Nuclear Modifications of Structure Functions at the LHC.

Carlos A. Salgado (CERN)

- Motivation
- Present experimental information $\longrightarrow$ LHC.
- DGLAP analyses: EKRS, HKM.
- Comparison with other approaches.
- Constraints and comparison with data

Workshop on Monte Carlo tools for the LHC.

CERN, July – 2003.

Motivation

- Subject interesting by itself: (high density QCD)
  - Non-linear terms: saturation; unitarization, ...
- Practical: PDF are needed in order to compute hard cross sections:

$$\sigma^{AB\to kl} \sim \sum_{ij} f_i^A(x_1, Q^2) f_j^B(x_2, Q^2) \otimes d\hat{\sigma}^{ij\to kl}(x_1, x_2, Q^2)$$

DIS experimental data: $R_{F_2}^A(x, Q^2) \equiv \frac{F_2^A(x,Q^2)}{AF_2^N(x,Q^2)} \neq 1$

where (LT, LO) $F_2^A(x, Q^2) = x \sum_q e_q^2 \boxed{f_q^A(x, Q^2)}$

So, nuclear effects to structure functions can be described by nuclear effects to individual PDF.

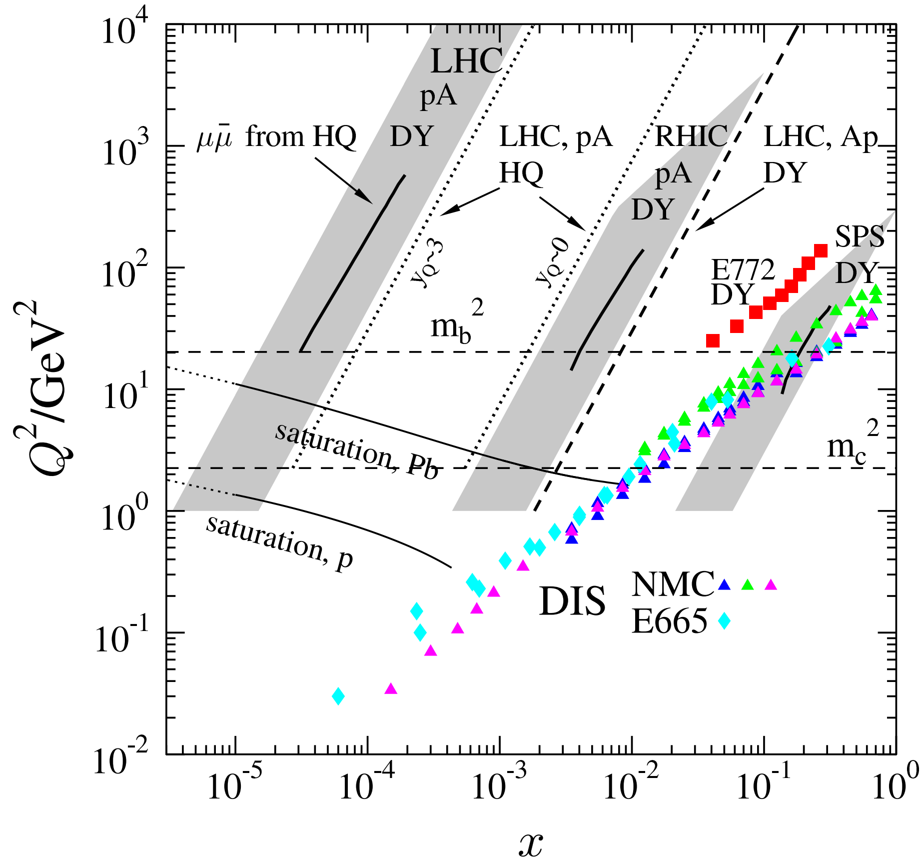
In protons, PDF $\leftrightarrow$ global fits (CTEQ, MRS, GRV...)

The goal of nDGLAP analyses: do the same for nuclei.

Kinematical regions for the LHC

CERN Yellow Report on Hard Probes in HIC at LHC

(contribution by Eskola *et al.* hep-ph/0302185)



Solid lines: Semileptonic decays of D and $\bar{D}$ mesons.

Dotted lines: Open HF production in pA for $y_Q = y_{\bar{Q}} = 0$ or $y_Q = y_{\bar{Q}} = 3$

Saturation for protons: GLRMQ + HERA data (see Eskola, NPB 660, 221) (extrapolation for Pb)

Nuclear effects to PDF's

Several attempts to describe the nuclear modifications to PDF:

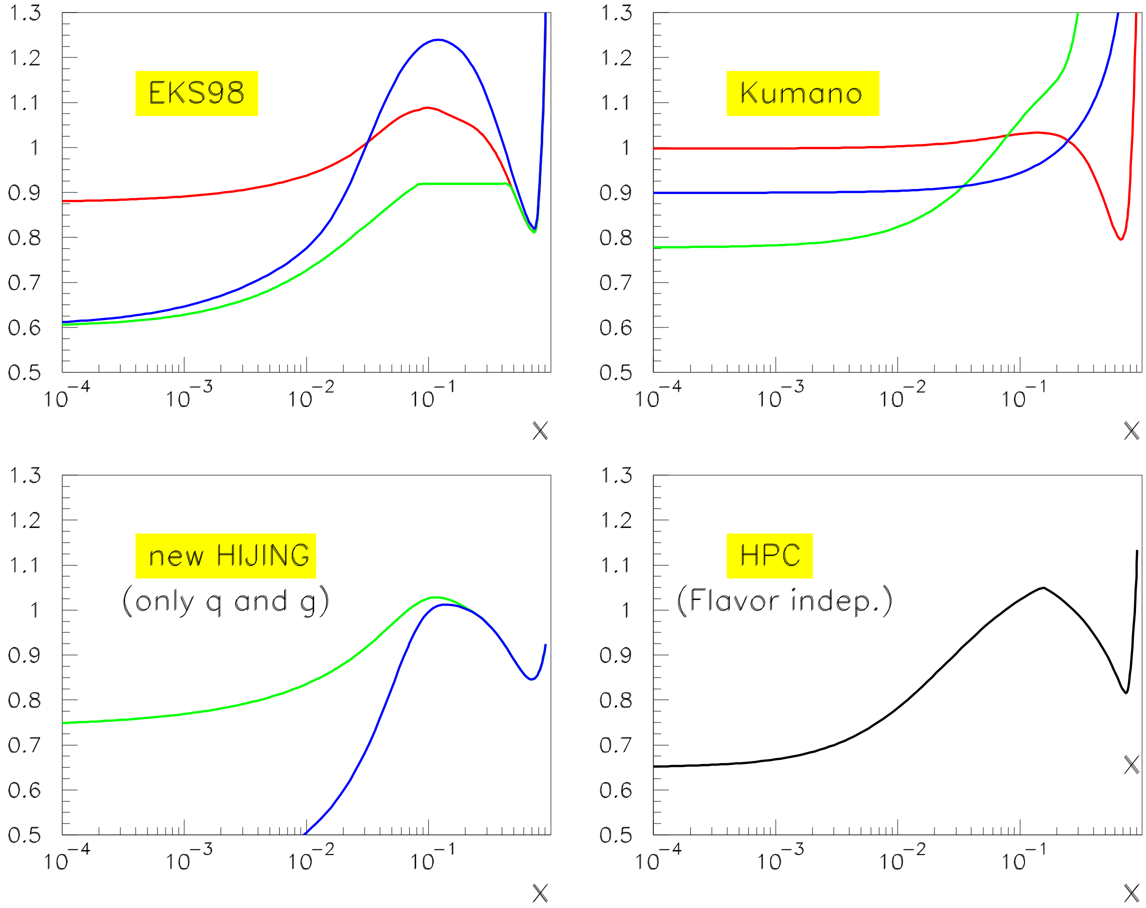
$$R_i^A(x,Q^2) \equiv \frac{f_i^A(x,Q^2)}{f_i^N(x,Q^2)}$$

1. Q^2-independent parameterizations:
   - Flavor-independent:
     $R_{Val}^A = R_{Sea}^A = R_g^A \equiv \boxed{R_{F_2}^A} \leftarrow$ data.
   - Flavor-dependent: new HIJING, different for glue and quarks.
2. Theoretical calculations: Eikonal, diffraction, pQCD, semi-classical (CGC), ...
3. DGLAP analyses – *Global fits*: EKRS, HKM.

Computations in 2. have normally Q^2-dependence.

(By pure DGLAP, or by non-linear equations.)

Initial ratios $R_i^A(x)$ for evolution.



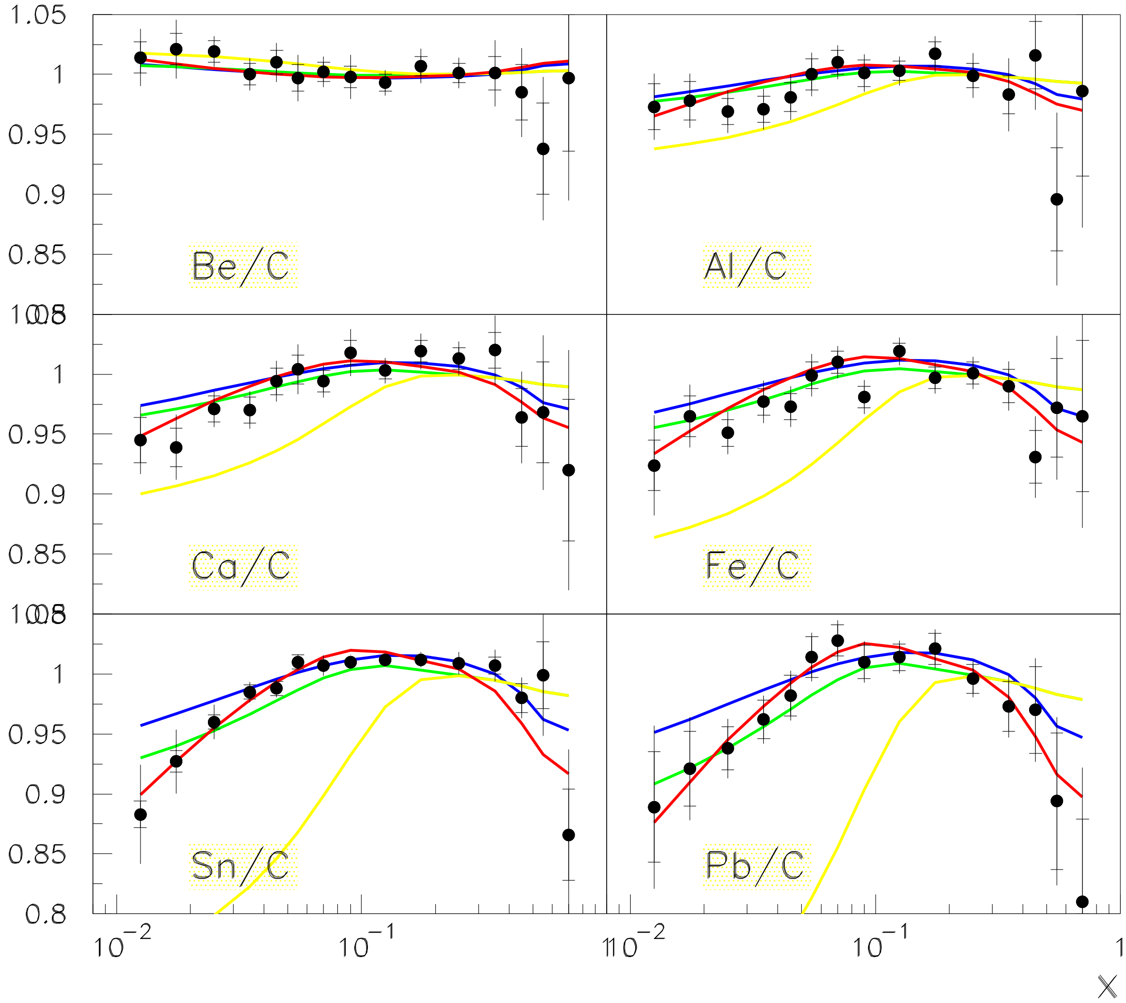
Green: Sea quarks

Blue: gluons

Red: Valence quarks

Different parameterizations to F_2^A/F_2^C

Comparison with NMC data.



Red: EKS98

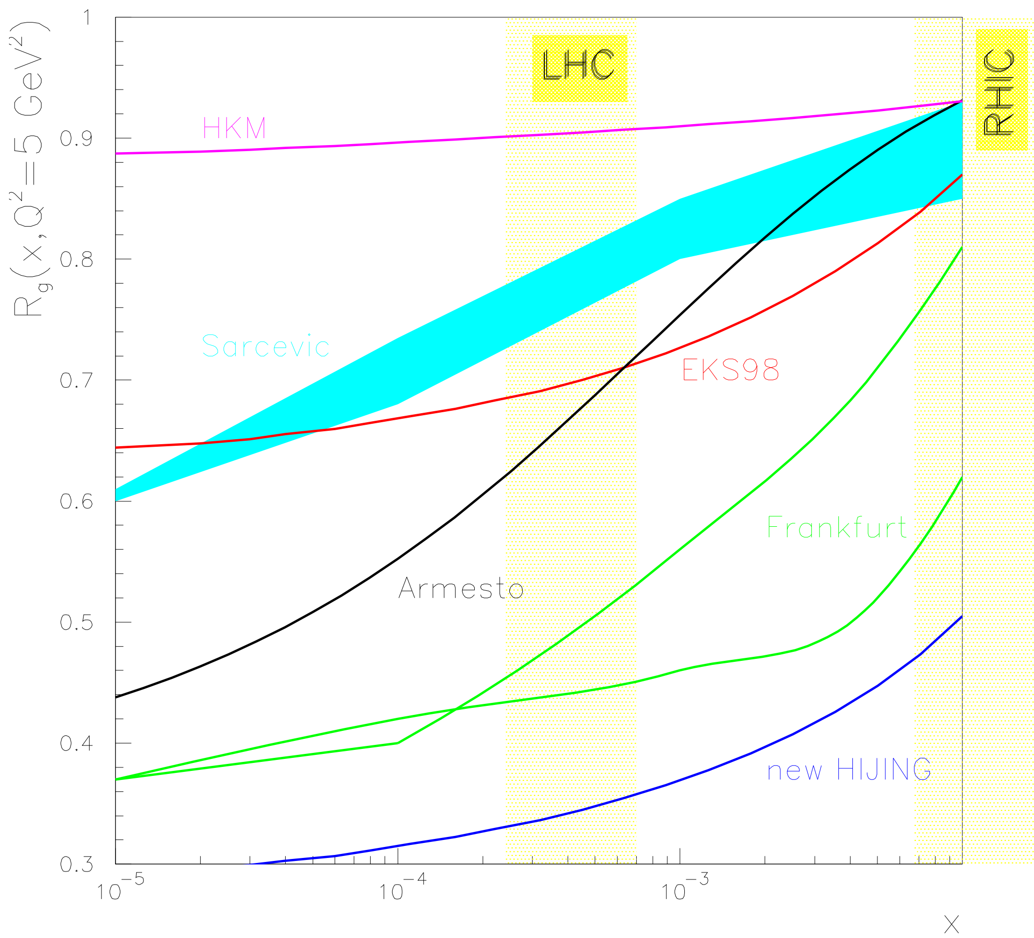
Blue: Kumano et al.

Green: new HIJING

Yellow: old HIJING

Data: Nucl. Phys. **B481**, 3.

Gluon Ratios for Pb at $Q^2 = 5$ GeV^2



Kumano: M. Hirai *et al.* Phys Rev **D64** 034003.

EKS98: K.J. Eskola *et al* Nucl. Phys **B535** 351; Eur. Phys. J. **C9**, 61.

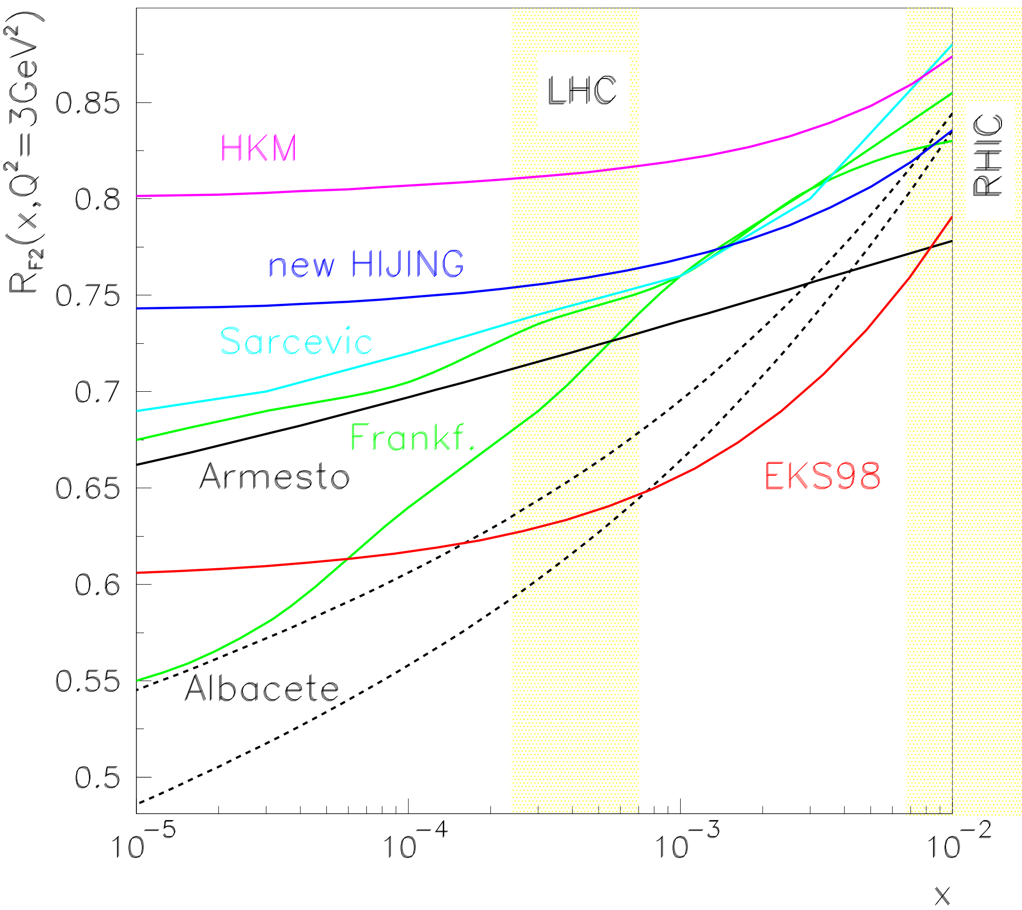
Sarcevic: Z. Huang *et al.* Nucl. Phys. A **637**, 79.

Frankfurt *et al* JHEP **0202**, 027.

Armesto *et al* Eur. Phys. J. C **22** 351.

new HIJING: S. y. Li and X. N. Wang, Phys. Lett. B **527** 85.

F_2 Ratios for Pb at $Q^2 = 3$ GeV^2



Kumano: M. Hirai *et al.* Phys Rev **D64** 034003.

EKS98: K.J. Eskola *et al* Nucl. Phys **B535** 351; Eur. Phys. J. **C9**, 61.

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Frankfurt *et al* JHEP **0202**, 027.

Armesto *et al* Eur. Phys. J. C **22** 351.

new HIJING: S. y. Li and X. N. Wang, Phys. Lett. B **527** 85.

Albacete: N. Armesto *et al.* hep-ph/0304119.

DGLAP analyses. How?

- Well established for protons:
  - Initial parametrization at Q_0^2 of each different flavor.
  - Constraints from momentum and baryon number conservation.
  - DGLAP evolution at LO, NLO, NNLO and fit to data.
- Do the same for nuclei. Problems (some):
  - Not many experimental data (mainly at large Q^2)
  - A new variable (A).
  - Theoretical uncertainties: higher twists, coherence, etc...

So, some assumptions need to be made for nuclei. But still, use the same method as for protons (with more parameters to describe A-dependence).

In practice: initial parametrization for $R_i^A(x, Q_0^2)$, taking some set of known PDF for protons:

$$f_i^A(x, Q_0^2) = R_i^A(x, Q_0^2) f_i^N(x, Q_0^2)$$

Hirai, Kumano and Miyama.

- A-dependence: $1 - A^{-1/3}$ is assumed
- x-dependence:

$$R_i^A(x, Q_0^2) = 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_i(A,Z) + H_i(x)}{(1-x)^{\beta_i}}$$

$H_i(x)$ is a polynomial. 2 different sets:

  - quadratic, $H_i(x) = b_i x + c_i x^2$
  - cubic, $H_i(x) = b_i x + c_i x^2 + d_i x^3$

- Approximations:
  - $\bar{u}^A = \bar{d}^A = \bar{s}^A \equiv \bar{q}^A$
  - β_V, b_V, c_V the same for u_V and d_V.
  - $\beta_{\bar{q}} = \beta_g = 1$, $b_g = -2c_g$
  - a_{u_V}, a_{d_V},a_g fixed by baryon, momentum and charge.

So the free parameters are:

$$b_V,\ c_V,\ \beta_V,\ a_{\bar{q}}\ b_{\bar{q}},\ c_{\bar{q}},\ c_g,\ d_V,\ d_{\bar{q}}$$

(only one free parameter for gluons)

- Minimum χ^2 fit using LO-DGLAP for $Q^2 > Q_0^2$

Eskola, Kolhinen, Ruuskanen and Salgado (EKS98).

- $R_{u_V} = R_{d_V} \equiv R_V$, $R_{\bar{u}} = R_{\bar{d}} = R_{\bar{s}} \equiv R_S$ (only for Q_0^2.)
- First step, fit $R_{F_2}^A(x, Q_0^2)$ then:
  - $R_V \sim R_{F_2}$ for large x.
  - $R_S \sim R_{F_2}$ for small x.
  - DY data $\longrightarrow R_V/R_S$ at medium x.

$$\sigma^{DY} \propto \sum_{\{q,\bar{q}\}} e_q^2 q(x_1, Q^2) \bar{q}(x_2, Q^2)$$

- Further assumptions:
  - Saturation of R_{F_2} at $x \longrightarrow 0$.
  - $R_g \sim R_{F_2}$ at small x.
  - EMC effect (large x) for R_S and R_g.
- Constraints:
  - Q^2-dep. data fixes x_0 where $R_g(x_0) = 1$.
  - Baryon number conservation $\longrightarrow$ valence.
  - Momentum sum rule $\longrightarrow$ gluon antishadowing.
- LO-DGLAP evolution and comparison with data.

Differences between EKRS-HKM.

- HKM is a minimum-χ^2 fit.
- Main difference: two sets of important data in EKRS not taken into account in HKM:
  - DY data (E772) – Fixes the relative effects in valence and sea.

    these data makes $R_S(x, Q_0^2) < 1$ at medium x

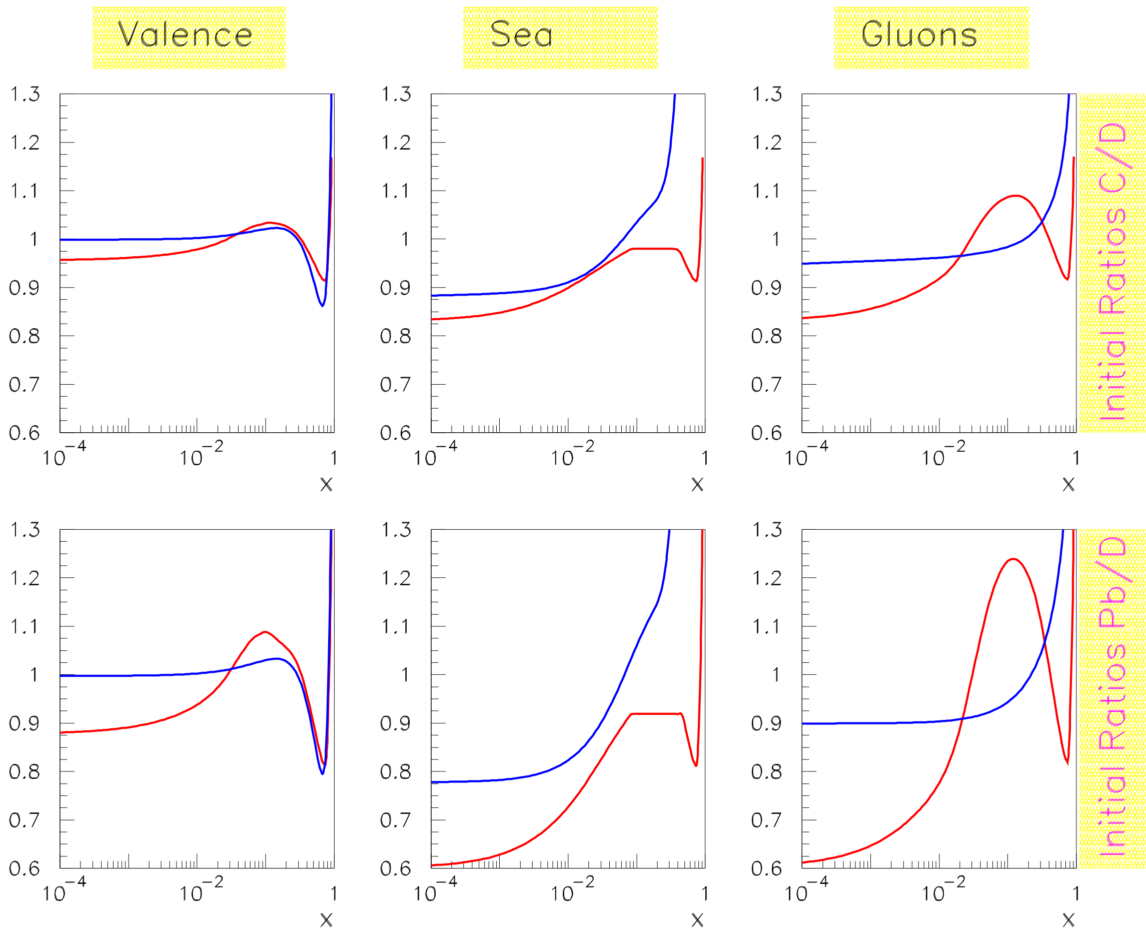
  - Q^2–dependence of F_2^{Sn}/F_2^C (NMC)

    Used to estimate the point where $R_g = 1$

  - Also, data in A–dependence by NMC not taken in Kumano (less important).

As a result sea and valence distributions are different in EKRS and HKM and gluons are not well constrained for Kumano et al.

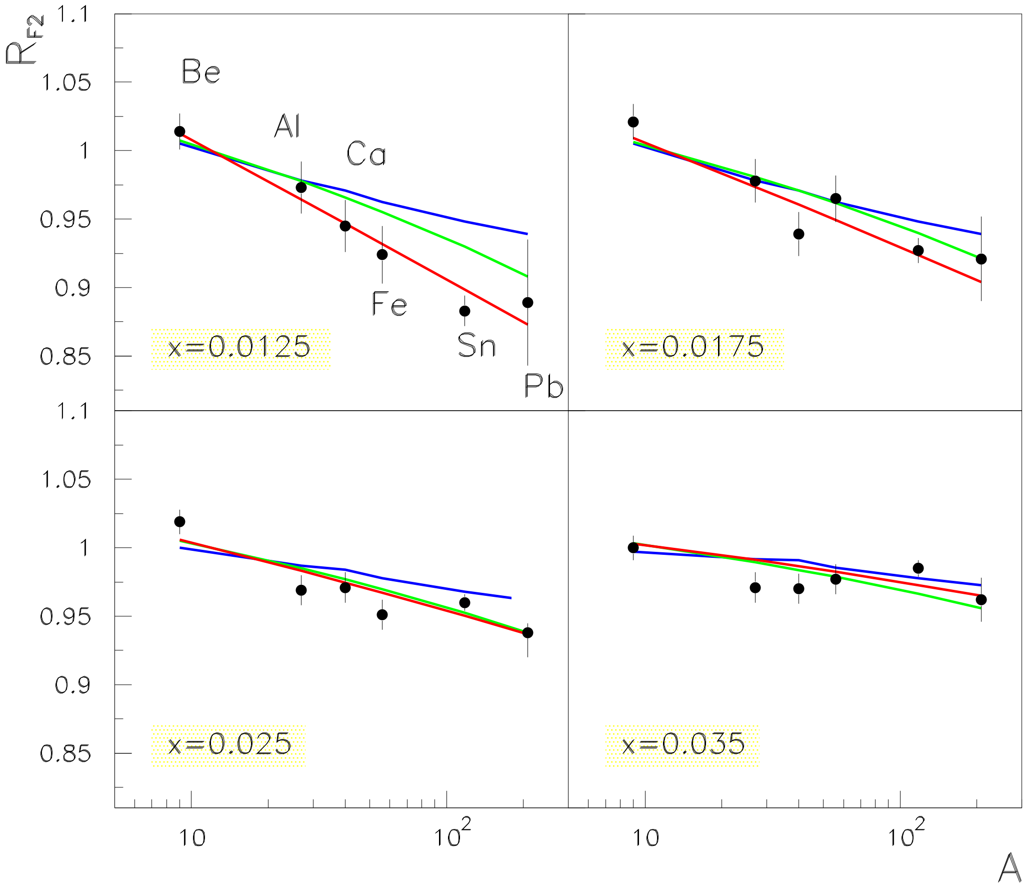
PDF DISTRIBUTIONS AT $Q_0^2 = 2.25$ GeV^2



Red: EKS98

Blue: Kumano et al.

A-dependence of F_2^A/F_2^C for different x



Data from NMC, Nucl. Phys. **B481**, 3.

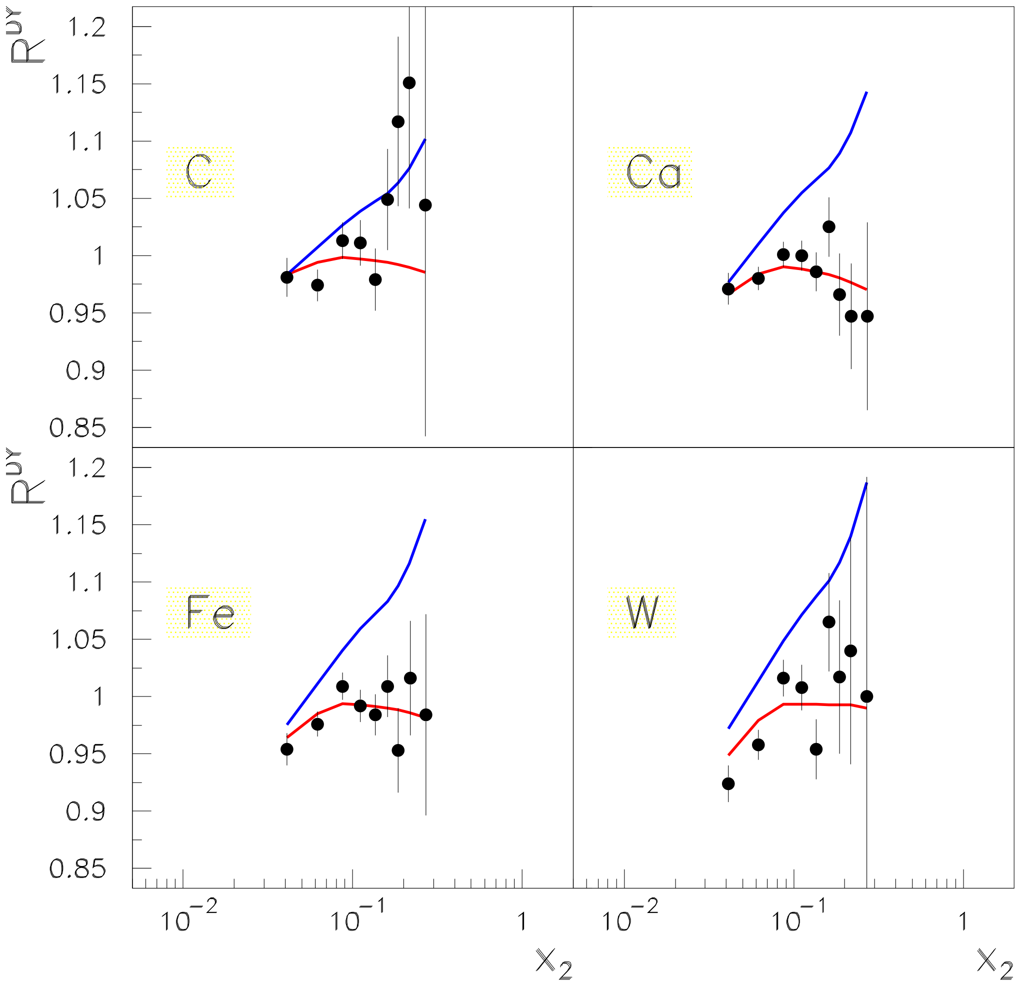
Red: EKS98

Blue: Kumano

Green: new HIJING

DY data from E772

(Data: Phys. Rev. Lett. **64** (1990) 2479)

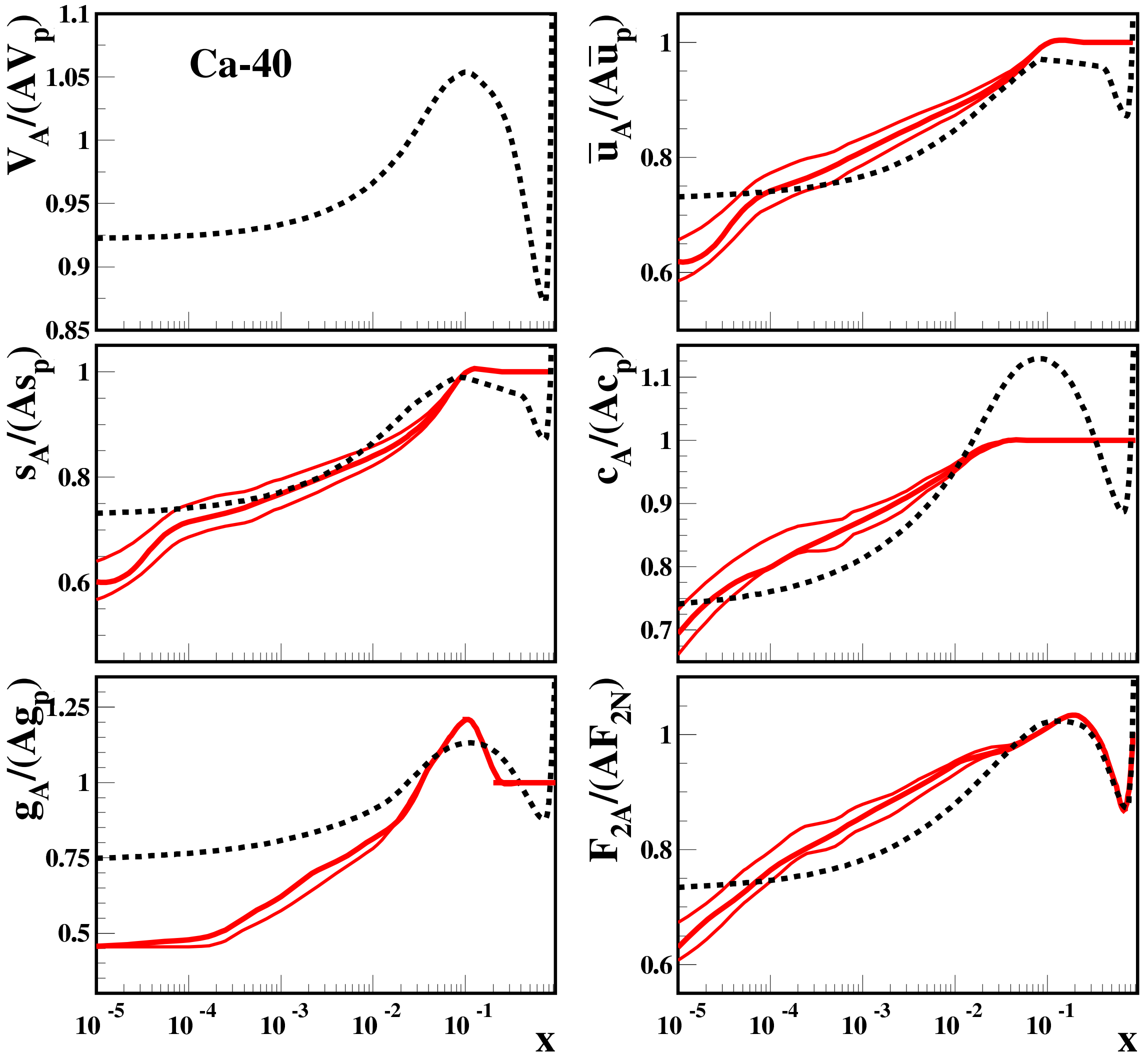


Red: EKS98

Blue: Kumano et al.

Comparison EKRS–FGS

Frankfurt, Guzey and Strikman [arXiv:hep-ph/0303022] compute initial conditions from diffraction in lp (HERA) and perform DGLAP (NLO) evolution.



Red lines: FGS, Black lines EKS98.

(valence quarks in FGS taken from EKS98)

Constraints to gluons from DIS data.

At small values of x, LO–DGLAP gives

$$\frac{\partial F_2^{p(n)}(x,Q^2)}{\partial \log Q^2} \approx \frac{10\alpha_s}{27\pi} xg(2x,Q^2).$$

This leads to

$$\frac{\partial R_{F_2}^A(x,Q^2)}{\partial \log Q^2} \approx \frac{10\alpha_s}{27\pi} \frac{xg(2x,Q^2)}{\frac{1}{2}F_2^{\rm D}(x,Q^2)} \left\{ R_g^A(2x,Q^2) - R_{F_2}^A(x,Q^2) \right\},$$

NMC–data in Q^2–dependence of F_2^{Sn}/F_2^C has positive slope $\longrightarrow R_g^A(2x,Q^2) \geq R_{F_2}^A(x,Q^2)$.

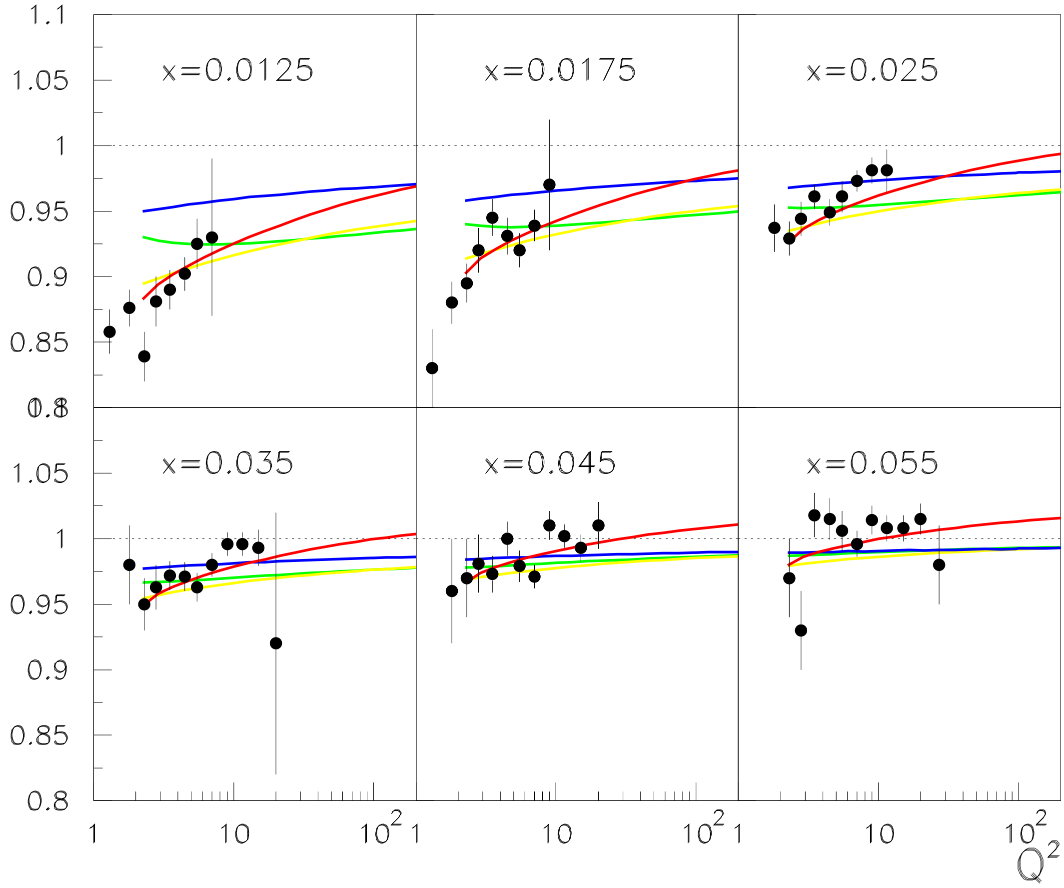
We have computed this for full DGLAP (no approximation made).

Four different parameterizations for Q_0^2 used:

- EKS98
- Kumano et al
- Hard Probe Collaboration (HPC)
- new HIJING $\leftarrow$ very strong gluon shadowing.

Q^2-dependence of the ratios F_2^{Sn}/F_2^C

Comparison with NMC data.



Red: EKS98

Blue: Kumano et al.

Green: new HIJING

Yellow: HPC

Data: Nucl. Phys. **B481**, 3.

Non-linear terms.

When the density of gluons becomes very large, non-linear terms as gluon fusion are expected to become important in the evolution eqs.

Gluon fusion corrections to DGLAP were studied by e.g. Mueller and Qiu.

$$\begin{aligned}
\frac{\partial x g_A}{\partial \log Q^2} &= \left(\frac{\partial x g_A}{\partial \log Q^2}\right)_0 - \frac{1}{Q^2}\mathcal{R}_{ggg}(x,Q^2) \\
\frac{\partial x \bar{q}_A}{\partial \log Q^2} &= \left(\frac{\partial x \bar{q}_A}{\partial \log Q^2}\right)_0 - \frac{1}{Q^2}\left[\mathcal{R}_{\bar{q}gg}(x,Q^2) - \mathcal{R}^{\mathrm{HT}}_{\bar{q}gg}(x,Q^2)\right] \\
\frac{\partial x g_{HT}}{\partial \log Q^2} &= -\mathcal{R}_{ggg}(x,Q^2)
\end{aligned}$$

Where $(\ldots)_0$ refers to the normal DGLAP. So, these terms modify Q^2–evolution.

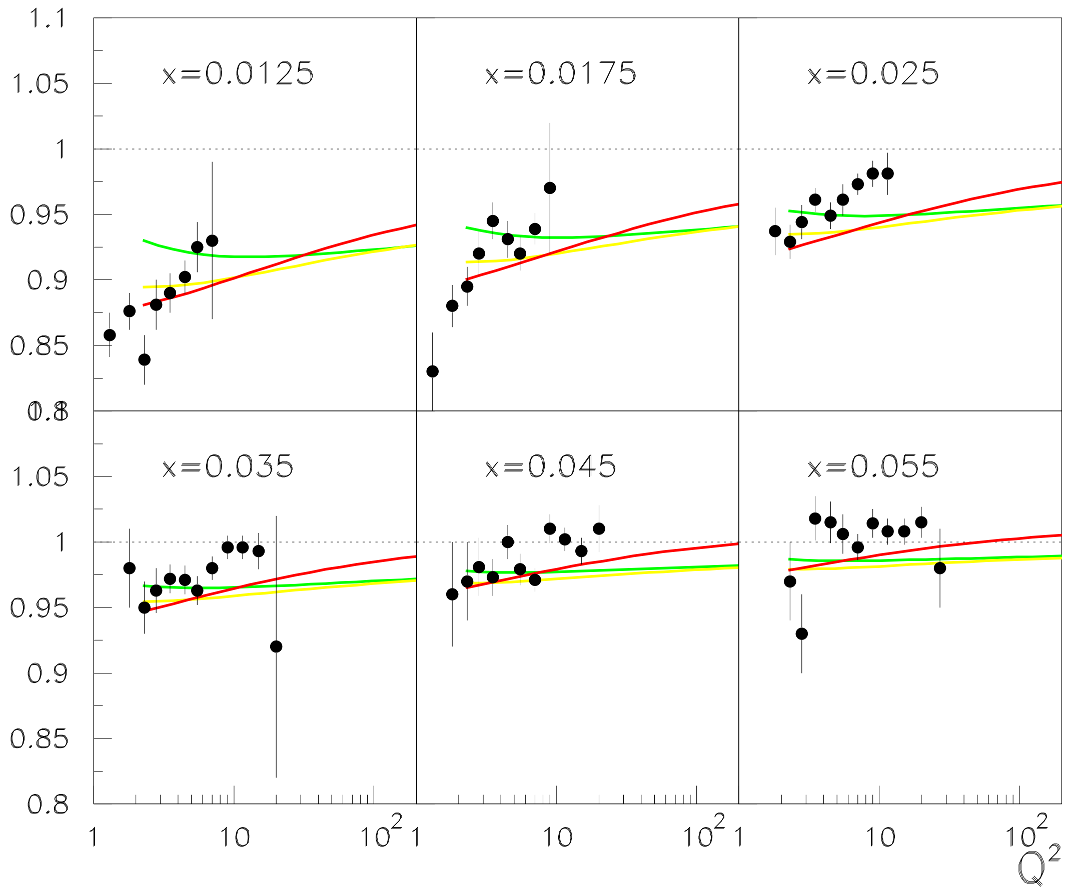
Does this allow for stronger gluon shadowing?

We repeat the evolution for EKS98, HPC and new HIJING including these terms.

(we don't try to repeat the fit, only see the influence)

MQ-terms reduce the slope

DGLAP corrected by MQ-terms



Red: EKS98

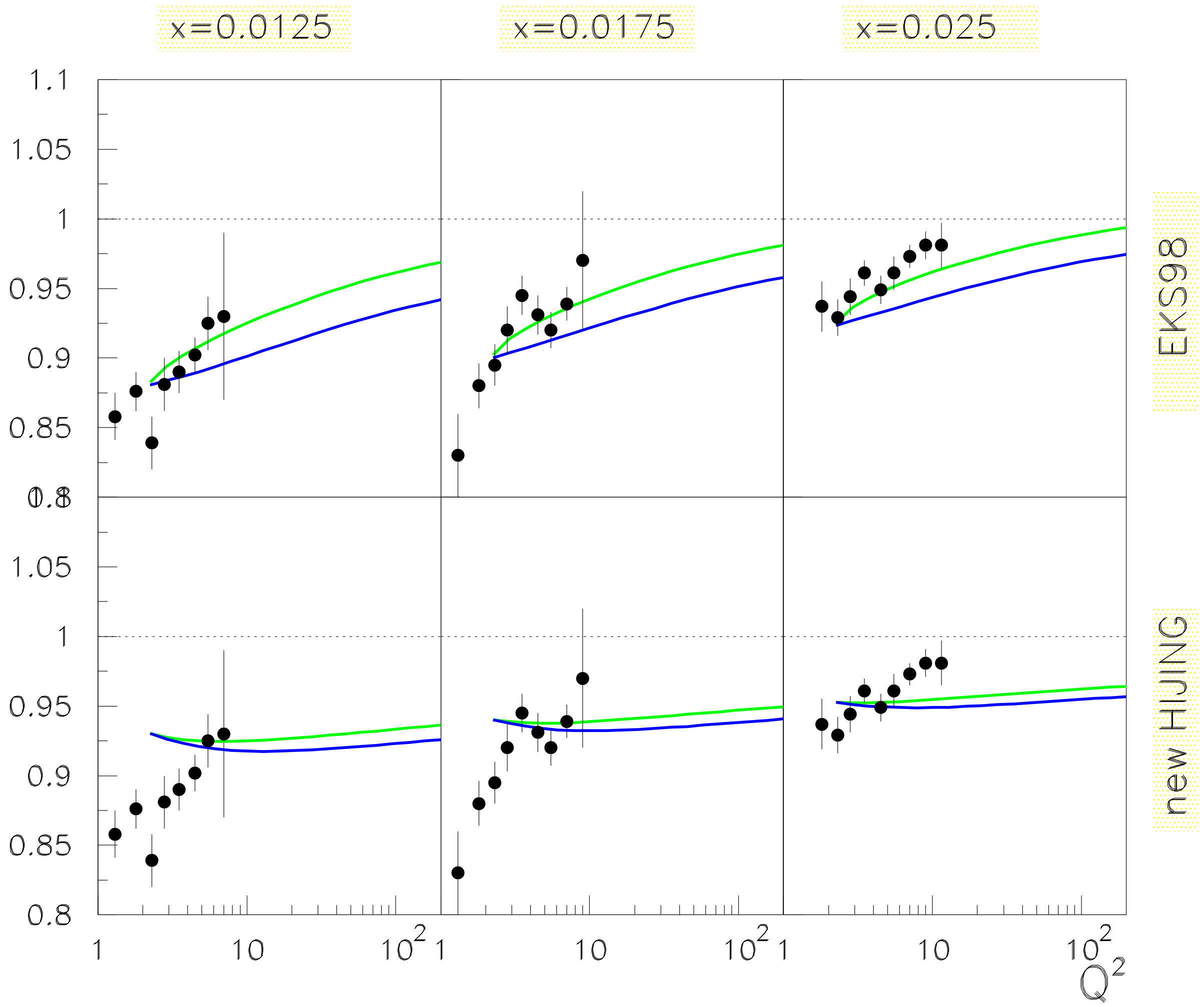
Green: new HIJING

Yellow: HPC

Data: Nucl. Phys. **B481**, 3.

Pure DGLAP vs DGLAP+MQ

EKS98 and new HIJING.



Green: DGLAP

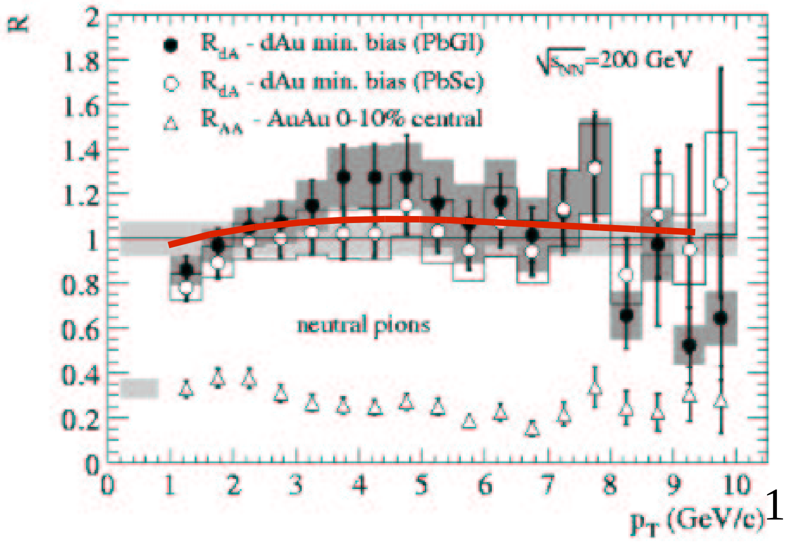
Blue: DGLAP+MQ

Slopes are smaller with MQ.

(More negative at Q_0^2 in the case of strong gluon shadowing)

Comparison EKS98 – RHIC data.

RHIC has measure the ratio of π^0 production in dAu collisions over pp collisions.

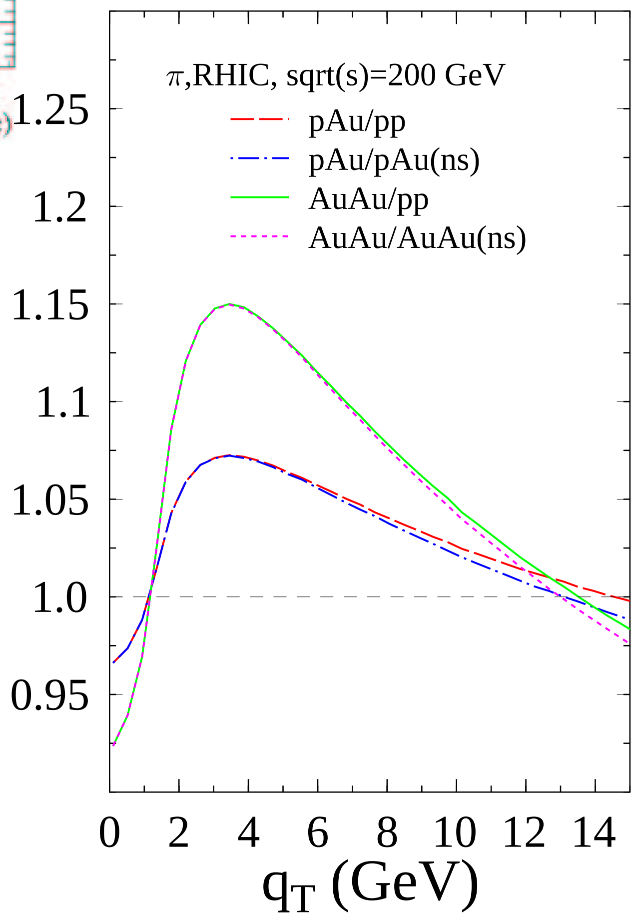


Red line: pQCD calculation at LO by K. Eskola and H. Honkanen, (NPA 713, 167).

However, more effects could be present here: Cronin...

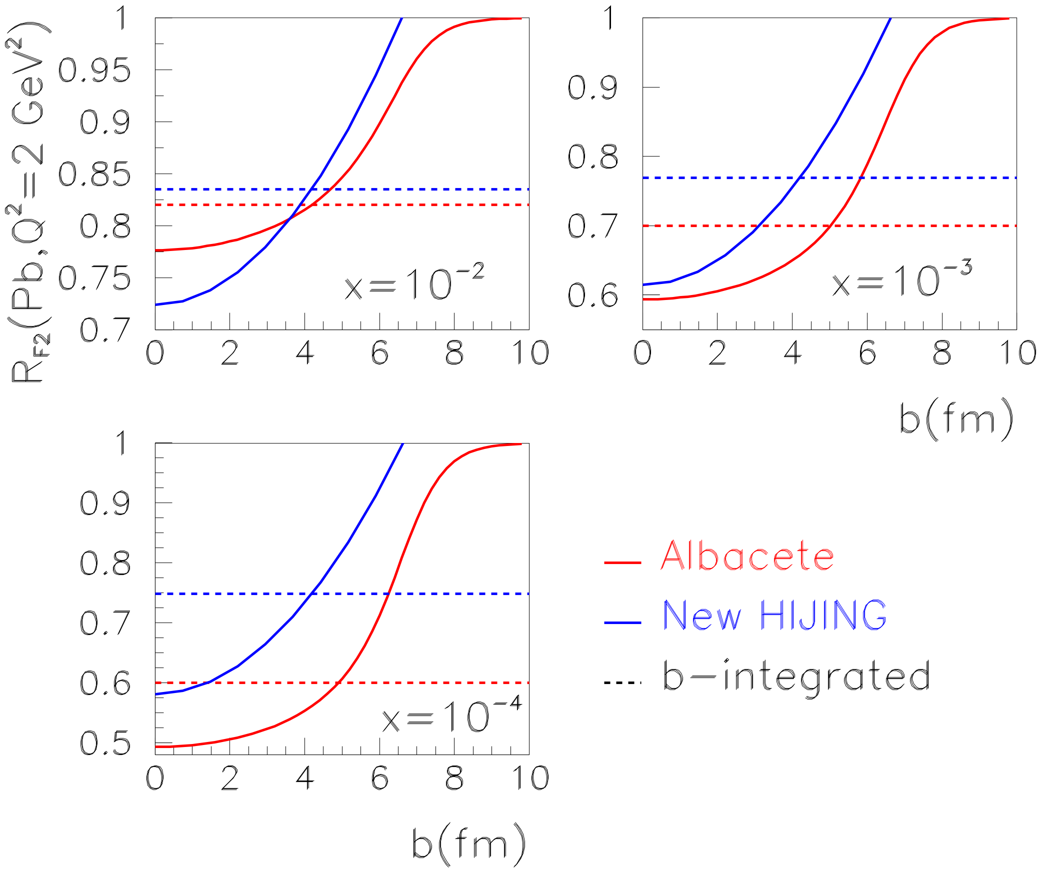
RHIC will also measure high-p_t particle production in the forward direction

$\longrightarrow$ small-x nPDF.



Centrality dependence.

No information from present experimental data.



Albacete *et al.* [hep-ph/0304119] $\longrightarrow$ shadowing from diffraction in lp.

New HIJING fits RHIC data in total multiplicities.

Conclusions.

- A description of nuclear effects in F_2^A is possible by including all the effects in nPDF.
- Two LT-LO-DGLAP analyses compared (EKRS, HKM). Including data on Q^2–dependence of F_2^{Sn}/F_2^C and DY production important to constraint sea and gluons. FGS DGLAP evolution with LT initial conditions from diffraction (also sum rules, etc..)
- Rather strong constraint to nuclear gluons come from NMC data on Q^2–dependence. These data rules out very strong gluon shadowing for $x \sim 0.01$
- Check: including MQ–terms in DGLAP evolution disfavors even more the strong gluon shadowing.
- A safe extrapolation of these results to LHC energies will need more data in the region $x \lesssim 10^{-3}$ (HERA, RHIC).
- Apart from the practical applications these studies are important in the search of non-linear effects, saturation of partonic densities, etc...