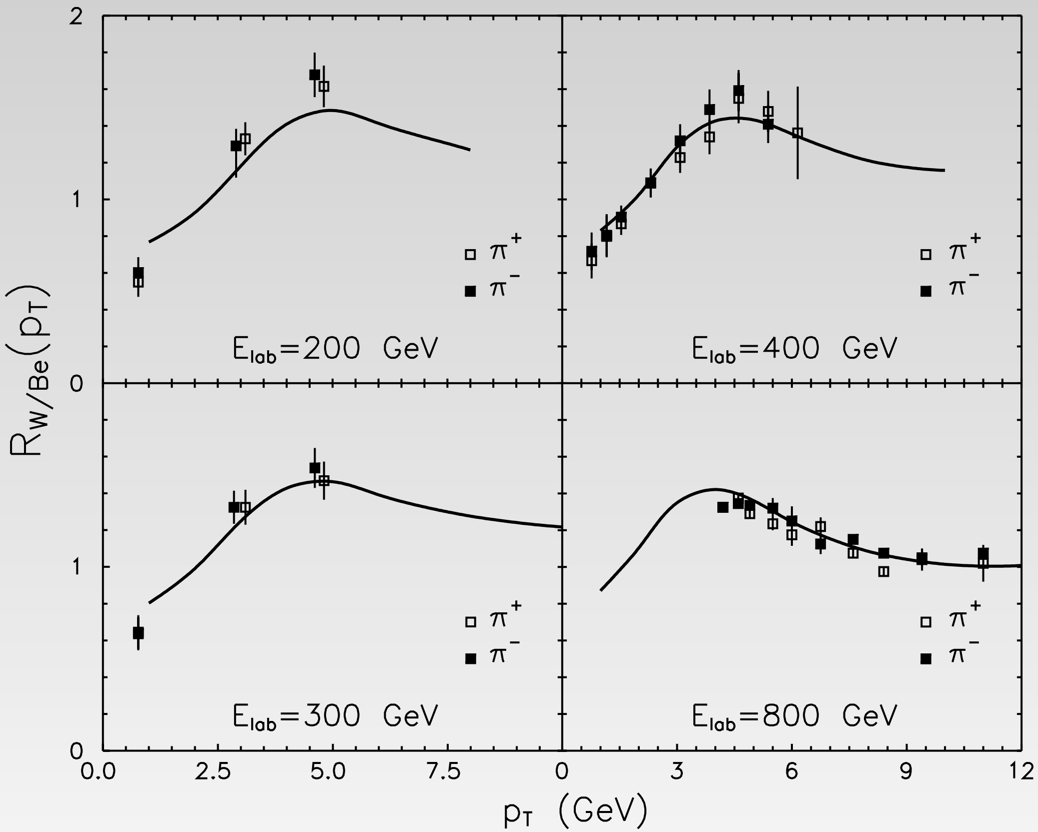
Dipole cross section $\sigma(r_T, x)$ is fitted to data for $F_2^p(x, Q^2)$. $\Omega^q_{in}(\vec{r}_1,\vec{r}_2)$ is the density matrix describing the impact parameter distribution of the quark in the incident hadron,

$$\Omega^q_{in}(\vec{r}_1,\vec{r}_2) = \frac{\langle k_0^2\rangle}{\pi}\, e^{-\frac{1}{2}(r_1^2+r_2^2)\langle k_0^2\rangle}\;,$$

where $\langle k_0^2\rangle$ is the mean value of the parton primordial transverse momentum squared.

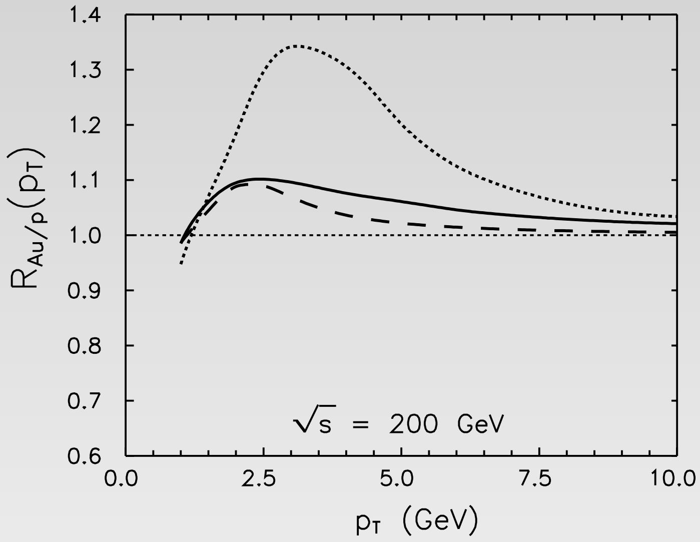
Cronin effect in pA collisions

BK, J.Nemchik, A.Schäfer, A.Tarasov, PRL, 88(2002)232303

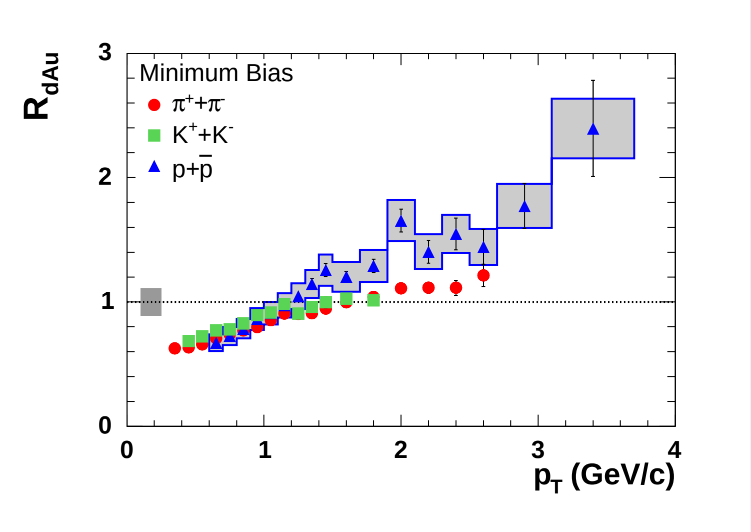


No fit to the data to be explained.

Cronin effect at RHIC



A much weaker Cronin enhancement was predicted for RHIC.



PHENIX results

High-p_T hadrons at large η

CFRJS

Quark-diquark break up of the proton

— the first possibility is to break up the proton remaining the diquark intact, $p \to \hat{q}q + q$. Dominates at low $q_T < 1\,\mathrm{GeV}$

— we treat the diquark as point-like and integrate over its momentum

— q_T distribution of the projectile valence quark, after propagation through nucleus at impact parameter $\vec{b}$, is given as

$$\frac{d\sigma(NA \to qX)}{d^2q_T\, d^2b} = \int \frac{d^2r_1 d^2r_2}{(2\pi)^2}\, e^{i\vec{q}_T(\vec{r}_1 - \vec{r}_2)}\Psi^\dagger_N(r_1)\,\Psi_N(r_2)\times$$
$$\left[1 + e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\vec{r}_1-\vec{r}_2)T_A(b)} - e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\vec{r}_1)T_A(b)} - e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\vec{r}_2)T_A(b)}\right]$$

— $q - \hat{q}q$ wave function has a form that matches the known pQCD behavior at large q_T, $\Psi_N(r) \propto K_0(r/R_p)$

High-p_T hadrons at large η

Diquark break up $\hat{q}q \to q + q$

— at larger q_T the interaction resolves the diquark and its break up should be included

— the valence quark has a much larger primordial transverse momentum

$$\frac{d\sigma(\widehat{qq}A \to qX)}{d^2q_T\, d^2b} = \int \frac{d^2r_1 d^2r_2}{2\,(2\pi)^2}\, e^{i\vec{q}_T(\vec{r}_1-\vec{r}_2)}\Psi^\dagger_D(r_1)\,\Psi_D(r_2) \times$$

$$\Big[2 - e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\vec{r}_1)T_A(b)} - e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\vec{r}_2)T_A(b)} - e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\vec{r}_1/2)T_A(b)}$$

$$-e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\vec{r}_2/2)T_A(b)} - e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\vec{r}_1-\frac{1}{2}\vec{r}_2)T_A(b)} - e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\vec{r}_2-\frac{1}{2}\vec{r}_1)T_A(b)}$$

$$+2\,e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\vec{r}_1-\vec{r}_2)T_A(b)} + 2\,e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(\frac{\vec{r}_1-\vec{r}_2}{2})T_A(b)}\Big]$$

— $\hat{q}q$ WF is also assumed to be $\Psi_D(r) \propto K_0(r/R_D)$ but with a mean separation, $R_D = 0.2 - 0.3$ fm

High-p_T hadrons at large η

Hard gluon radiation $q \to Gq$

— at large $\boldsymbol{q_T}$ the dipole approach should recover the parton model, which describes high- $\boldsymbol{p_T}$ process as a result of binary collision of two partons (in the leading order) with final T-momenta of both partons of the order of $\boldsymbol{q_T}$

— in the dipole approach one assumes that the projectile valence quark acquires high transverse momentum as a result of multiple rescatterings, while the radiated gluons that balance this momentum are summed to build up the dipole cross section. The latter is fitted to DIS data involving gluons of rather low transverse momenta

— one should include explicitly the radiation of a gluon with large T-momentum which approximately equilibrates $\boldsymbol{q_T}$, i.e. the process $qN \to qGX$

High-p_T hadrons at large η

Hard gluon radiation $q \to Gq$

— in the dipole approach the cross section is given by the same formula

$$\frac{d\sigma(qA \to qX)}{d^2q_T\, d^2b} = \int \frac{d^2r_1 d^2r_2}{(2\pi)^2}\, e^{i\vec{q}_T(\vec{r}_1-\vec{r}_2)} \Psi^\dagger_{qG}(r_1)\, \Psi_{qG}(r_2) \times$$

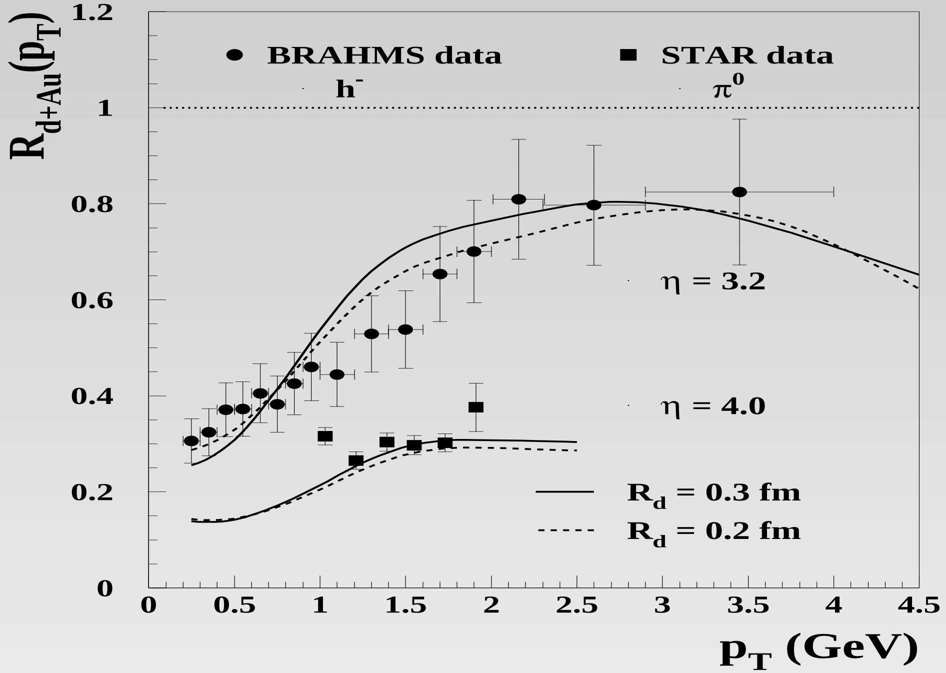
$$\left[1 + e^{-\frac{1}{2}\sigma^N_{GG}(\vec{r}_1-\vec{r}_2)T_A(b)} - e^{-\frac{1}{2}\sigma^N_{GG}(\vec{r}_1)T_A(b)} - e^{-\frac{1}{2}\sigma^N_{GG}(\vec{r}_2)T_A(b)}\right]$$

— the nucleon wave function is replaced by the quark-gluon light-cone wave function, $\Psi_N(r_T) \Rightarrow \Psi_{qG}(r_T)$, where

$$\Psi_{qG}(\vec{r}_T) = -\frac{2i}{\pi}\sqrt{\frac{\alpha_s}{3}}\, \frac{\vec{r}_T \cdot \vec{e}^{\,*}}{r_T^2} \exp\left(-\frac{r_T^2}{2r_0^2}\right)$$

with $r_0 = 0.3$ fm $\Rightarrow$ small gluonic spots

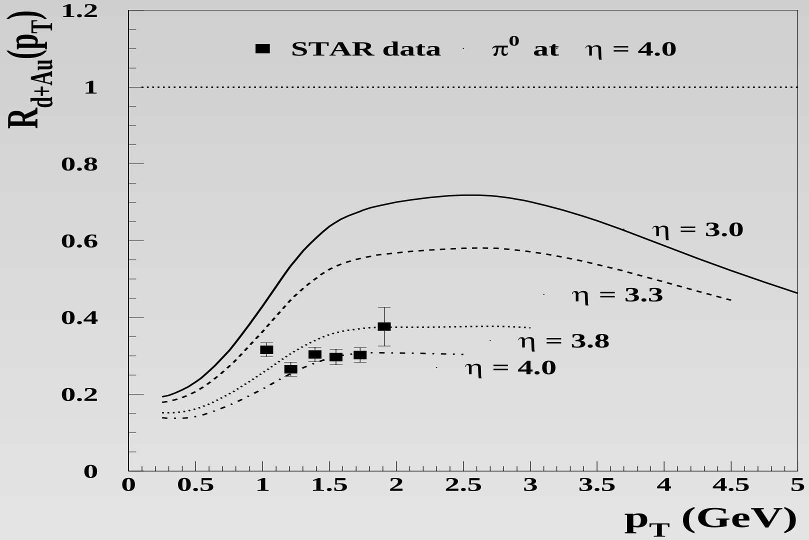
High-p_T hadrons at large η



— fragmentation functions $\boldsymbol{u \to \pi^-}$ and $\boldsymbol{d \to \pi^-}$ - from [D. de Florian et al., PR D76,074033 (2007)]

— isospin effects - more negative hadrons are produced by deuterons than by protons - enhancement of the ratio for $\boldsymbol{h^-}$ by a factor of 3/2 at large $\boldsymbol{p_T}$

High-p_T hadrons at large η



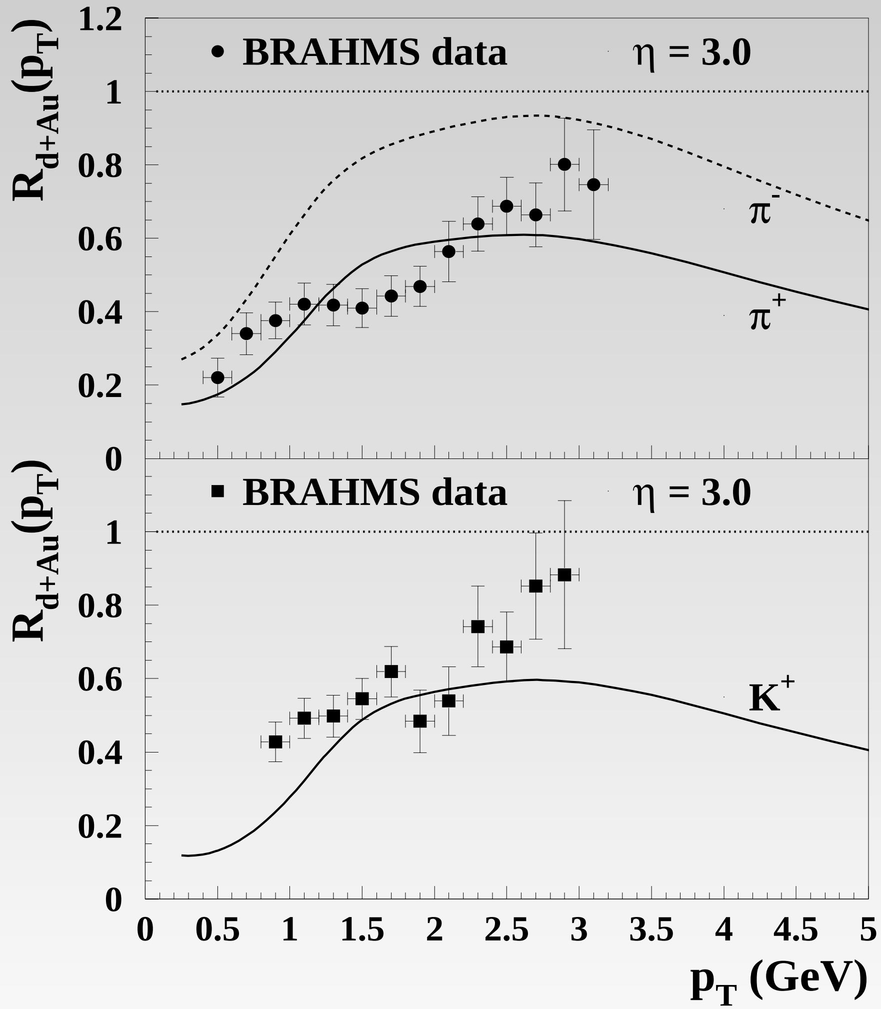
Nuclear modification factor for π^0 in $d + Au$ collisions

— to eliminate isospin effects in $d + Au$ collisions one should study neutral hadron (pion) production

— changing the value of η from 3 to 4 one can see a large rise of nuclear suppression about a factor of 2

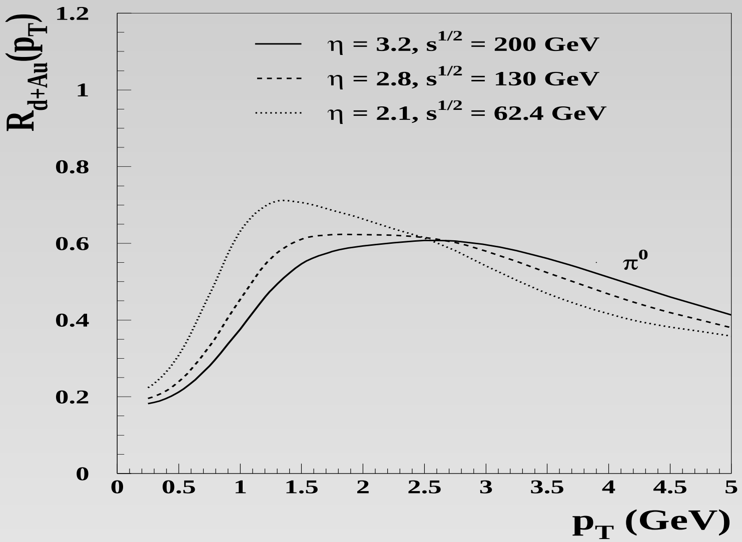
— rise of nuclear suppression with η is affected by a stronger onset of the Sudakov factors $S(x_1)^n$ at larger x_1 in the PDFs.

High-p_T hadrons at large η



Nuclear modification factor for hadrons in $d + Au$ collisions

High-p_T hadrons at large η

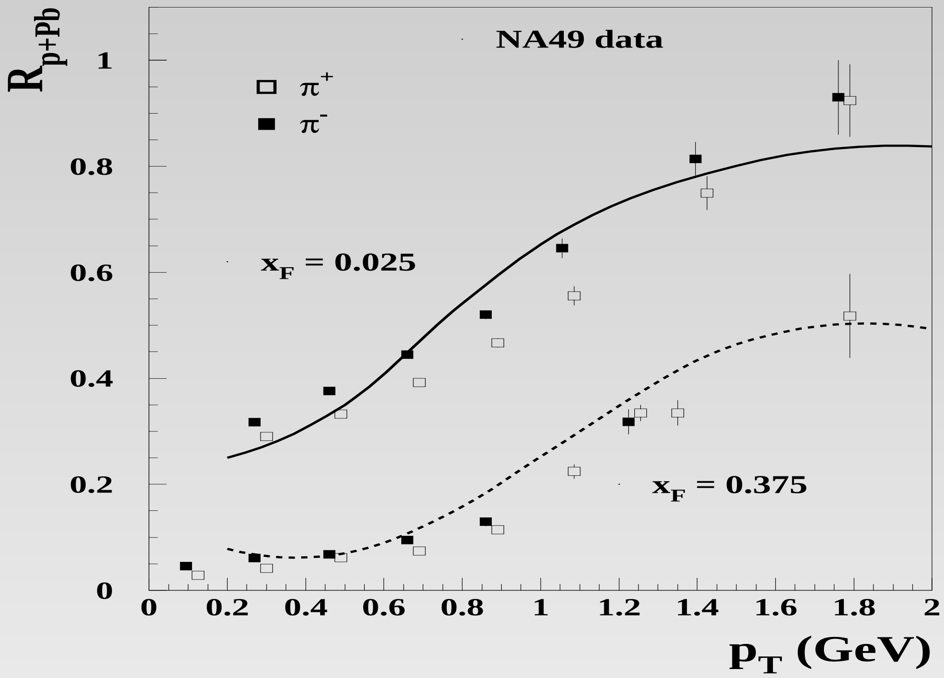


Theoretical predictions of an approximate $exp(\eta)/\sqrt{s}$- scaling

— as a consequence of a strong nuclear suppression caused by the Sudakov factor $S(x_1)$ - we expect the same nuclear effects at different energies and η corresponding to the same value of x_1

— at fixed energy it allows then to study nuclear effects also at midrapidities and at such large p_T which correspond to the same x_1- values as at forward rapidities

NA49 data

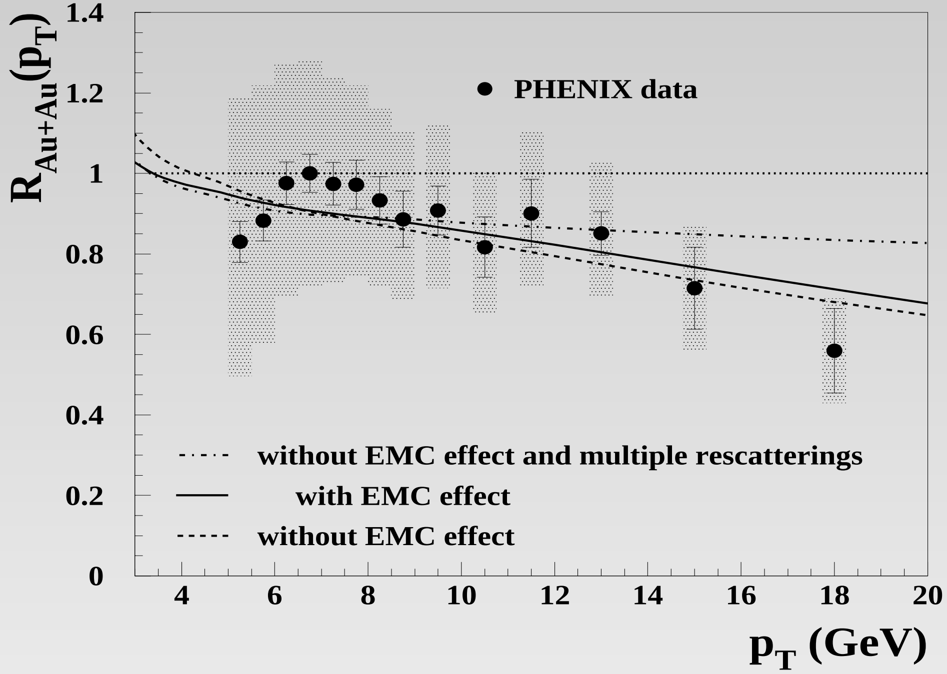


Nuclear modification factor for pions in $p + Pb$ collisions as a function of p_T for two different fixed values of x_F

— larger x_F means larger pseudorapidity

— nuclear suppression rises with x_F as a consequence of multiple parton rescatterings

Direct photons in A-B collisions

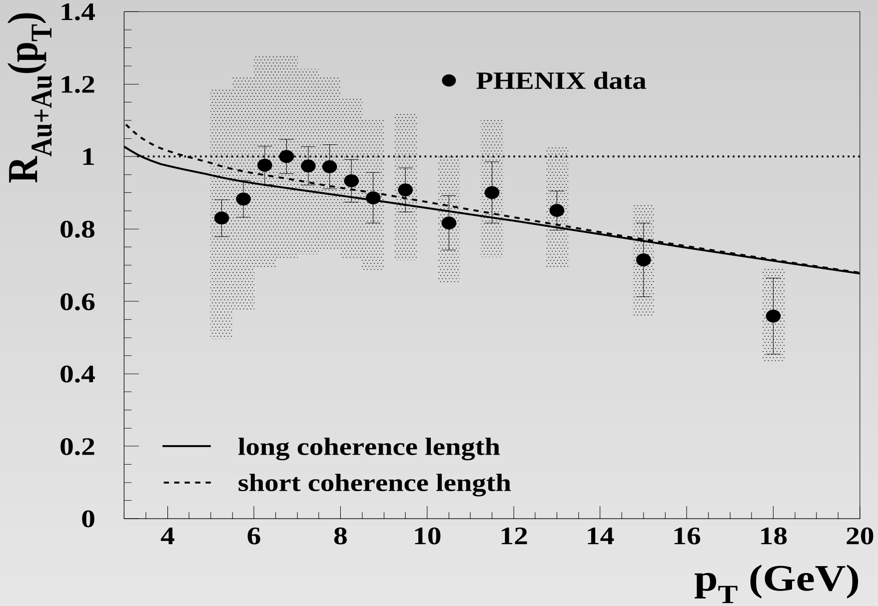


Nuclear modification factor for direct photon production

— according to $x_F(x_1)$- scaling, one can study nuclear suppression also at midrapidities but at larger corresponding p_T

— at large p_T - only valence quarks dominate - isospin effects give a prediction for $R_{Au+Au} \to 0.8$

Direct photons in A-B collisions

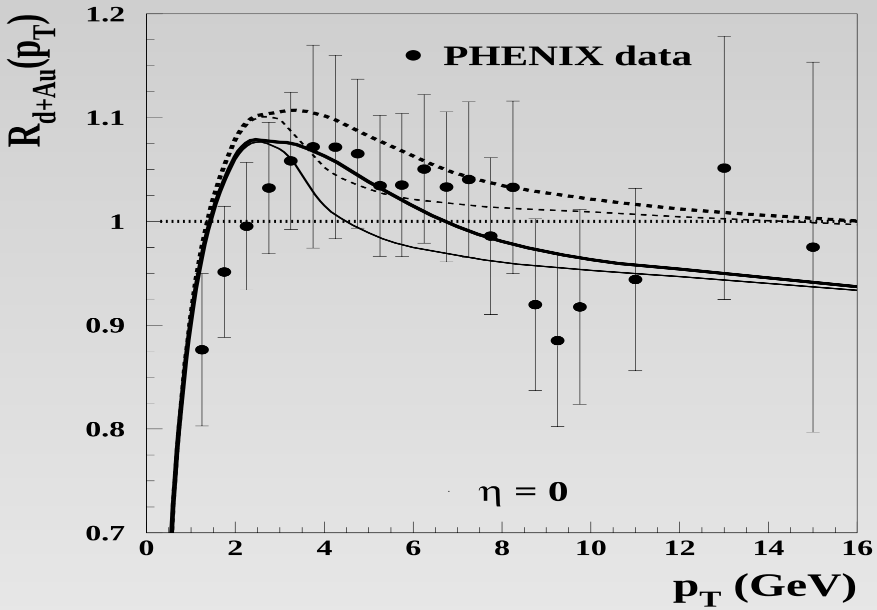


Nuclear modification factor for direct photon production

— SCL = l_c is much shorter than the mean internucleon separation $\sim$ 2 fm$\Rightarrow$ no effect of coherenece (shadowing)

— LCL = $l_c \gg R_A \Rightarrow$ interference of multiple interaction amplitudes with bound nucleons - shadowing effects

Hadrons at $\eta = 0$

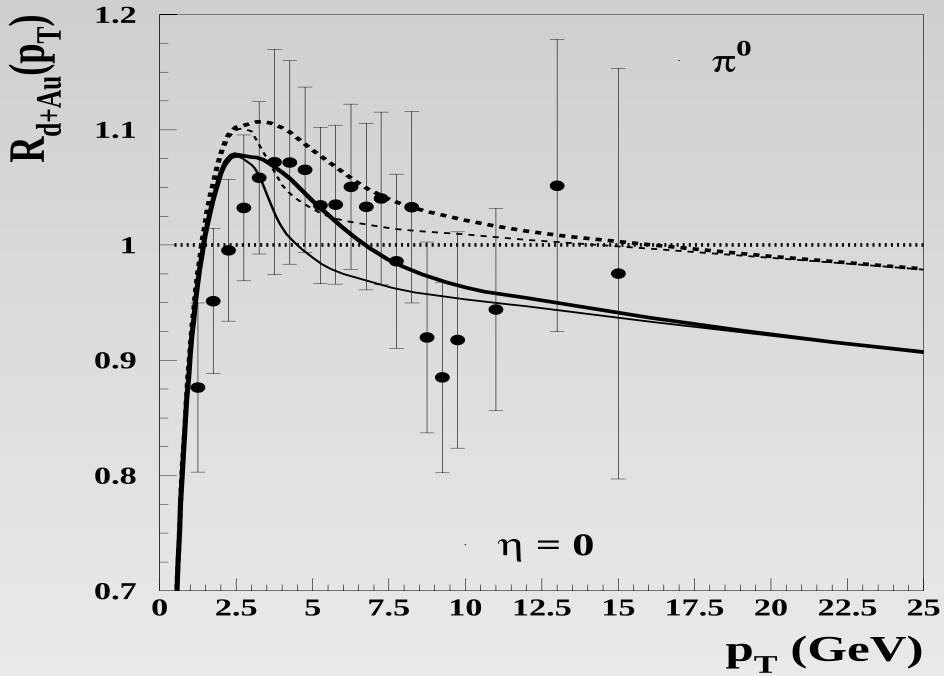


Nuclear modification factor for large-p_T neutral pion production

— sick dashed and solid lines = corrections for SCL - effective at medium p_T

— we predict again a nuclear suppression at large $p_T > 8$ GeV in accordance with an experimental evidence from PHENIX $\Leftarrow$ large error bars

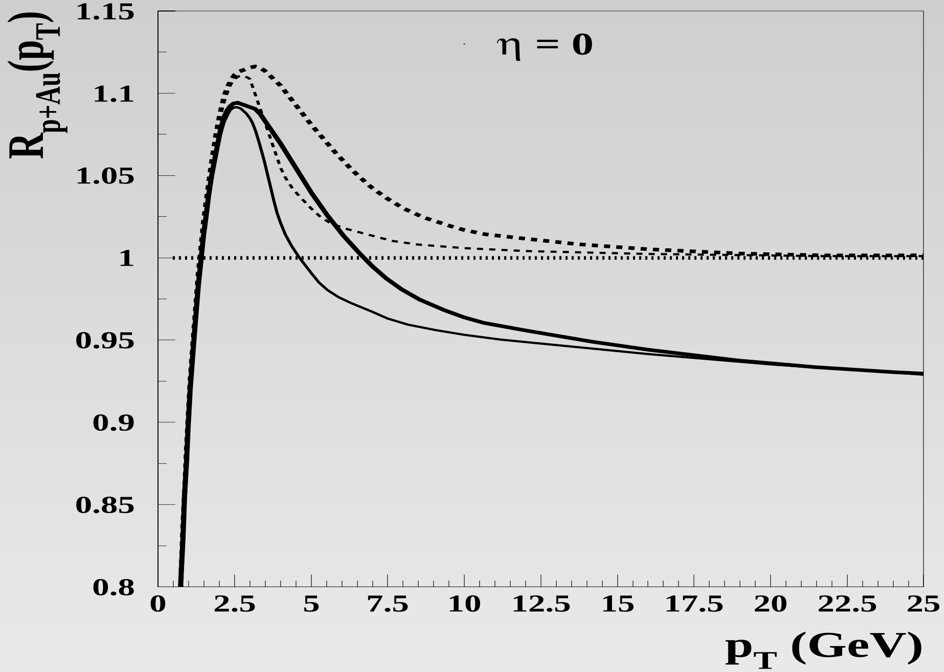
Hadrons at $\eta = 0$



Nuclear modification factor for large-p_T neutral pion production

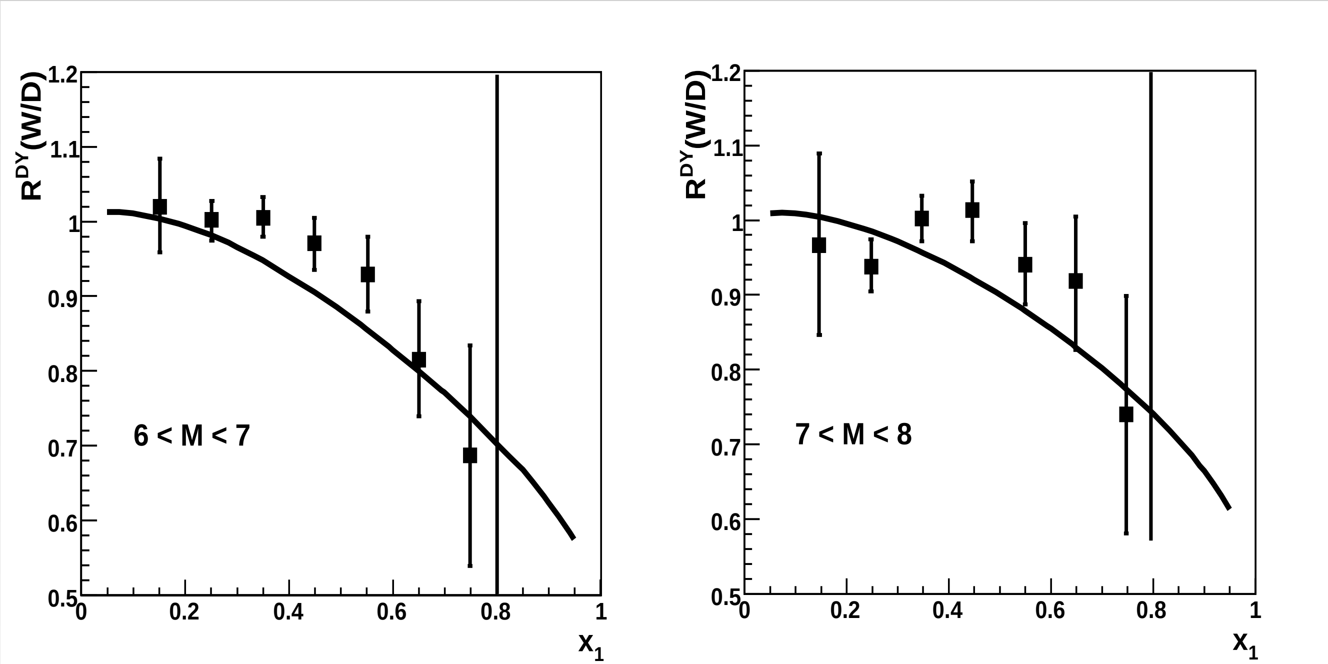
— small isospin effects at large p_T = deviation from unity **when multiple parton rescatterings are not taken into account**

Hadrons at $\eta = 0$



Nuclear modification factor for large-p_T neutral pion production

Drell-Yan reaction



Ratio of DY cross section on W and D as a function of x_1, at large dilepton masses to eliminate nuclear shadowing

— suppression of the DY process at large x_F is also well explained including quark multiple rescatterings

Summary

- QCD factorization fails at the kinematic limits, $x_F \to 1$, $x_1 \to 1$, ...
- Nuclear targets cause a suppression of partons with $x \to 1$, due to energy sharing problems
- Suppression of high-p_T hadrons at large rapidity observed by the BRAHMS and STAR Collaborations is well explained
- We predict x_1 (x_F)- scaling = the same nuclear effects at different energies and rapidities corresponding to the same value of x_1. It is in accord with the observed x_F- scaling of nuclear suppression for J/Ψ.
- Model predictions of nuclear suppression at different fixed values of x_F are in a reasonable agreement with NA49 data

Summary

- Predicted strong nuclear suppression at large p_T in direct photon production in $Au - Au$ collisions is not in disagreement with existing PHENIX data
- According to x_1 scaling we predict nuclear suppression effects at large p_T also for hadron production off nuclei even at $\eta = 0$
- Similarly, suppression of Drell-Yan pairs at large x_F observed by E772 and E866 Collaborations is well explained.