# Nuclear Modifications of Structure Functions at the LHC.

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- 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.

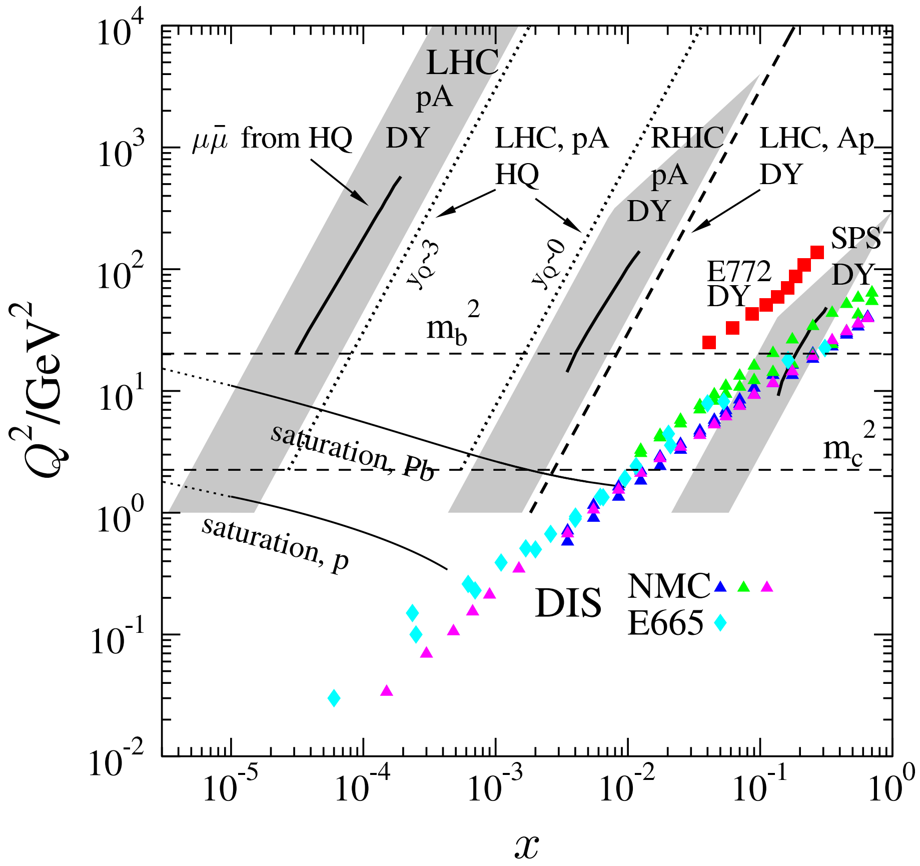
In protons, PDF $\leftrightarrow$ global fits (CTEQ, MRS, GRV...)

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)

## $\boxed{\text{Nuclear effects to PDF's}}$

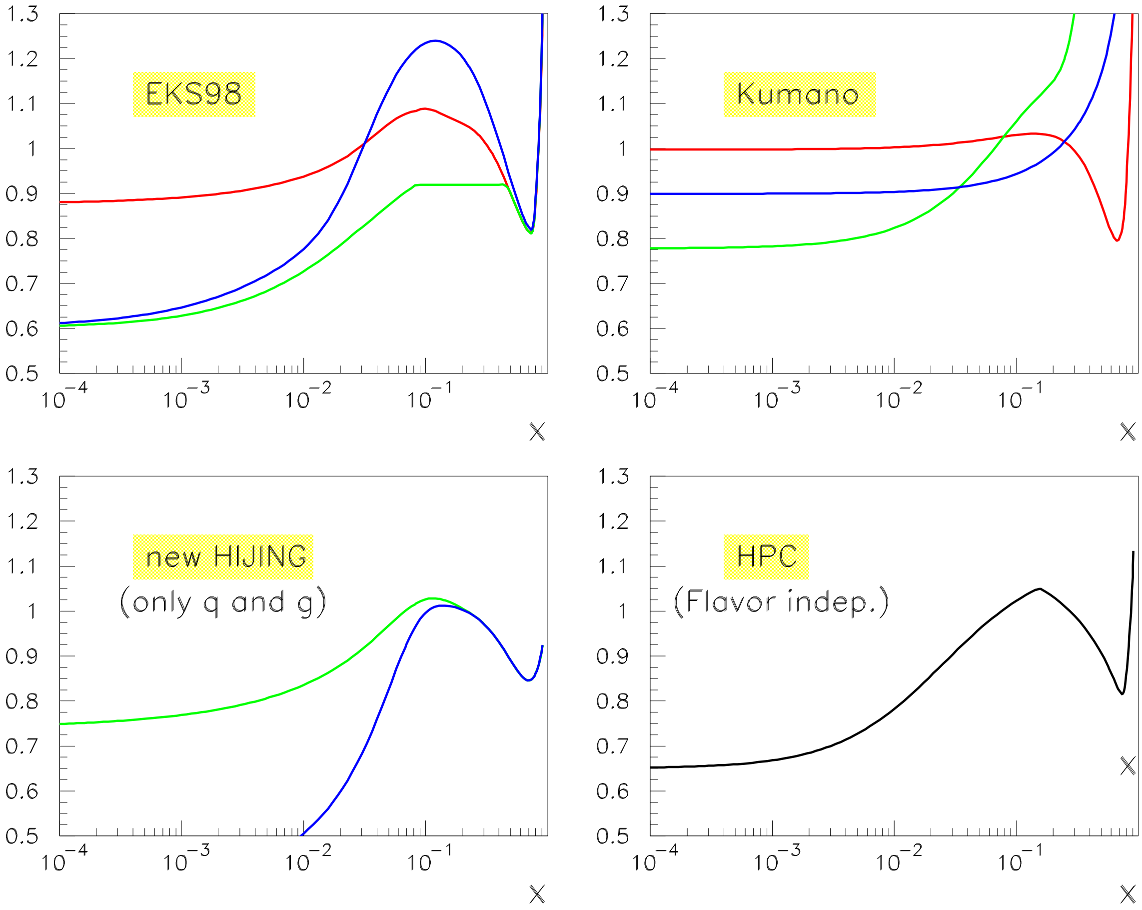
Several attempts to describe the nuclear modifications to PDF:

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

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.



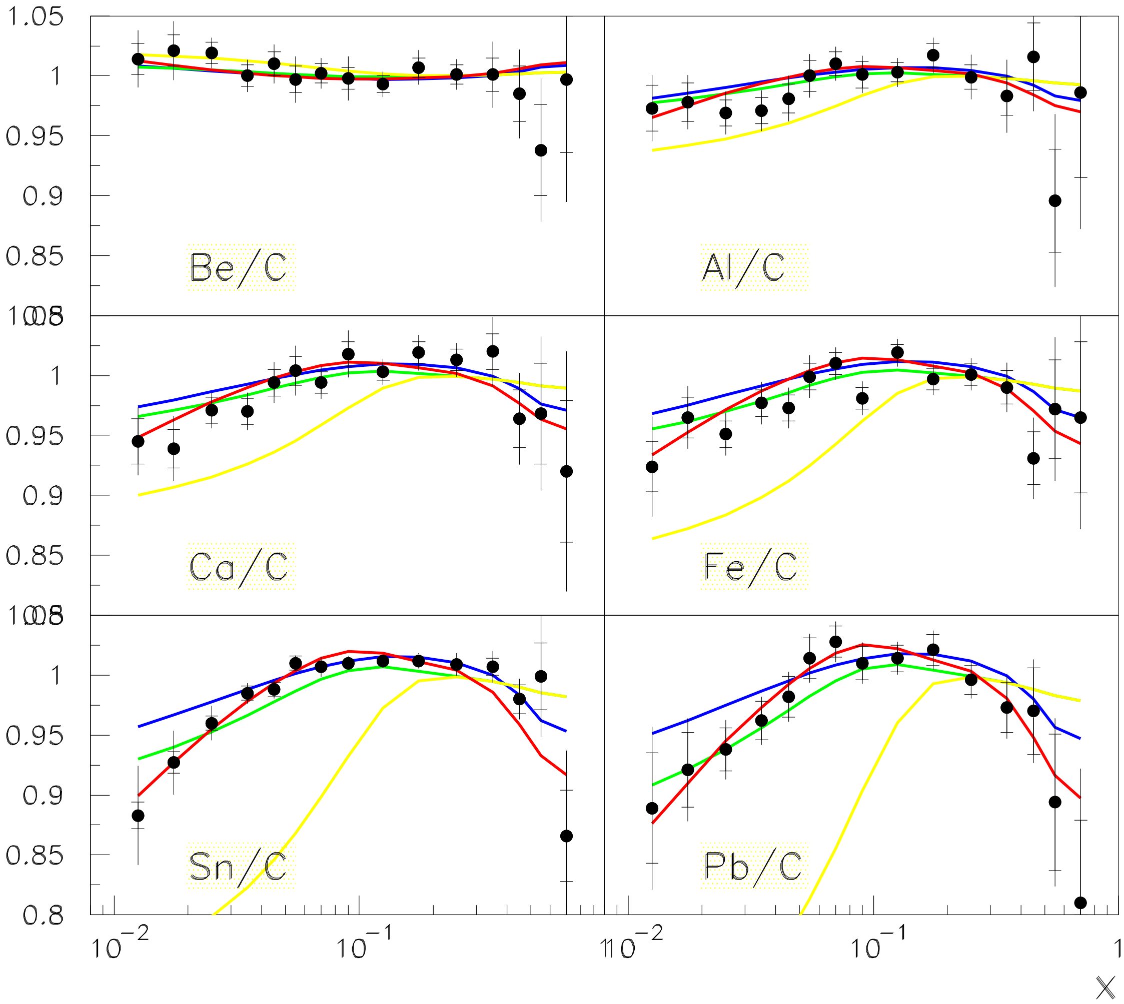

Green: Sea quarks

Blue: gluons

Red: Valence quarks

# Different parameterizations to $F_2^A/F_2^C$

# Comparison with NMC data.




Red: EKS98

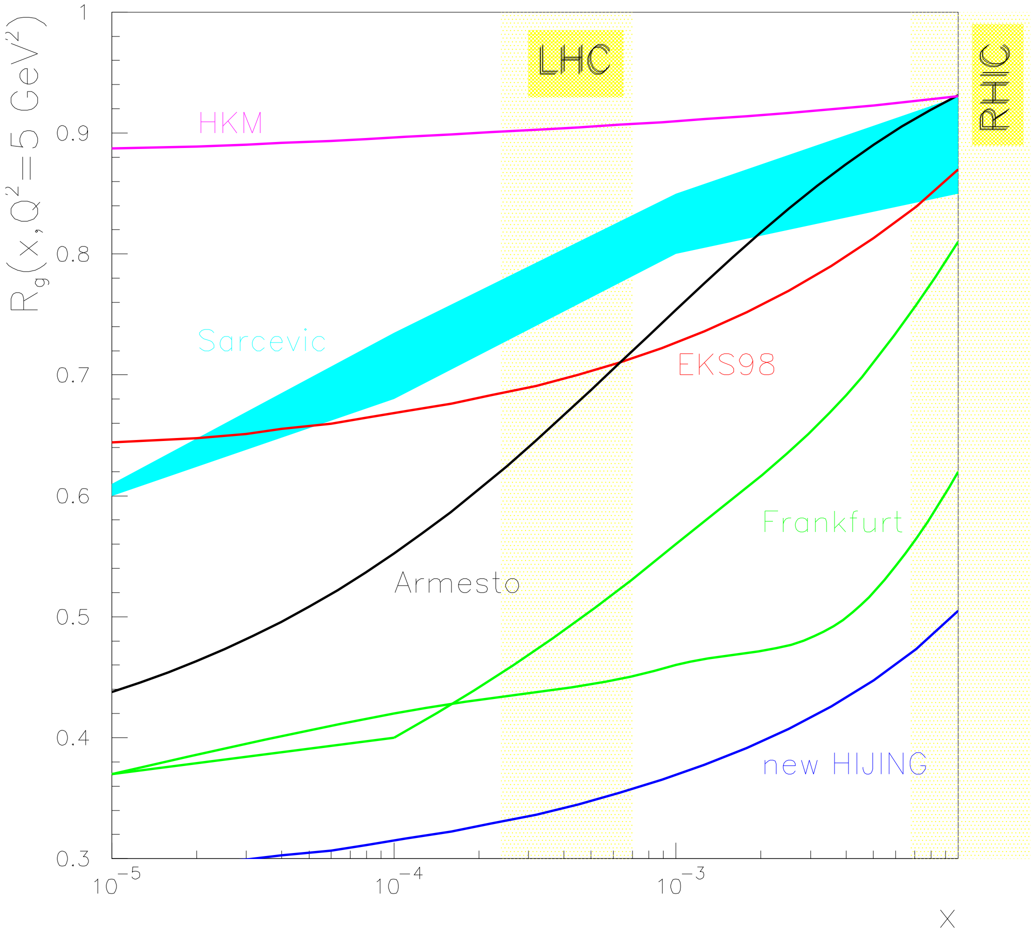
Blue: Kumano et al.

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.

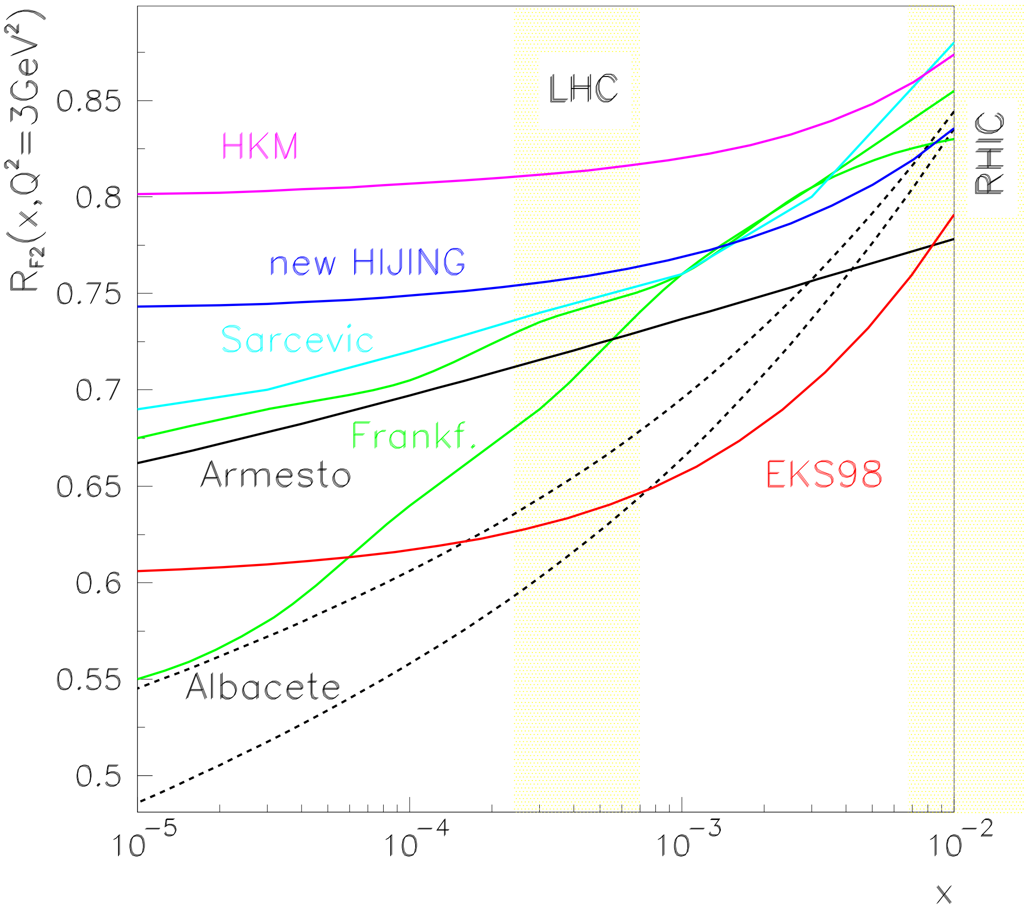
Sarcevic: Z. Huang *et al.* Nucl. Phys. A **637**, 79.

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.

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.

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:

  – $\bar{u}^A = \bar{d}^A = \bar{s}^A \equiv \bar{q}^A$

  – $\beta_V$, $b_V$, $c_V$ 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:

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

(only one free parameter for gluons)

- Minimum $\chi^2$ 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.

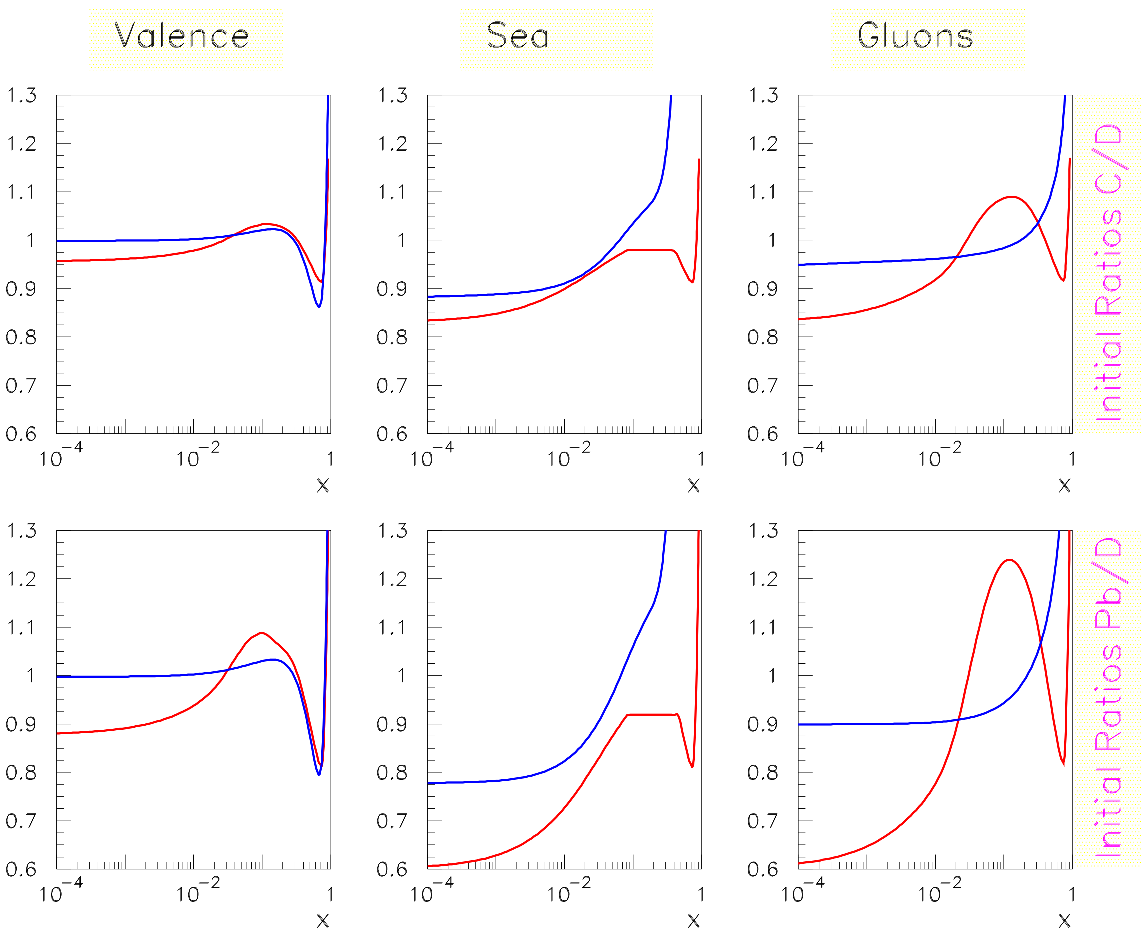
- HKM is a minimum-$\chi^2$ fit.
- Main difference: two sets of important data in EKRS not taken into account in HKM:
  - DY data (E772) – Fixes the relative effects in valence and sea.

    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.

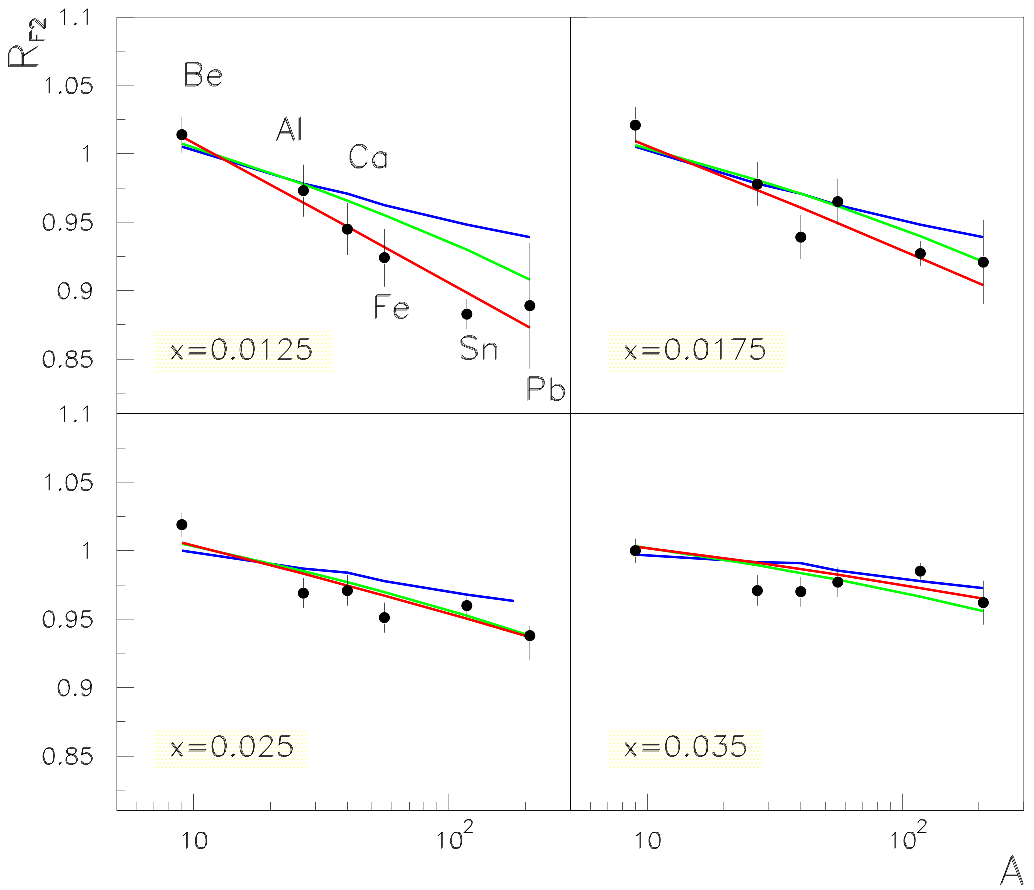
# PDF DISTRIBUTIONS AT $Q_0^2 = 2.25$ GeV$^2$




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.

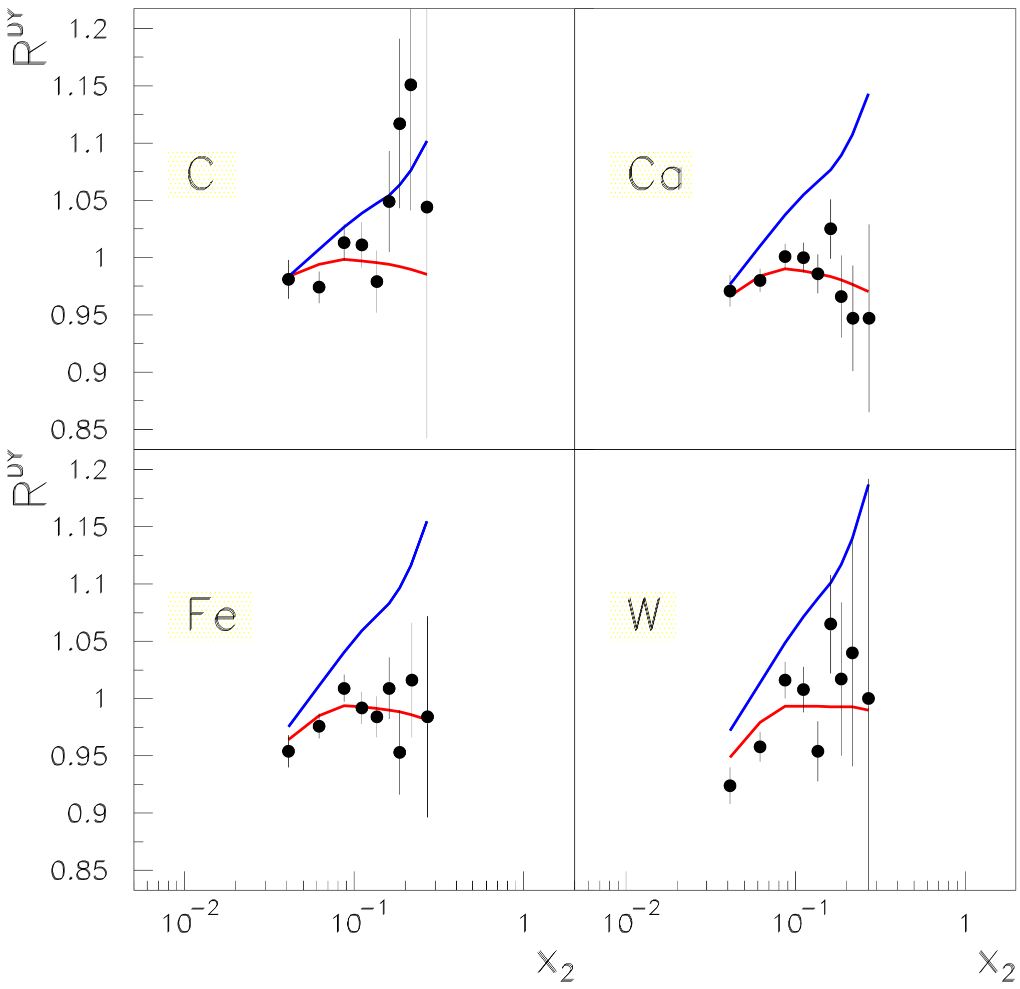
Red: EKS98

Blue: Kumano

Green: new HIJING

# DY data from E772

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

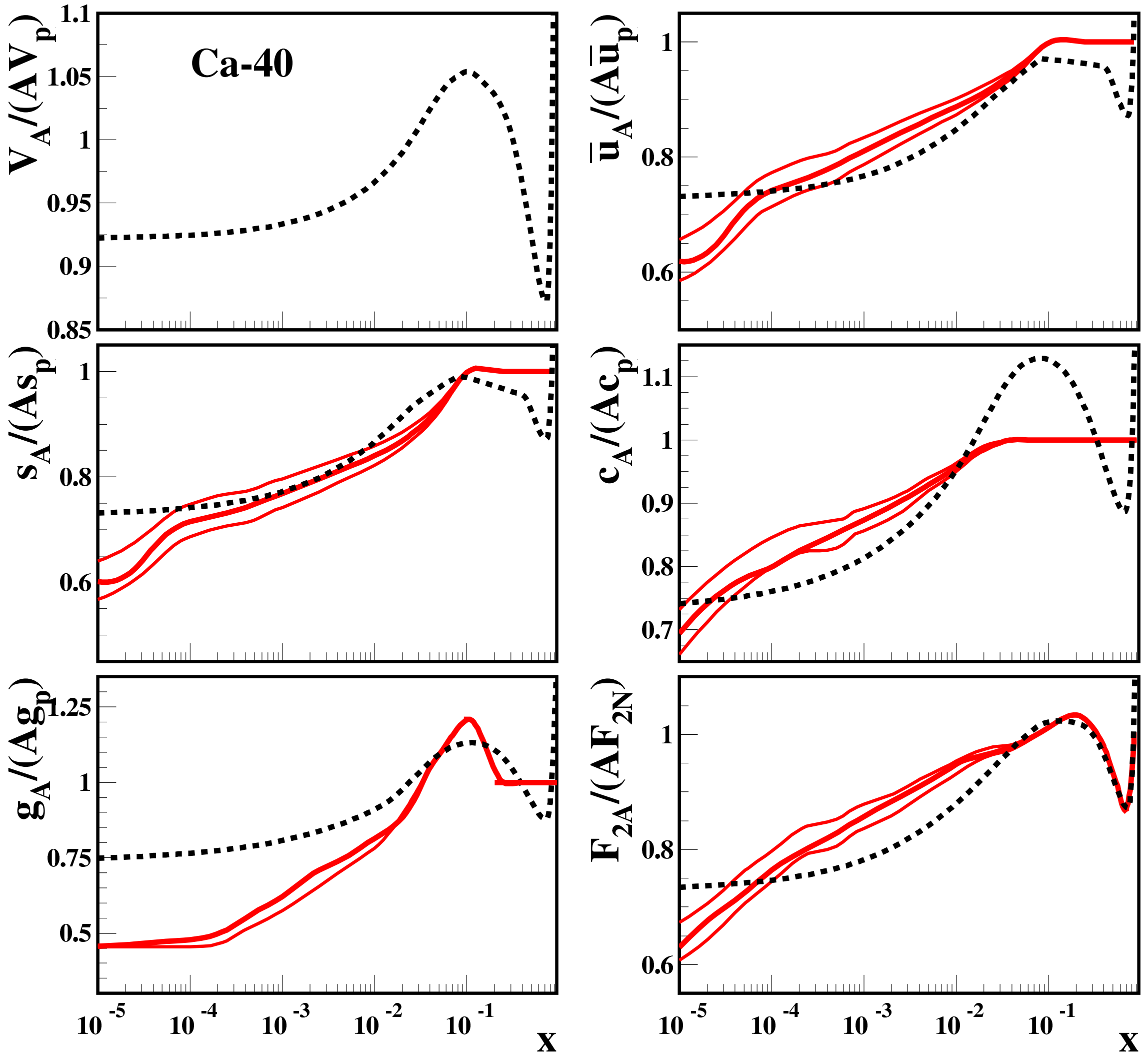



Red: EKS98

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

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

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

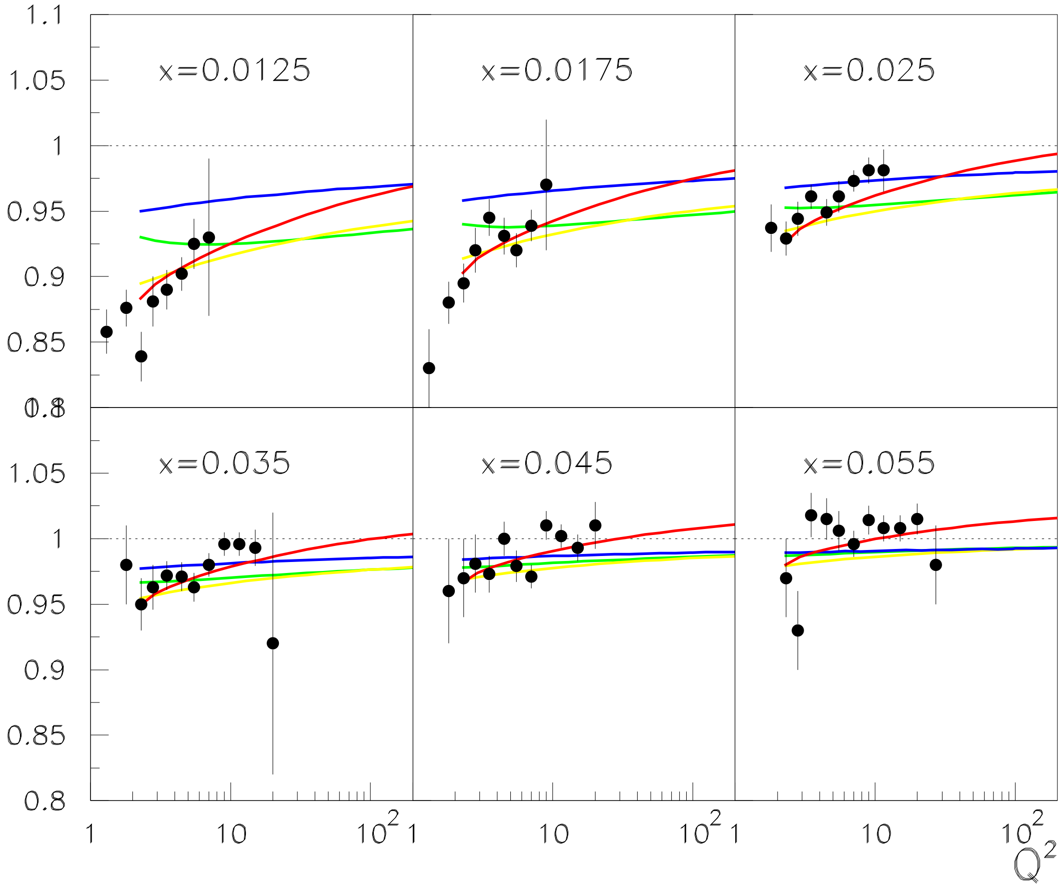
We have computed this for full DGLAP (no approximation made).

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.

## $\boxed{\text{Non-linear terms.}}$

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.

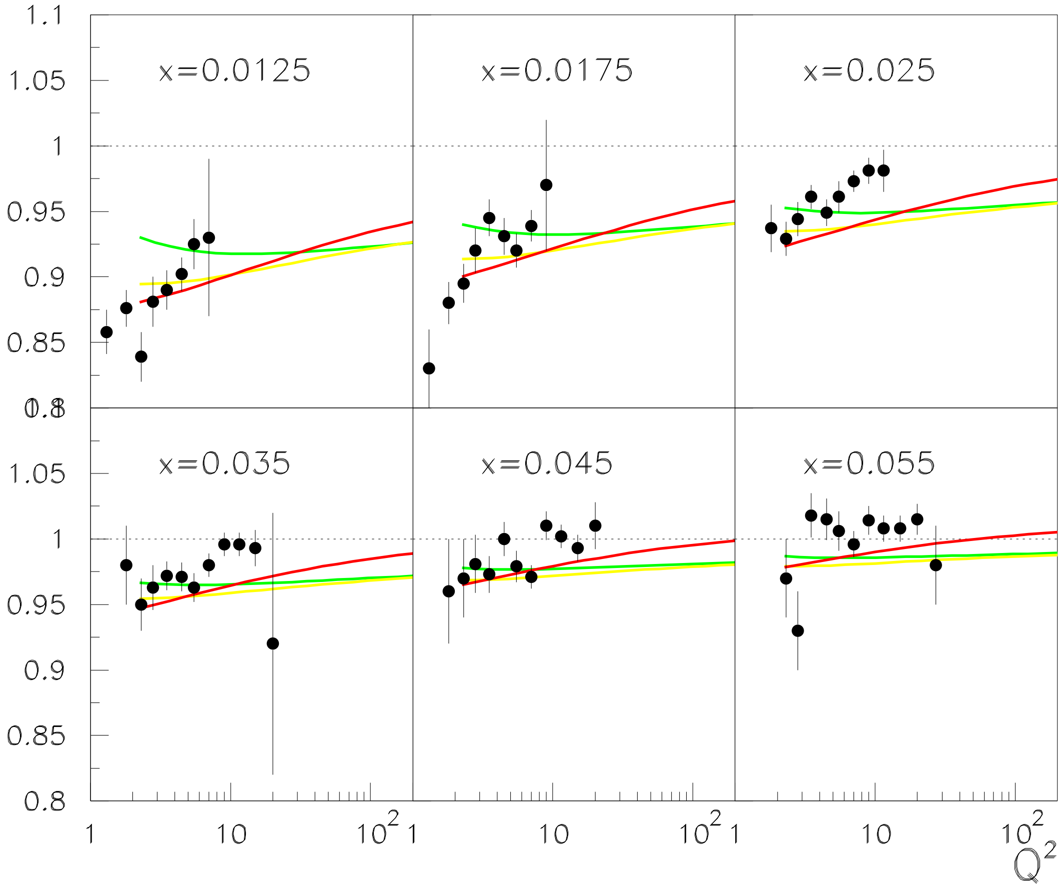
$\boxed{\text{Does this allow for stronger gluon shadowing?}}$

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)

$\boxed{\text{MQ-terms reduce the slope}}$

# DGLAP corrected by MQ-terms




Red: EKS98

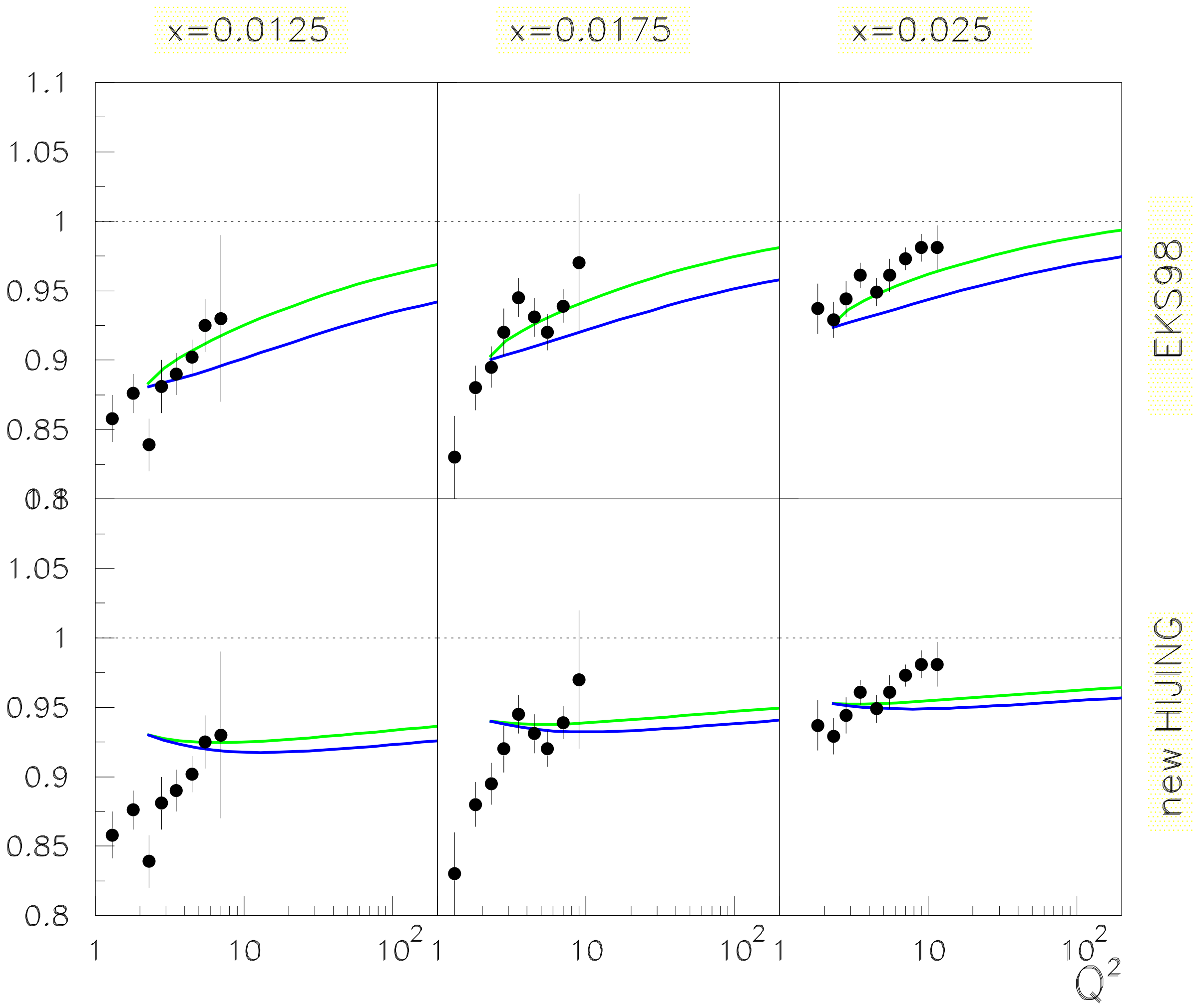
Green: new HIJING

Yellow: HPC

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

# Pure DGLAP vs DGLAP+MQ

## EKS98 and new HIJING.




Green: DGLAP

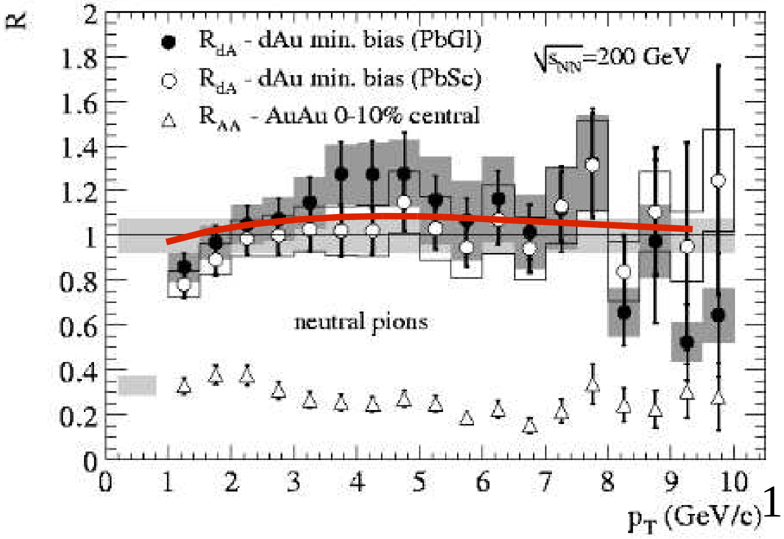
Blue: DGLAP+MQ

**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 $\pi^0$ production in dAu collisions over pp collisions.

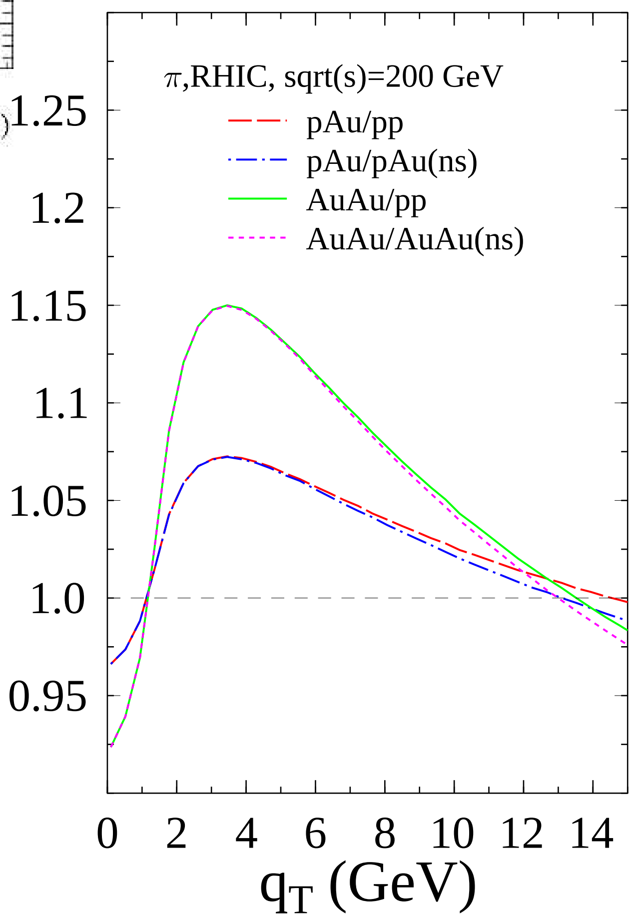



Red line: pQCD calculation at LO by K. Eskola and H. Honkanen, (NPA 713, 167).

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

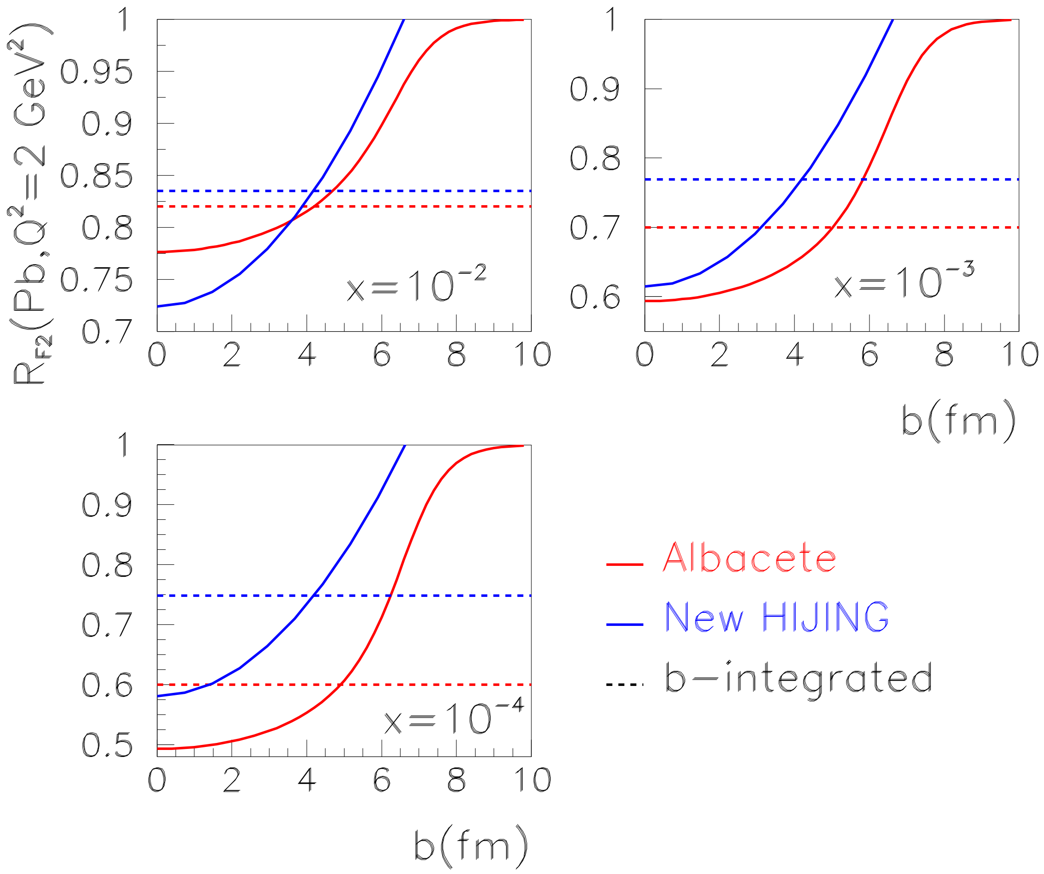
RHIC will also measure high-$p_t$ particle production in the forward direction

$\boxed{\longrightarrow \text{small-}x \text{ nPDF.}}$



## 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...