

NPDF FROM NEUTRINO & CHARGED LEPTON DATA

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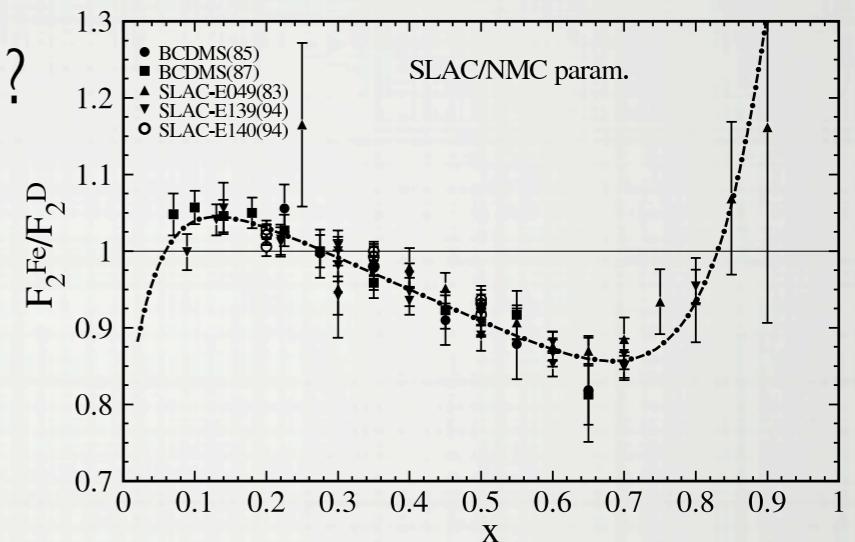
arXiv:0710.4897 [hep-ph] arXiv:0907.2357 [hep-ph]

OUTLINE

1. Introduction to parton distribution functions
2. Nuclear effects in PDFs
3. Overview of global nPDF analysis
4. Generalized CTEQ framework
5. Results and Outlook

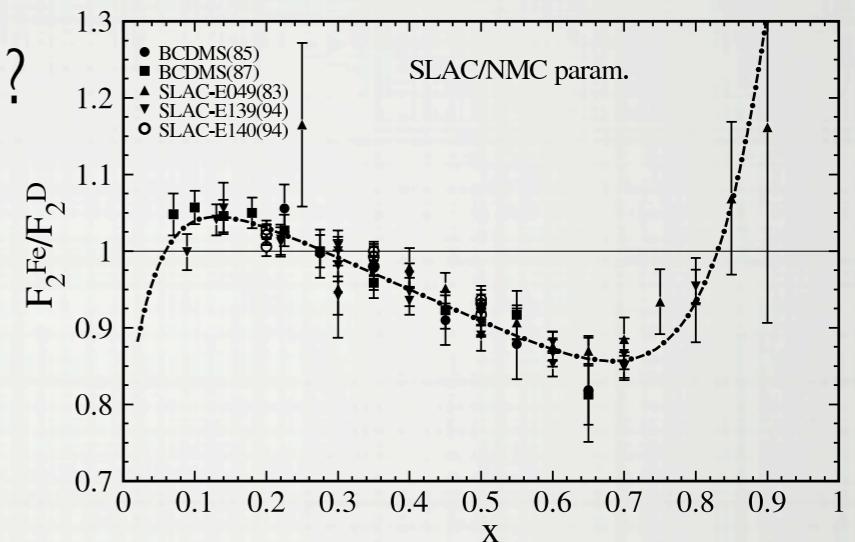
NUCLEAR PDFS

- What are nuclear parton density functions (nPDF) ?
 - parton densities for partons in bound proton & neutron



NUCLEAR PDFS

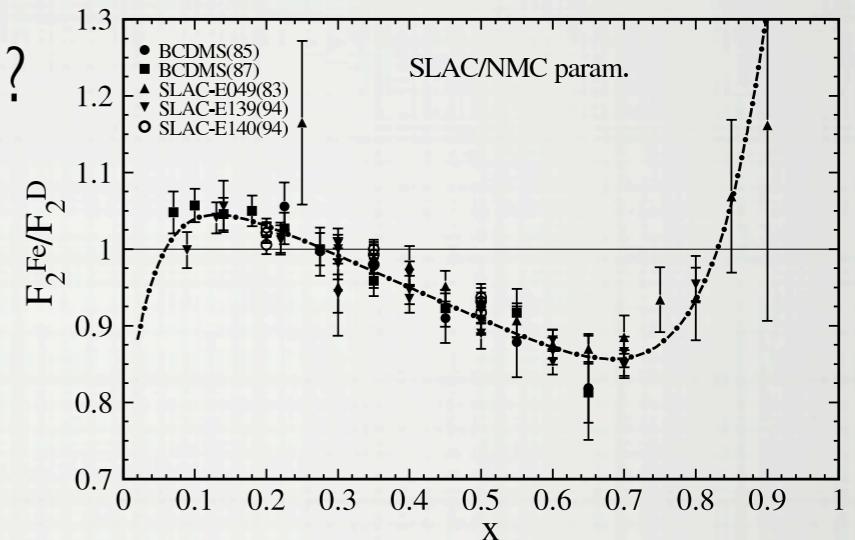
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- Where are nuclear parton density functions useful ?

NUCLEAR PDFS

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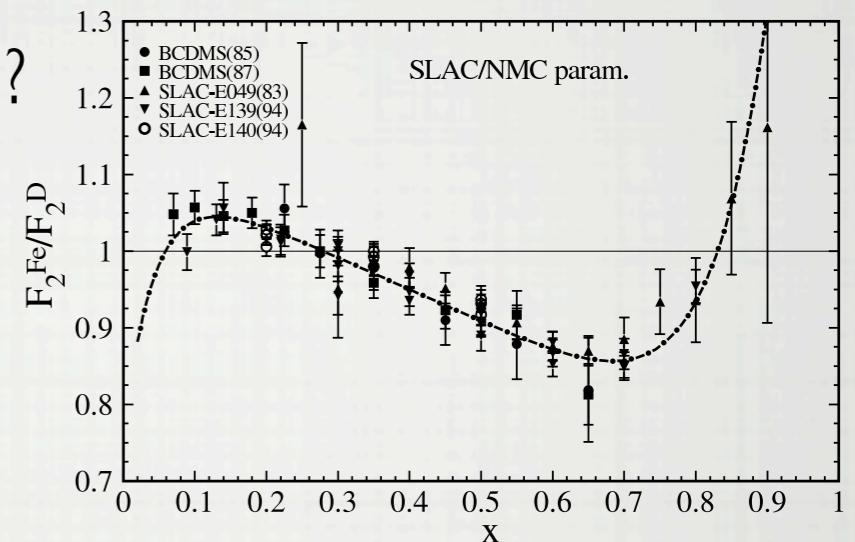


- Where are nuclear parton density functions useful ?
 - I. Strange quark content of the proton

strange PDF from neutrino DIS with heavy nuclei - nuclear effects very important

NUCLEAR PDFS

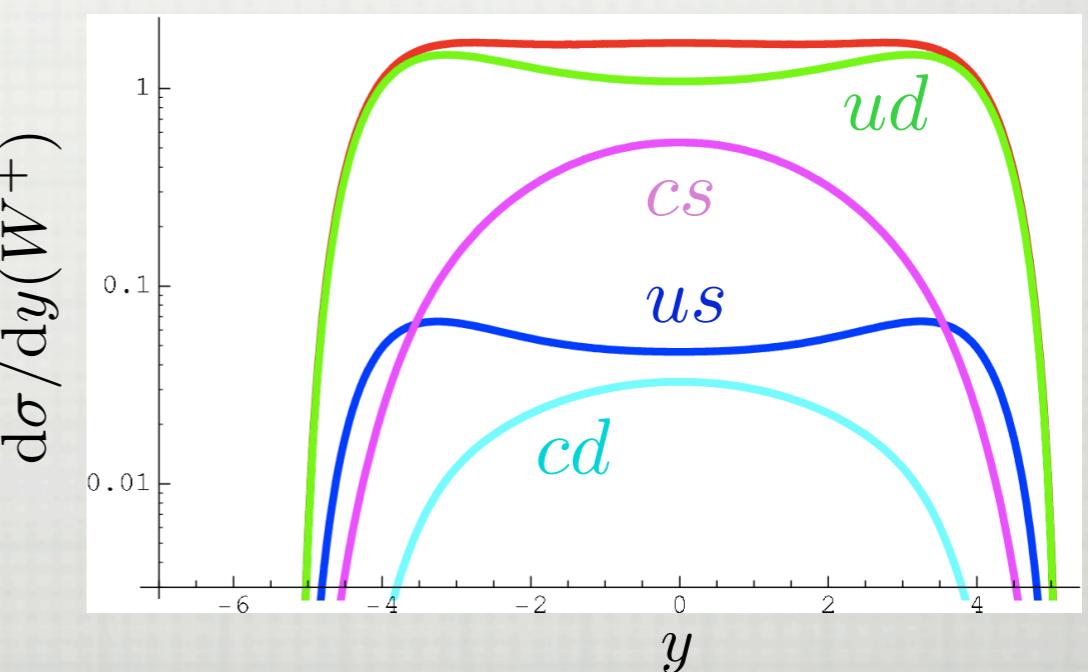
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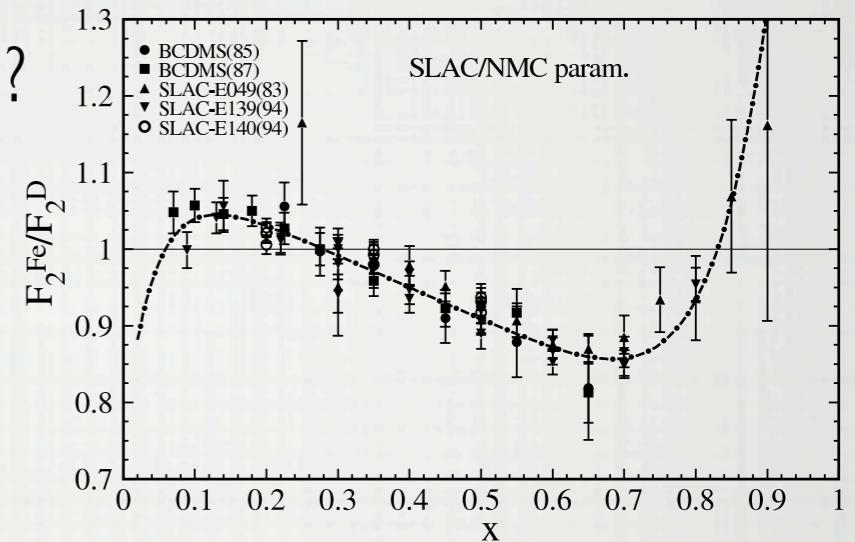
strange PDF from neutrino DIS with heavy nuclei - nuclear effects very important

crucial for: W-boson production at the LHC
(standard candle process)



NUCLEAR PDFS

- What are nuclear parton density functions (nPDF) ?
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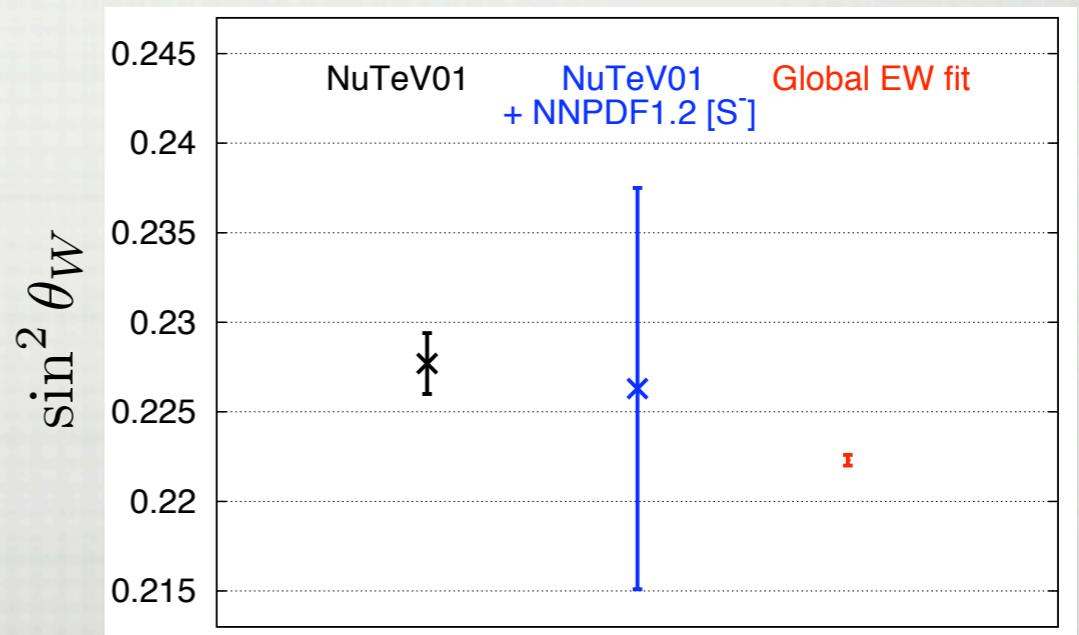


- Where are nuclear parton density functions useful ?

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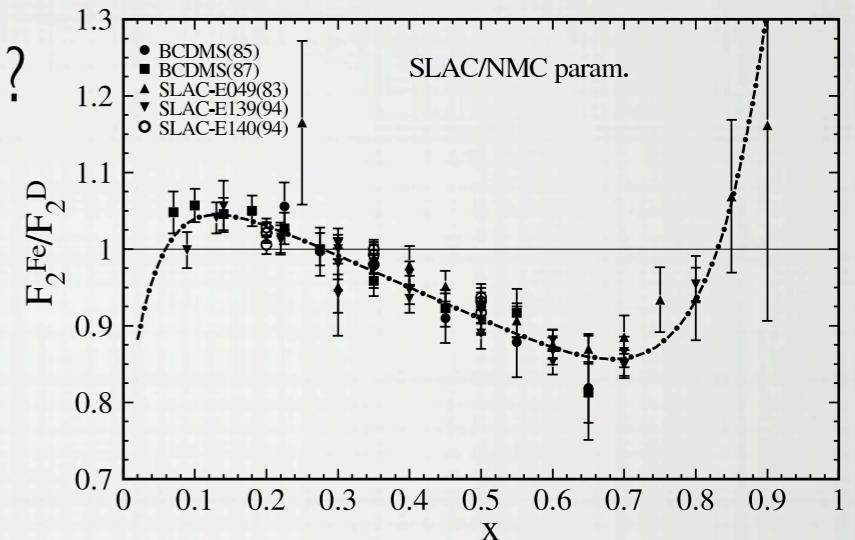
strange PDF from neutrino DIS with heavy nuclei - nuclear effects very important

crucial for: determining weak mixing angle
from NuTeV experiment



NUCLEAR PDFS

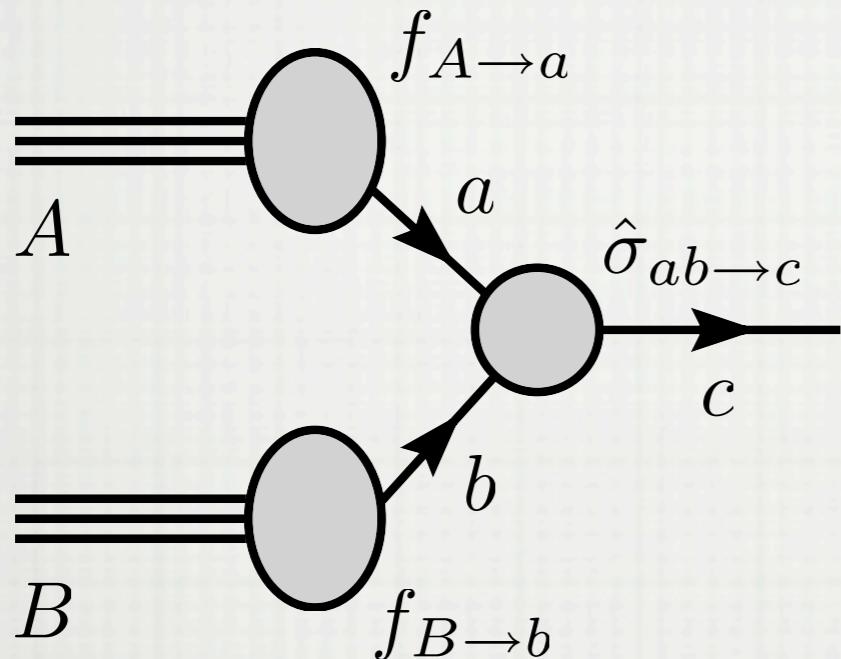
- What are nuclear parton density functions (nPDF) ?
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- Where are nuclear parton density functions useful ?
 - I. Strange quark content of the proton
 2. Collisions of protons and nuclei at RHIC, ALICE & CMS
 3. Neutrino scattering experiments e.g. MINERvA
 4. Neutrino oscillations experiments e.g. MINOS
 5. Even new physics - direct detection of dark matter

INTRO TO PDFS

Factorization & PDFs



$$\sigma = f_{A \rightarrow a} \otimes f_{B \rightarrow b} \otimes \hat{\sigma}_{ab \rightarrow c}$$

↑
from experiment

↑
from pQCD

Parton distribution functions (PDFs)

$$f_{A \rightarrow a}(x, \mu_F)$$

- universal, non-perturbative objects
- describe the structure of hadrons (in terms of partons - quarks & gluons)
- obey DGLAP evolution equations

The hard cross-section $\hat{\sigma}_{ab \rightarrow c}$

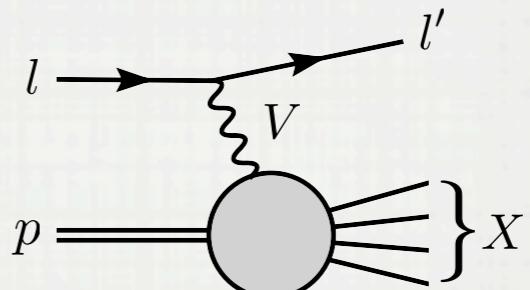
- free of long distance effects
- calculable in pQCD
- process dependant

INTRO TO PDFS

- Universality of PDFs - same parton distribution functions for all processes

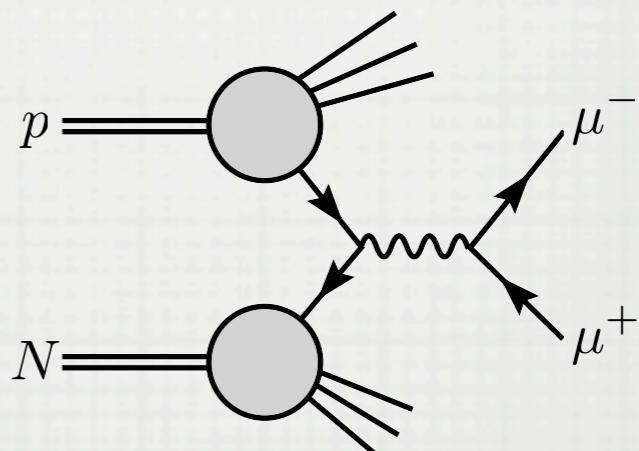
- Deep Inelastic Scattering (DIS)

$$F_2^A(x, \mu^2) = \sum_i [f_i^A \otimes C_{2,i}](x, \mu^2)$$



- Drell-Yan processes (DY)

$$\sigma_{A+B \rightarrow l^+ + l^- + X} = \sum_{i,j} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j \rightarrow l^+ + l^- + X}$$



- hadron production

$$\sigma_{A+B \rightarrow H + X} = \sum_{i,j,k} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j \rightarrow k + X} \otimes D_k^H$$

- PDFs give predictions for unexplored kinematic regions and for new physics at the LHC

INTRO TO PDFS

- ⦿ How to determine PDFs $f_{A \rightarrow a}(x, \mu_F)$ from experimental data ?
- ⦿ Scale dependence of PDFs obeys the DGLAP equations

$$\frac{df_i(x, \mu_F)}{d \ln \mu_F^2} = \frac{\alpha_S(\mu_F)}{2\pi} \int_x^1 \frac{dy}{y} P_{ij}(y) f_j(x/y, \mu_F)$$

- ⦿ The set of equations can be solved exactly in momentum space
 - **BUT** one needs the knowledge of initial PDFs at scale μ_0 for all values of $x \in (0, 1)$
- ⦿ Current global analysis - CTEQ, MRST etc...
 - solve set of DGLAP equations numerically
 - input needed only for as low x as needed
 - at the input scale one chooses a parameterization in x to fit data

INTRO TO PDFS



CTEQ framework to fit PDFs from experimental data

CTEQ6M [hep-ph/0201195](#)

- the input scale set to $\mu_0 = Q_0 = 1.3 \text{ GeV}$
- parameterization of the PDFs in x

$$x f_k(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5} \quad k = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s}$$

$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1 - x)^{c_4}$$

- make sure # of free parameters not too high - CTEQ approx. 20 free params
- carefully choose data sets & kinematic cuts to constrain free parameters
- perform χ^2 fit to data

INTRO TO PDFS

- CTEQ framework to fit PDFs from experimental data

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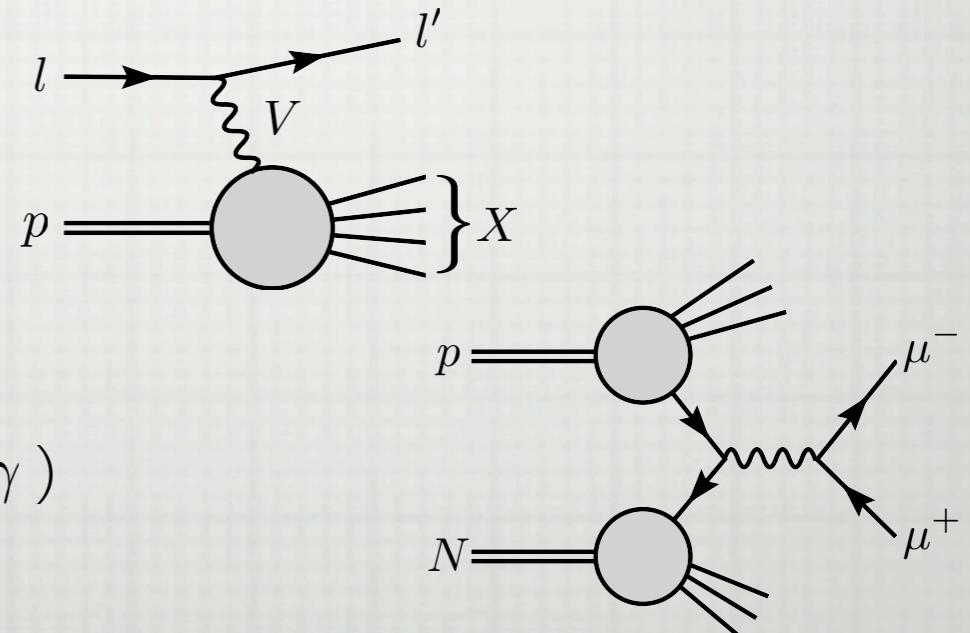
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- Which data sets are included ?

- Deep Inelastic Scattering ($l^\pm p, l^- d, \nu N, \bar{\nu} N$)
- Neutrino DIS di-muon production
- Drell-Yan & vector boson production (W^\pm, Z^0, γ)
- hadronic jet data



NUCLEAR PDFS

Review of existing global analyses of nuclear PDF

- first differentiating factor - how to relate nuclear PDF to proton PDF

I. Multiplicative nuclear correction factor

$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

↑ ↑
bound parton density free parton density

Hirai, Kumano, Nagai [PRC76(2007)065207] arXiv: 0709.0338

Eskola, Paukkunen, Salgado [JHEP0904(2009)065] arXiv: 0902.4154

2. Convolution relation

$$f_i^A(x_N, Q_0^2) = \int_{x_N}^A \frac{dy}{y} W_i(y, A, Z) f_i(x_N/y, Q_0^2)$$

↑
nucleon density in nucleus with y/A mom. fraction

de Florian, Sassot [PRD69(2004)074028] hep-ph/0311227

- second differentiating factor - data sets included in the analysis

NUCLEAR PDFS

- Review of existing global analyses of nuclear PDF

DE FLORIAN, SASSOT'04 [PRD69(2004)074028]
LO, NLO

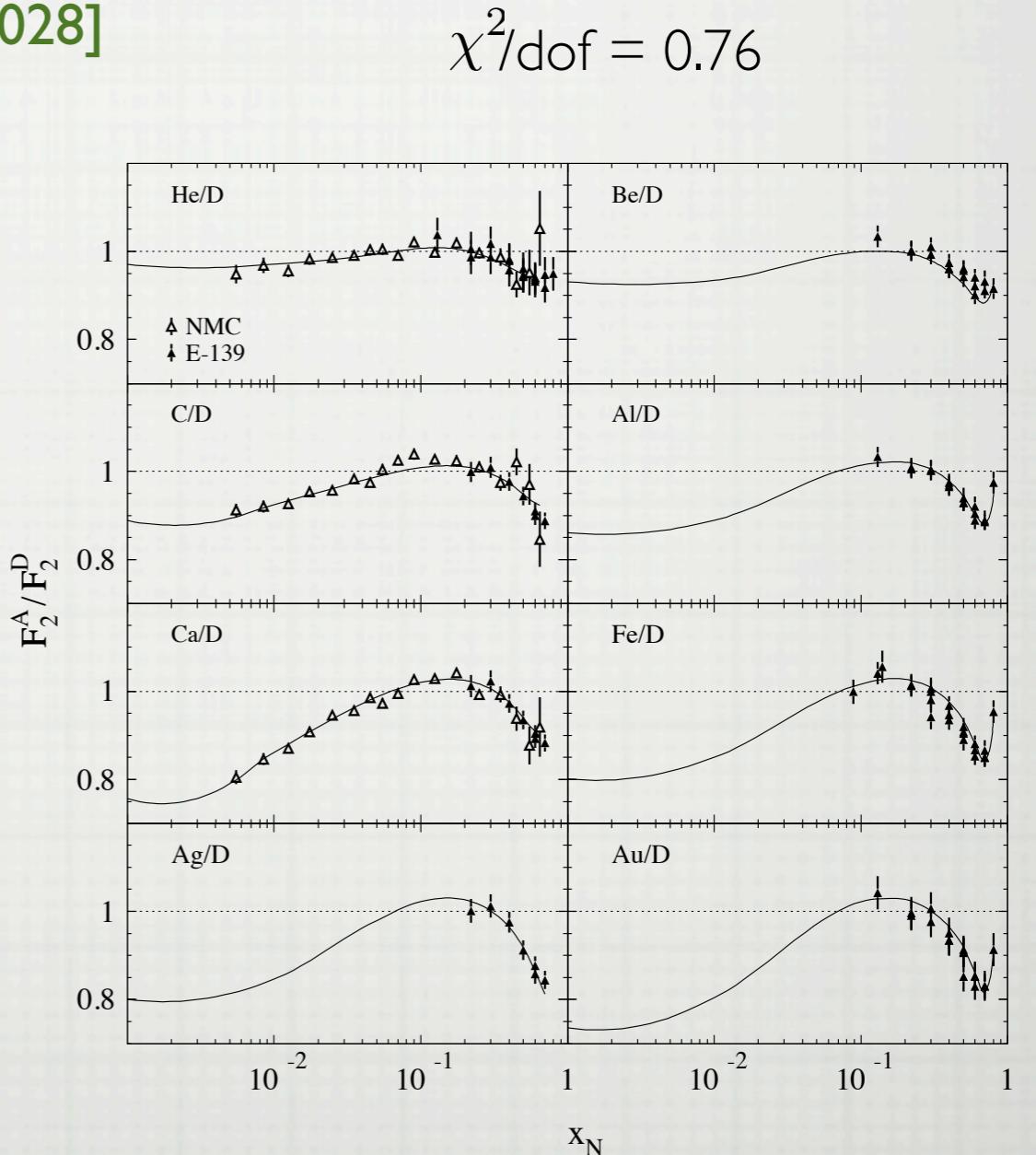
- first NLO analysis of nuclear data
- the only group using convolution relation

$$f_i^A(x_N, Q_0^2) = \int_{x_N}^A \frac{dy}{y} W_i(y, A, Z) f_i(x_N/y, Q_0^2)$$

- typical nucleon density for valence quarks

$$W_v(y, A, Z) = A[a_v \delta(1 - \epsilon_v - y) + (1 - a_v) \delta(1 - \epsilon_{v'} - y)] + n_v \left(\frac{y}{A}\right)^{\alpha_v} \left(1 - \frac{y}{A}\right)^{\beta_v} + n_s \left(\frac{y}{A}\right)^{\alpha_s} \left(1 - \frac{y}{A}\right)^{\beta_s}$$

- the only framework using evolution in Mellin space & have PDFs also for $x_N > 1$
- only standard DIS data sets (semi-global)
- no error analysis



NUCLEAR PDFS

- Review of existing global analyses of nuclear PDF

$$\chi^2/\text{dof} = 1.2$$

HIRAI, KUMANO, NAGAI'07 [PRC76(2007)065207]
LO, NLO, ERROR PDFS

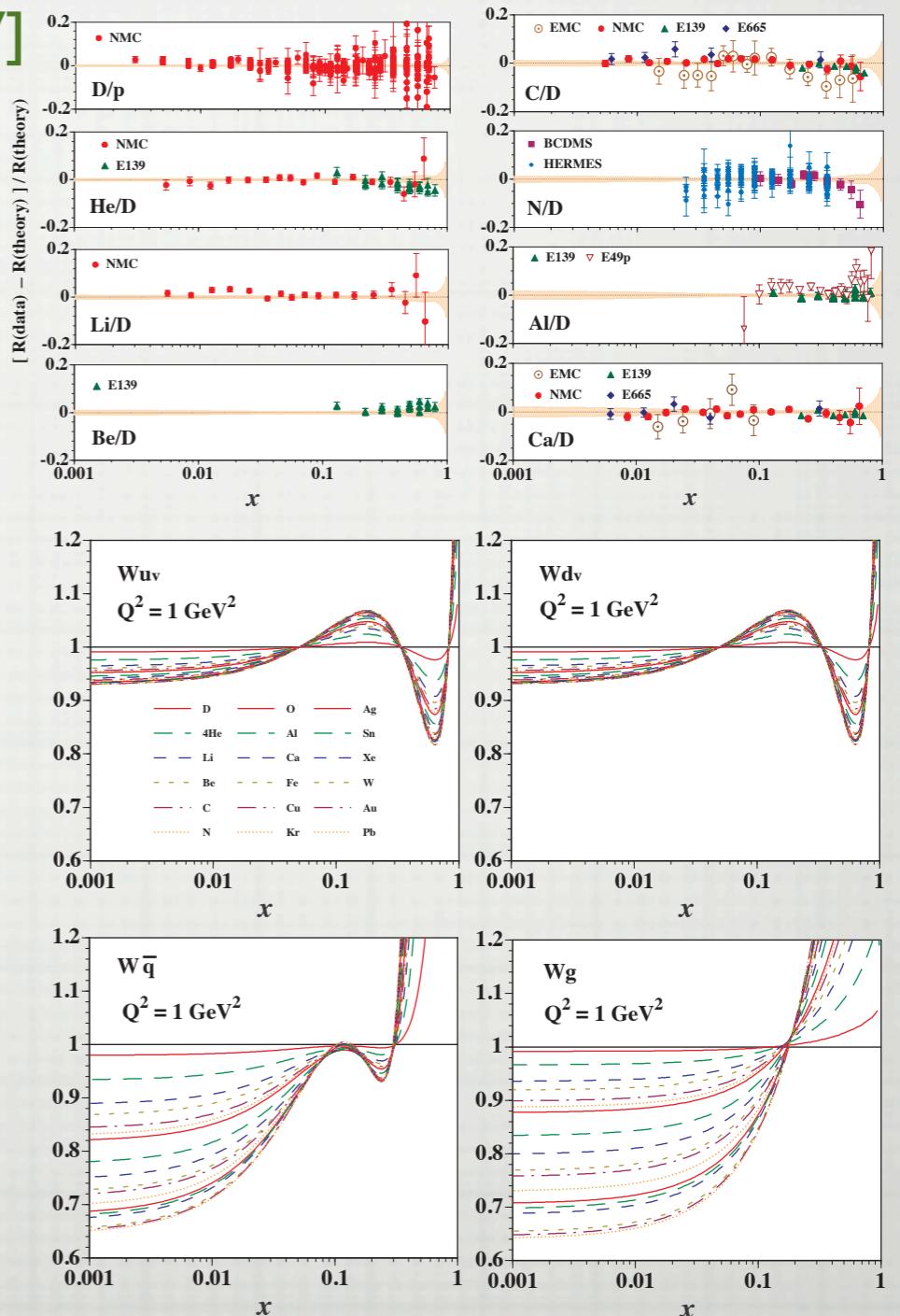
- uses multiplicative factor

$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

where proton PDF in MRST 1998 and factor

$$R_i(x, A, Z) = 1 + \left(1 - \frac{1}{A^\alpha}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$

- neglects region $x > 1$
- includes all current DIS & DY data set (same as our analysis - discussed later)
- use Hessian method to produce error PDFs



NUCLEAR PDFS

- Review of existing global analyses of nuclear PDF

ESKOLA, PAUKKUNEN, SALGADO'09 [JHEP0904(2009)065]
LO, NLO, ERROR PDFS

- uses multiplicative factor

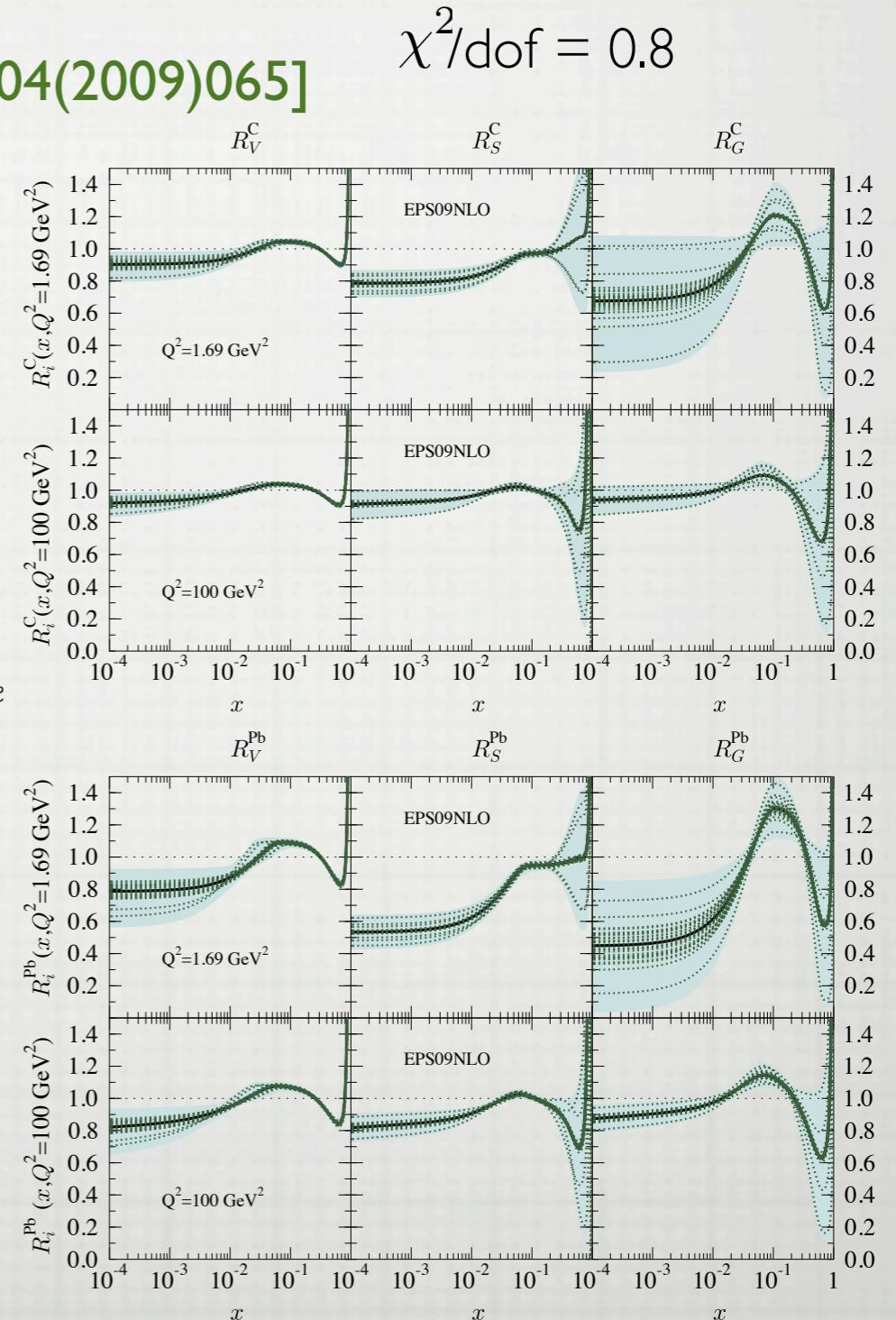
$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

where proton PDF in CTEQ6.1M and factor is a complicated piecewise defined function

$$R_i(x, A, Z) = \begin{cases} a_0 + (a_1 + a_2 x)(e^{-x} - e^{-x_a}) & x \leq x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \leq x \leq x_e \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \leq x \leq 1 \end{cases}$$

with A-dependent parameters

- neglects region $x > 1$
- includes all current DIS & DY data set & π^0 RHIC data to constrain gluon
- use Hessian method to produce error PDFs



NUCLEAR PDFS

• Why another set of NPDFs ?

1. the more global analysis available the better - the error PDFs underestimate the true error since they do not take into account the variation of the framework (parameterization) & all other physical assumptions & technical details
2. we would like a NPDF analysis with a close relation to the existing CTEQ proton analysis - allows to calculate nuclear correction factors in a flexible way (Q dependent & based on global analysis)
3. Our analysis aims at including also neutrino DIS data

NUCLEAR CTEQ

- CTEQ framework for nuclear PDF - based on CTEQ6M proton fit
 - functional form for bound protons same as for free proton PDF (restrict x to $0 < x < 1$)

$$x f_k(x, Q_0) = c_0 x^{c_1} (1 - x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5} \quad k = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s}$$

$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1} (1 - x)^{c_2} + (1 + c_3 x)(1 - x)^{c_4}$$

- coefficients with A -dependance (reduces to proton for $A=1$)

$$c_k \rightarrow c_k(A) \equiv c_{k,0} + c_{k,1} (1 - A^{-c_{k,2}}), \quad k = \{1, \dots, 5\}$$

- PDF for a nucleus with A -nucleons out of which Z -protons

$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A - Z}{A} f_i^{n/A}(x, Q)$$

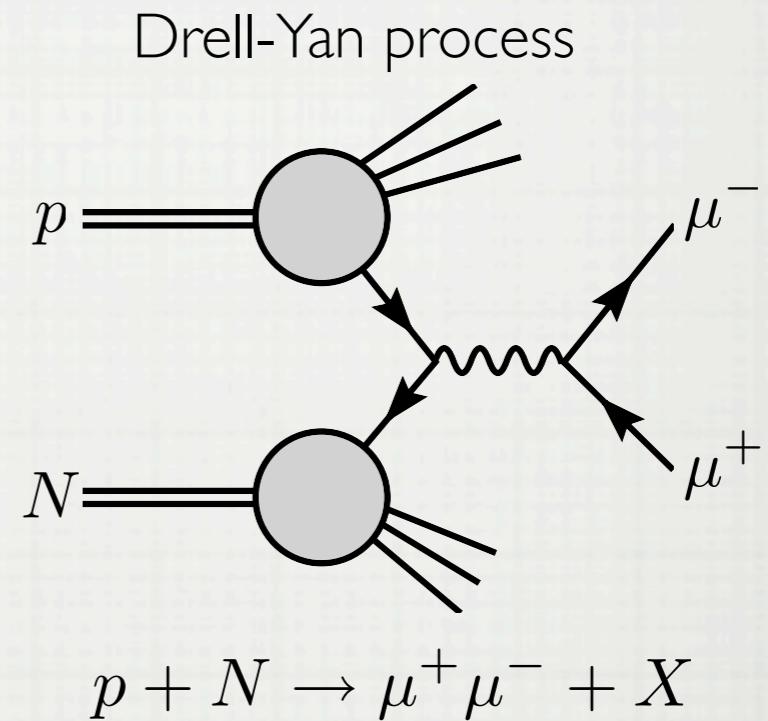
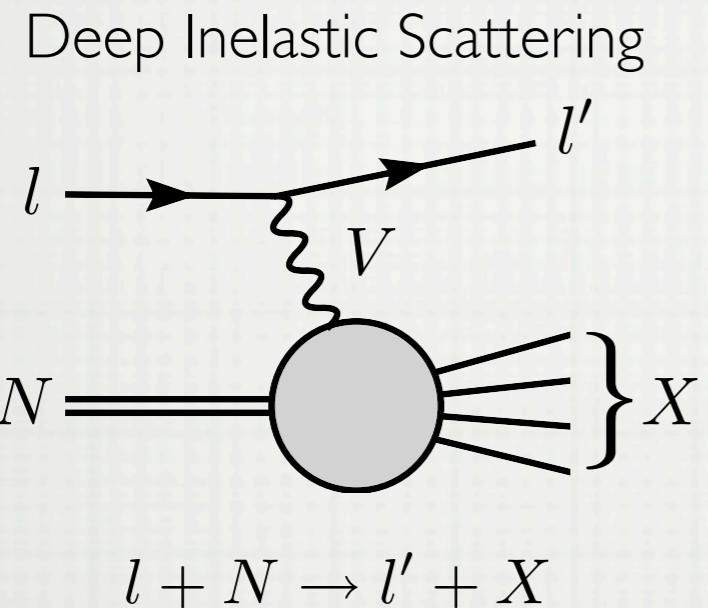
Note: PDF of neutron are related to the proton by isospin symmetry

- Input scale and other input parameters as in CTEQ6M proton analysis

$$Q_0 = m_c = 1.3 \text{ GeV} \quad m_b = 4.5 \text{ GeV} \quad \alpha_s(m_Z) = 0.118$$

RESULTS

- Experiments included in the analysis:



CERN BCDMS & EMC & NMC

$N = (\text{D}, \text{Al}, \text{Be}, \text{C}, \text{Ca}, \text{Cu}, \text{Fe}, \text{Li}, \text{Pb}, \text{Sn}, \text{W})$

FNAL E-665

$N = (\text{D}, \text{C}, \text{Ca}, \text{Pb}, \text{Xe})$

DESY Hermes

$N = (\text{D}, \text{He}, \text{N}, \text{Kr})$

SLAC E-139 & E-049

$N = (\text{D}, \text{Ag}, \text{Al}, \text{Au}, \text{Be}, \text{C}, \text{Ca}, \text{Fe}, \text{He})$

FNAL E-772 & E-886

$N = (\text{D}, \text{C}, \text{Ca}, \text{Fe}, \text{W})$

RESULTS

- NPDF fit properties:

- we fit nuclear data with NLO QCD predictions & include heavy quark effects (ACOT)
- added nuclear observables to CTEQ fitting routines (need to treat 2 nuclei at once)

$$\text{DIS: } F_2^A / F_2^{A'} \quad \text{Drell-Yan: } \sigma_{DY}^{pA} / \sigma_{DY}^{pA'}$$

- applied standard CTEQ kinematical cuts $Q > 2\text{GeV}$ & $W > 3.5\text{GeV}$

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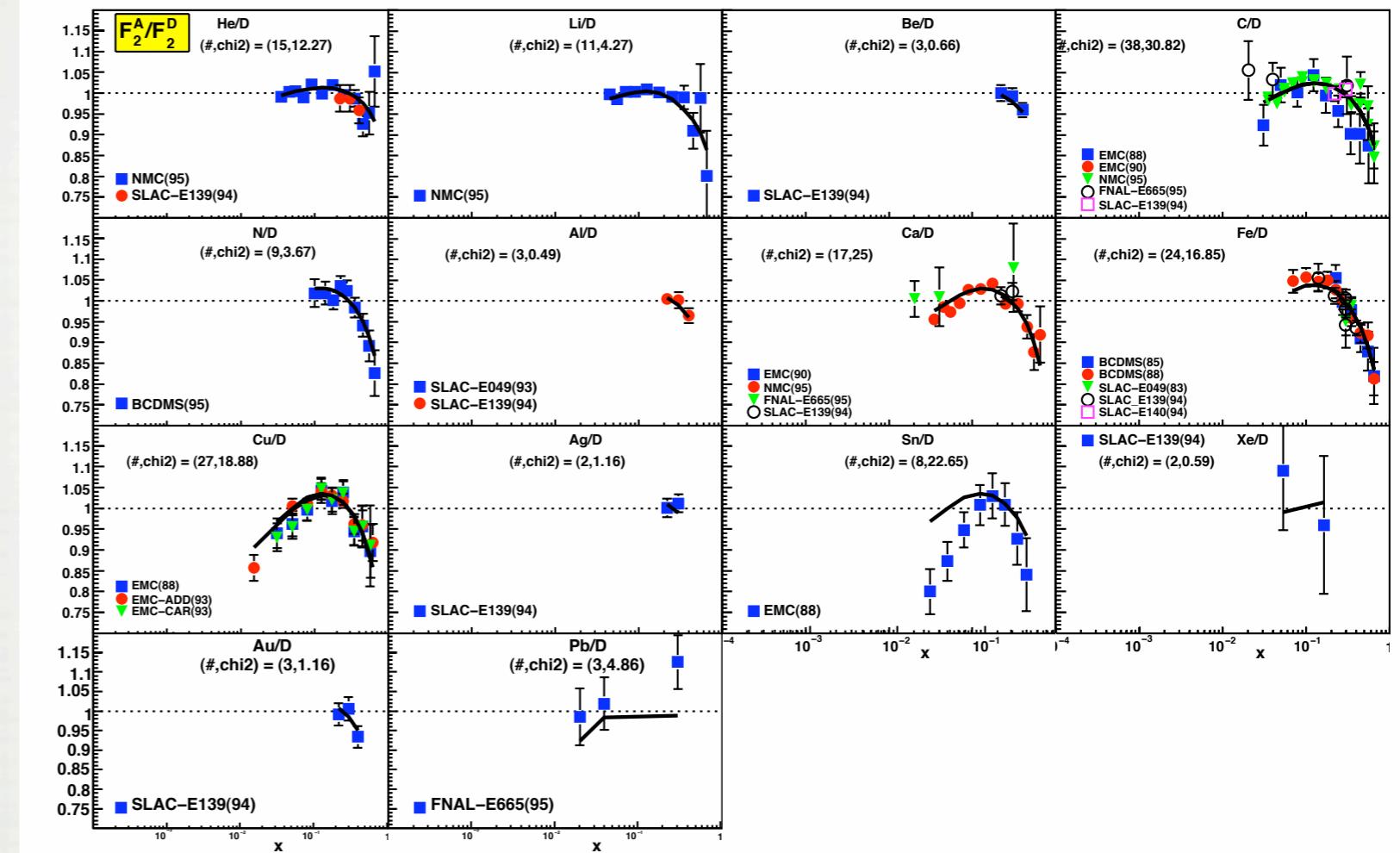
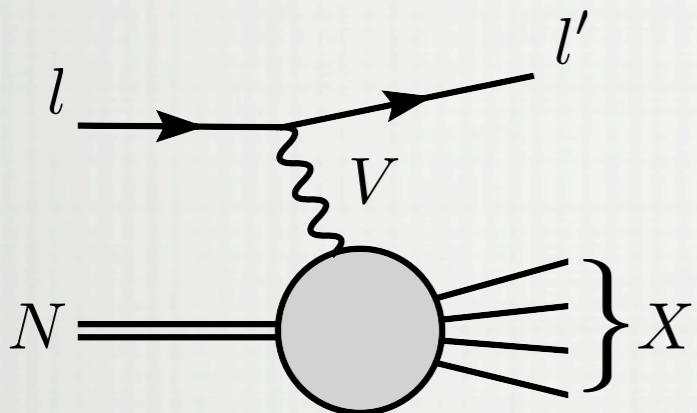
• NPDF fit results:

- 708 (1233) data points after (before) cuts
- 32 free parameters - 675 degrees of freedom
- overall $\chi^2/\text{dof} = 0.95$
- individually for different data sets

- for $F_2^A / F_2^D \quad \chi^2/\text{pt}=0.92$
- for $F_2^A / F_2^{A'} \quad \chi^2/\text{pt}=0.69$
- for $\sigma_{DY}^{pA} / \sigma_{DY}^{pA'} \quad \chi^2/\text{pt}=1.08$

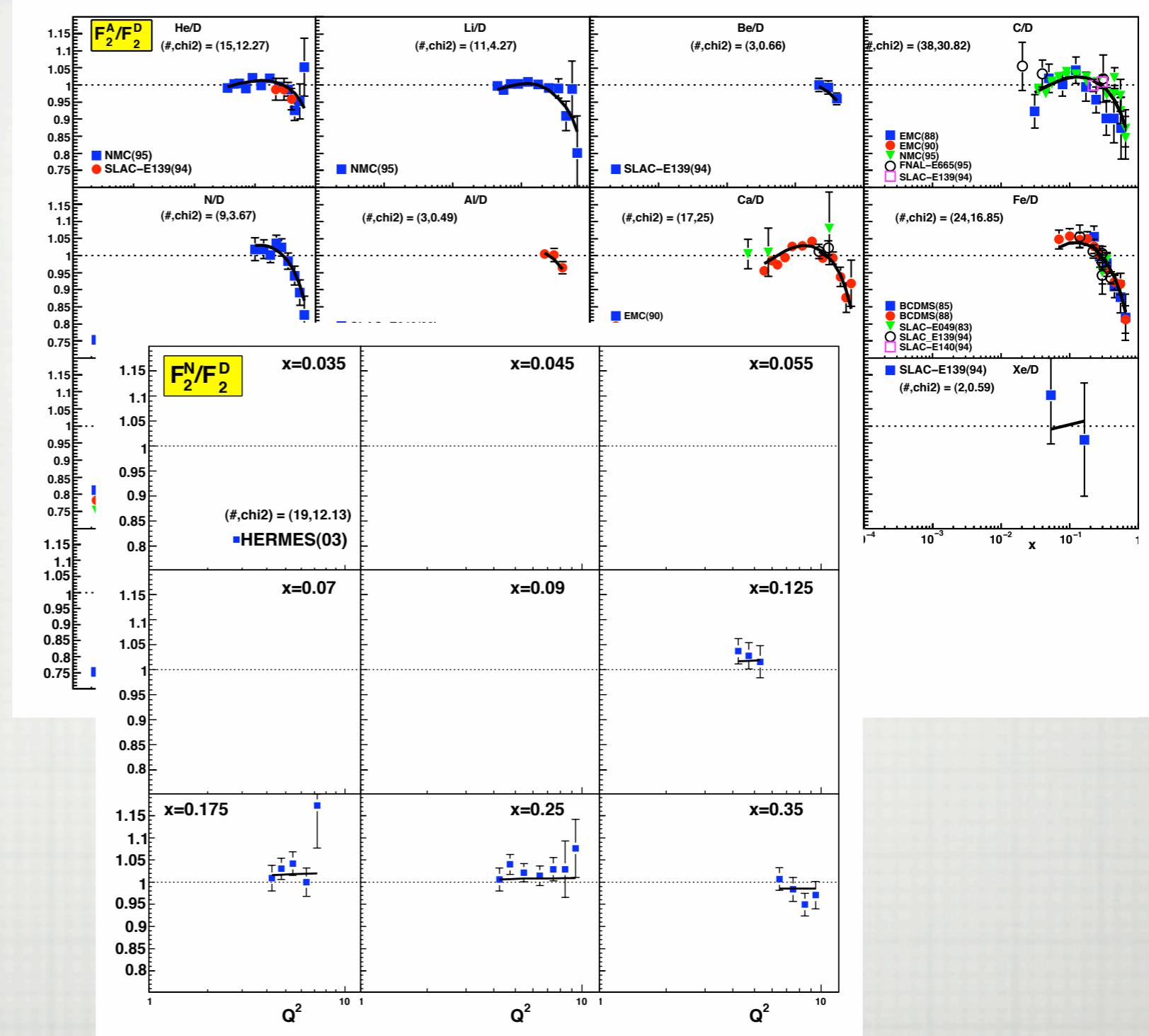
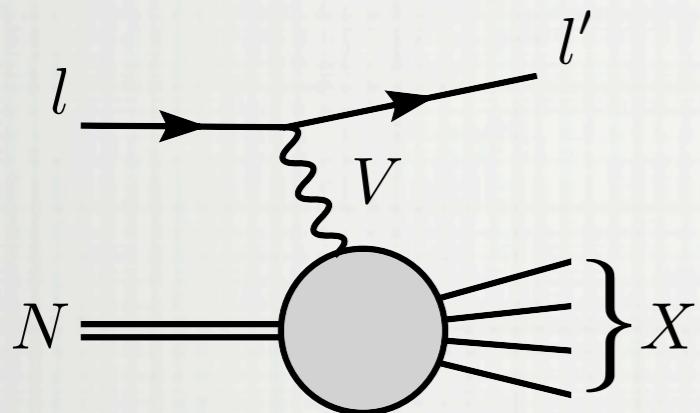
RESULTS

Deep Inelastic Scattering



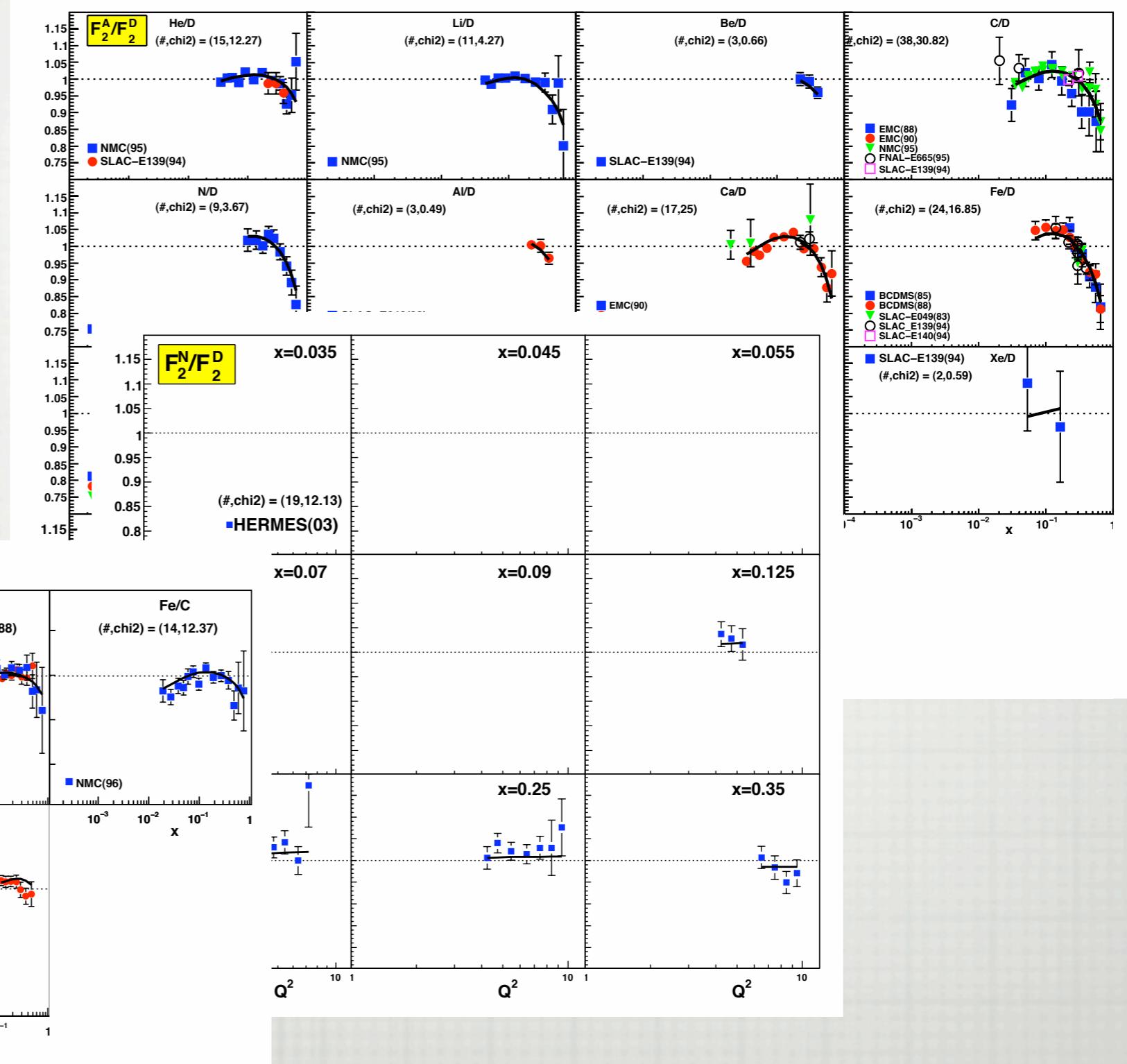
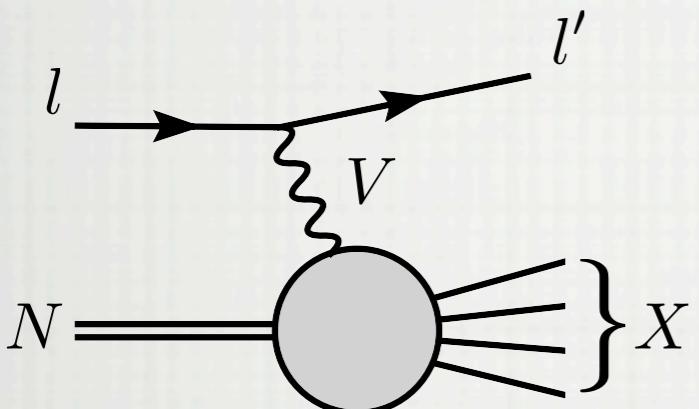
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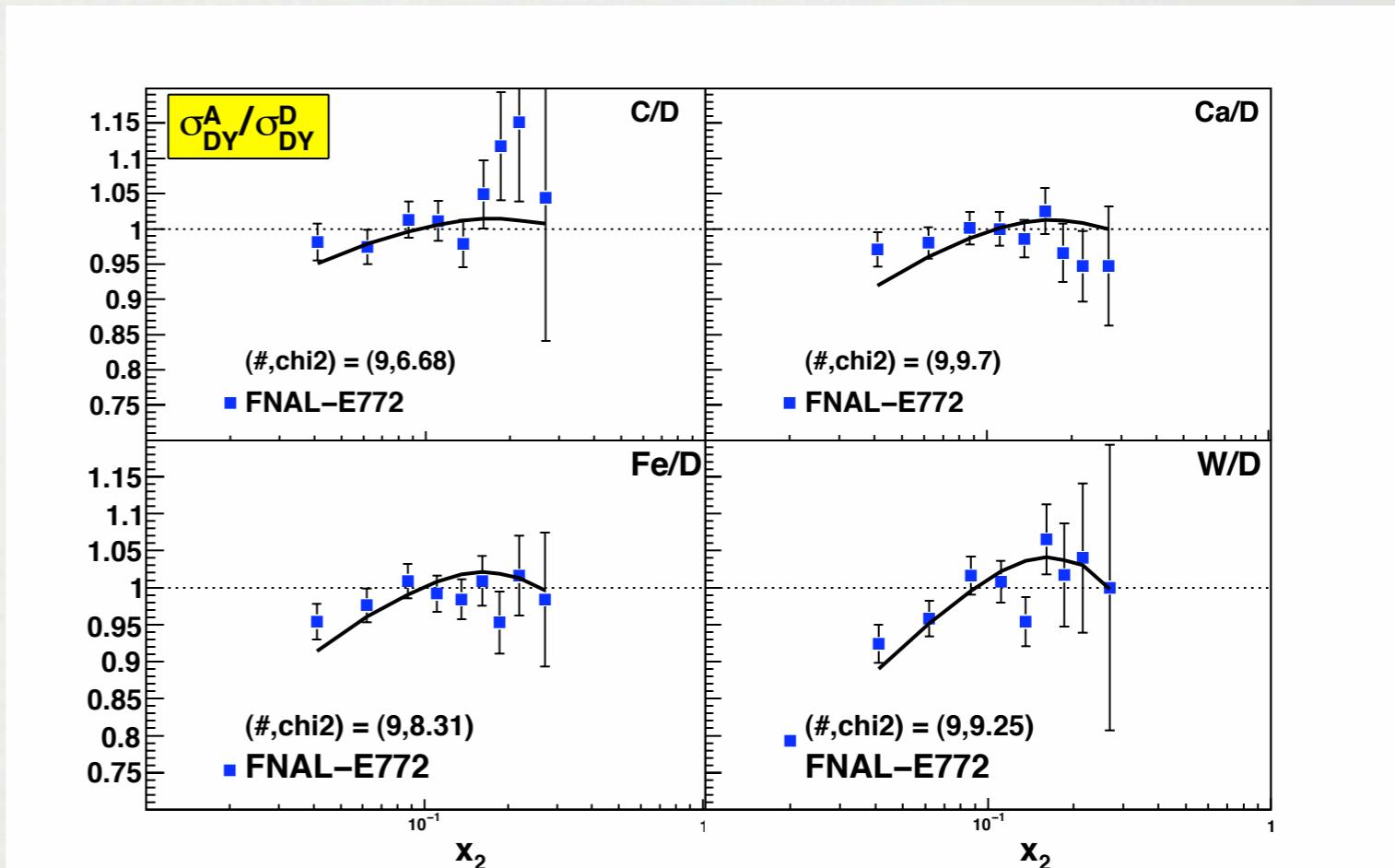
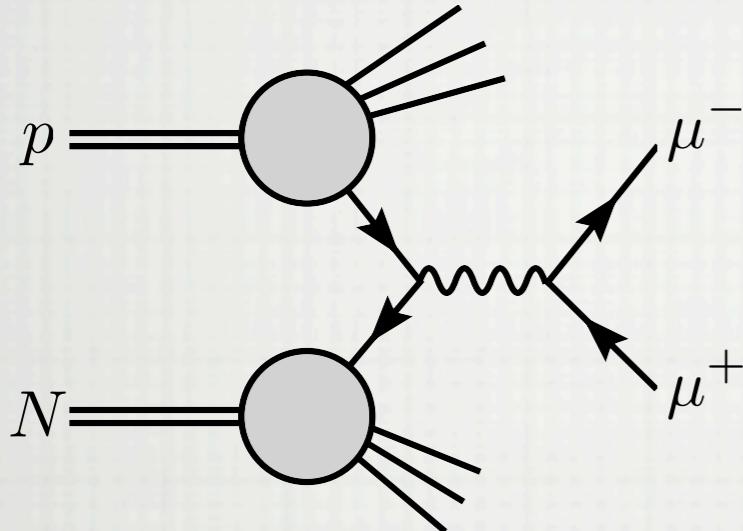
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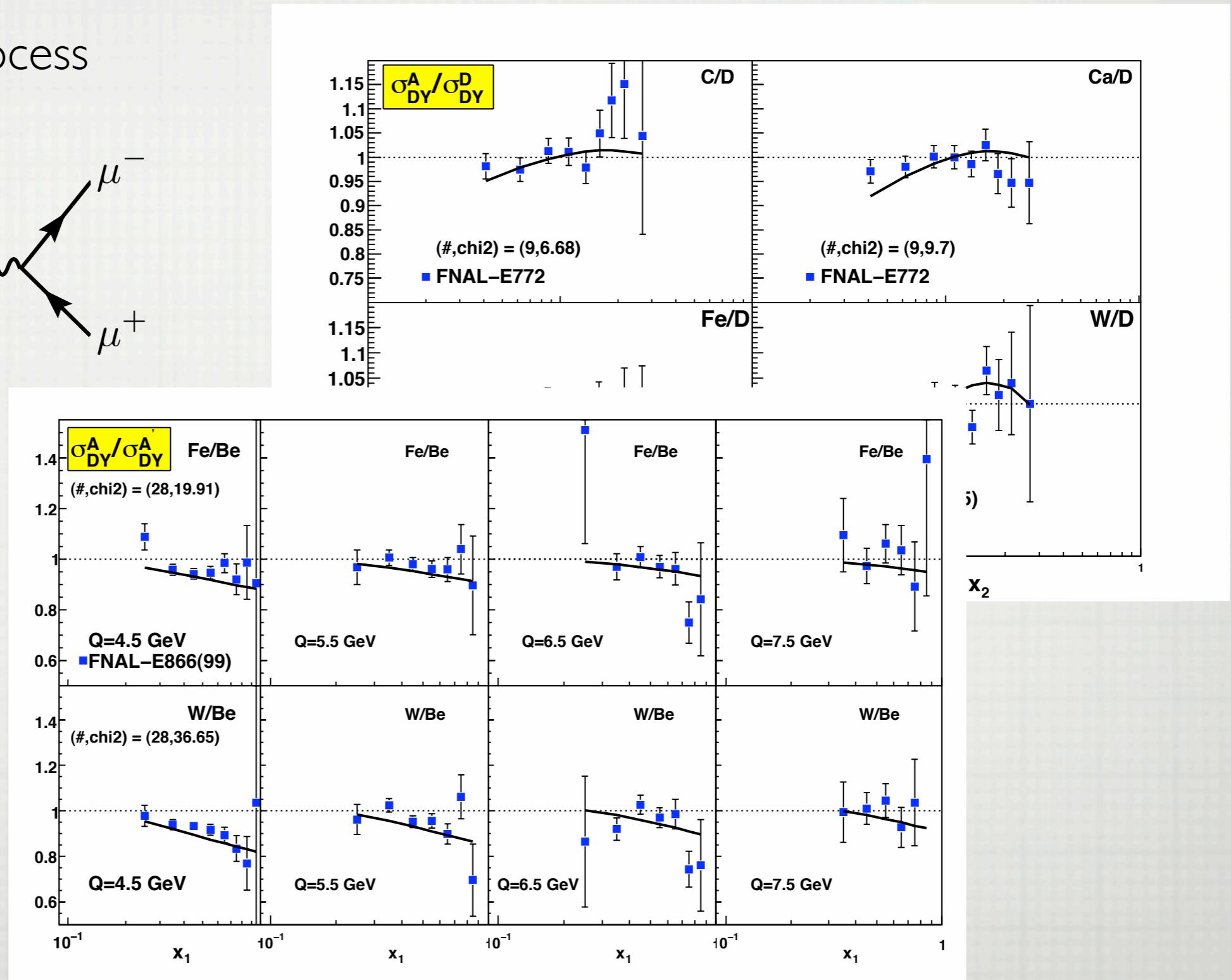
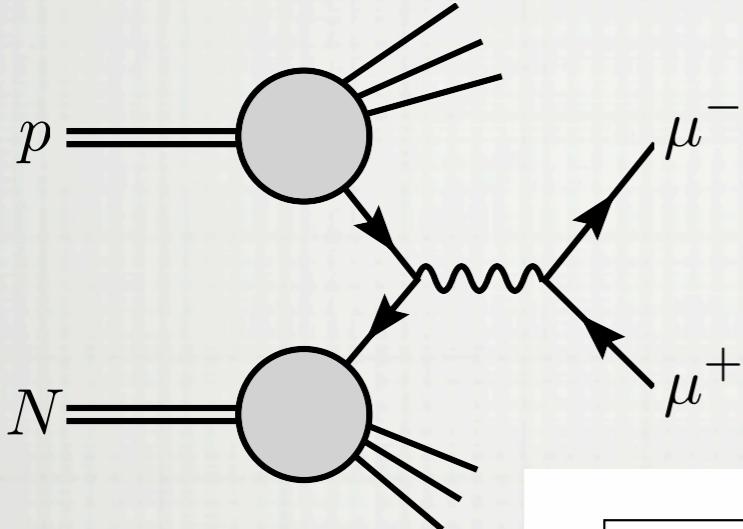
RESULTS

Drell-Yan process



RESULTS

Drell-Yan process

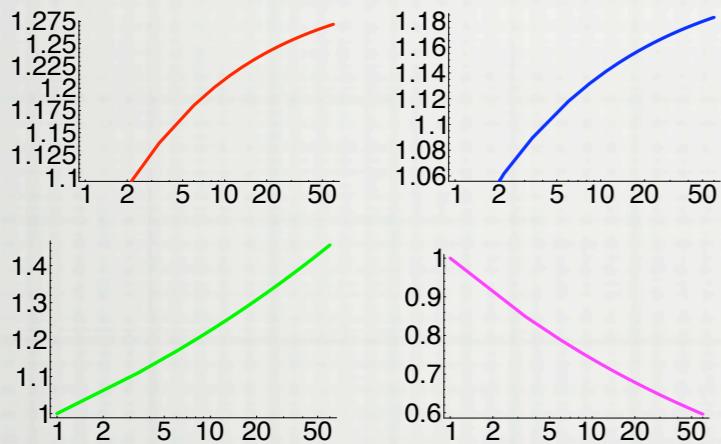


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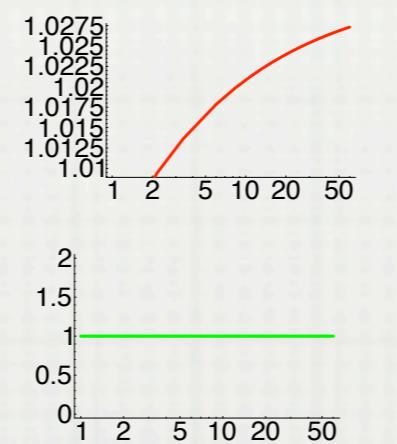
- CTEQ parameters dependent on atomic number A - $c_k(A)/c_{k,0}$

for parton distributions $\begin{pmatrix} d_v & u_v \\ g & \bar{u} + \bar{d} \end{pmatrix}$

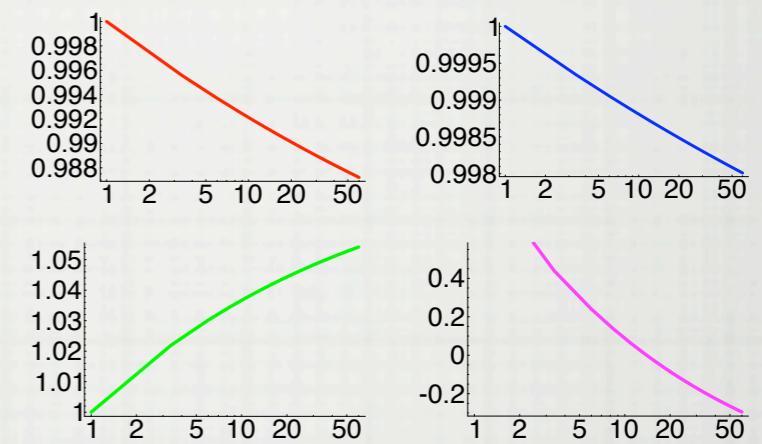
$c_1(A)/c_{k,0}$



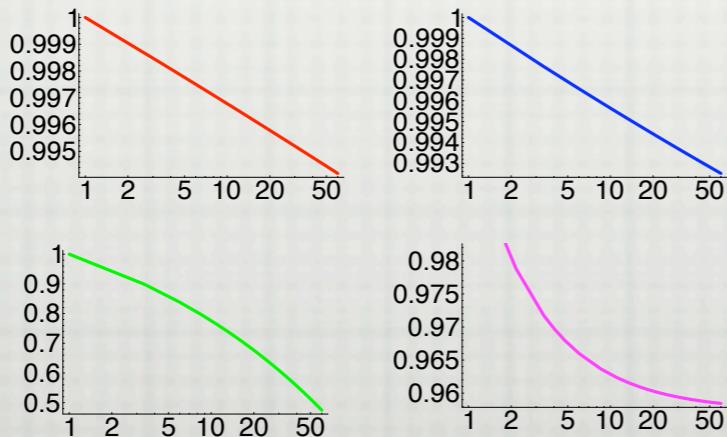
$c_2(A)/c_{k,0}$



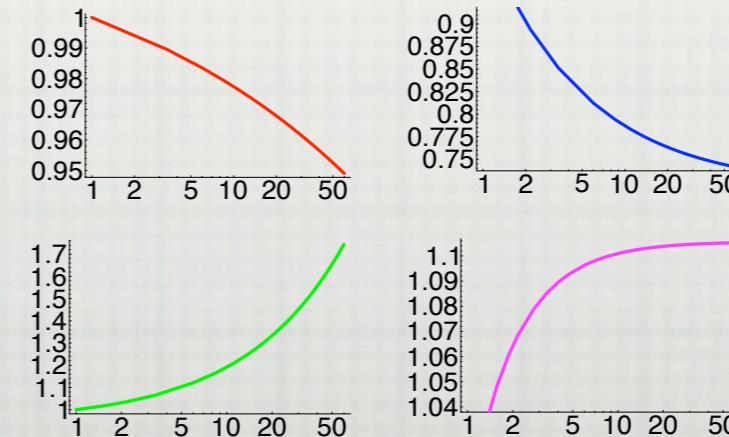
$c_3(A)/c_{k,0}$



$c_4(A)/c_{k,0}$



$c_5(A)/c_{k,0}$

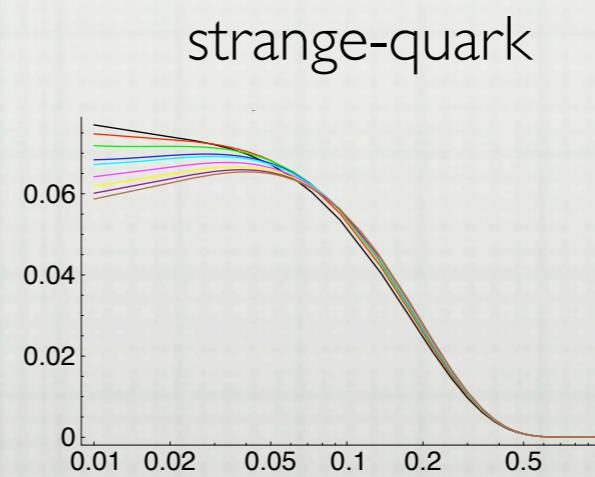
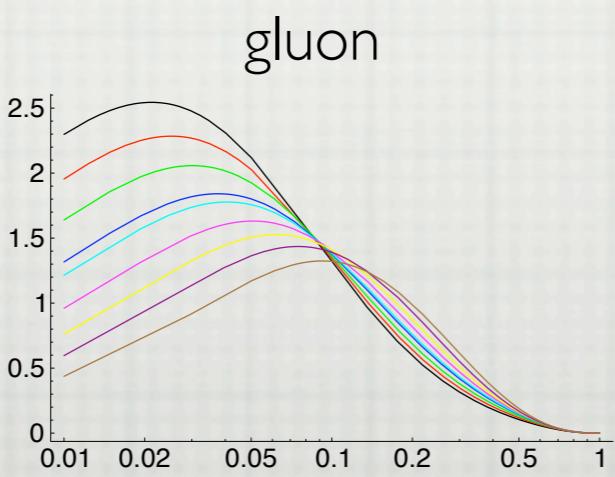
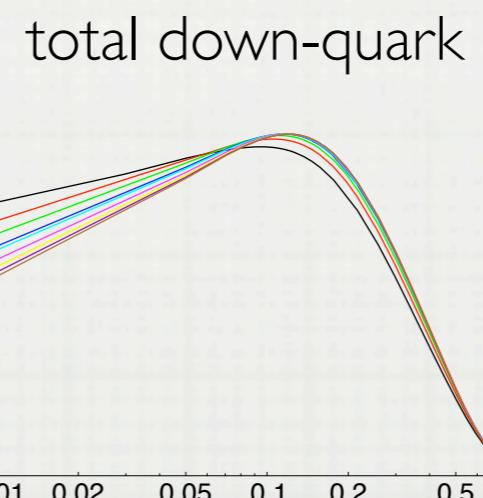
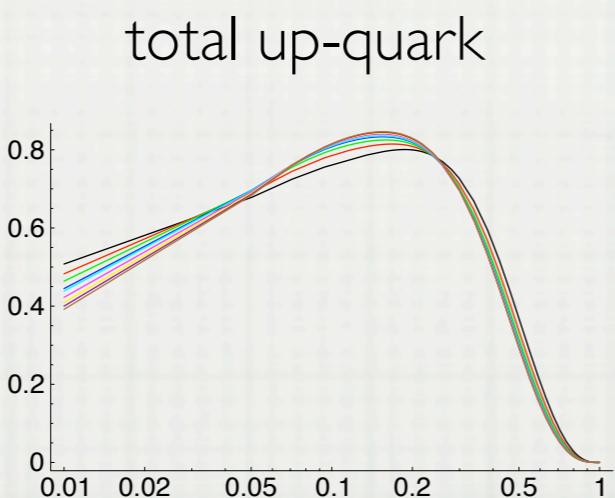


RESULTS

- Parton density functions for bound partons as a function of x

$$x f_k^A(x, Q) \text{ for } A = (1, 2, 4, 9, 12, 27, 56, 108, 207)$$

black yellow brown
red purple



RESULTS

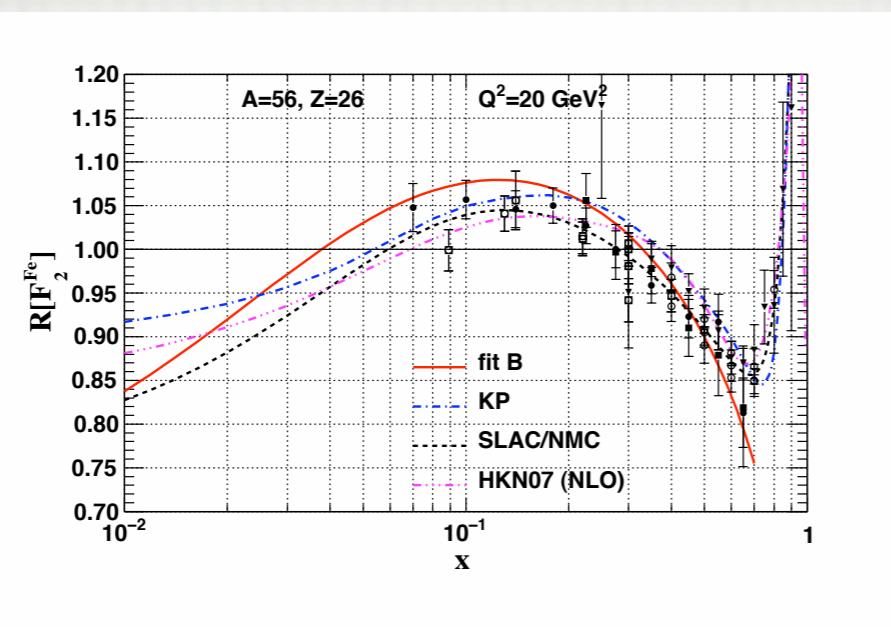
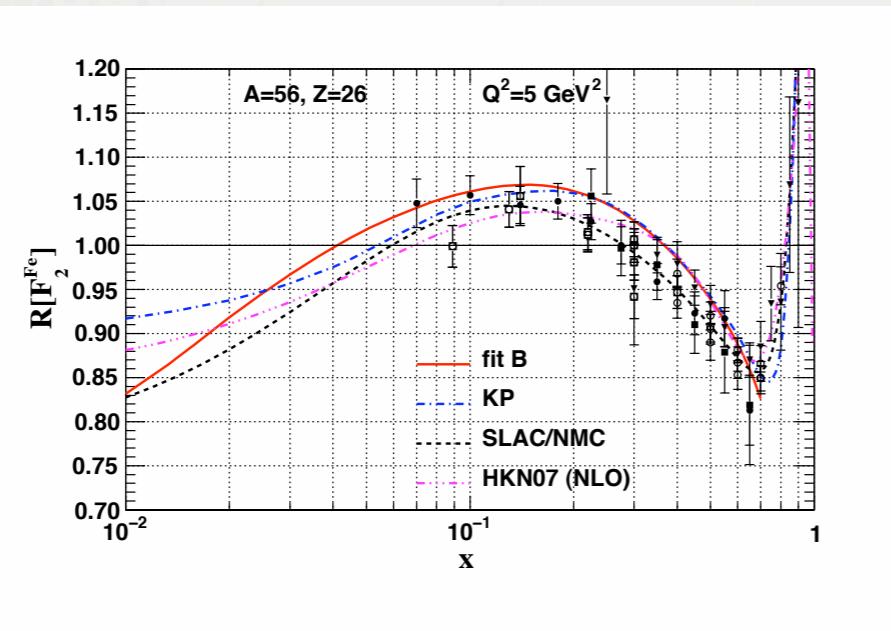
- Comparison of iron F_2 from neutrino and charged lepton DIS

$$R[F_2^{Fe}] = F_2^{Fe}/F_2^D$$

RESULTS

- Comparison of iron F_2 from neutrino and charged lepton DIS

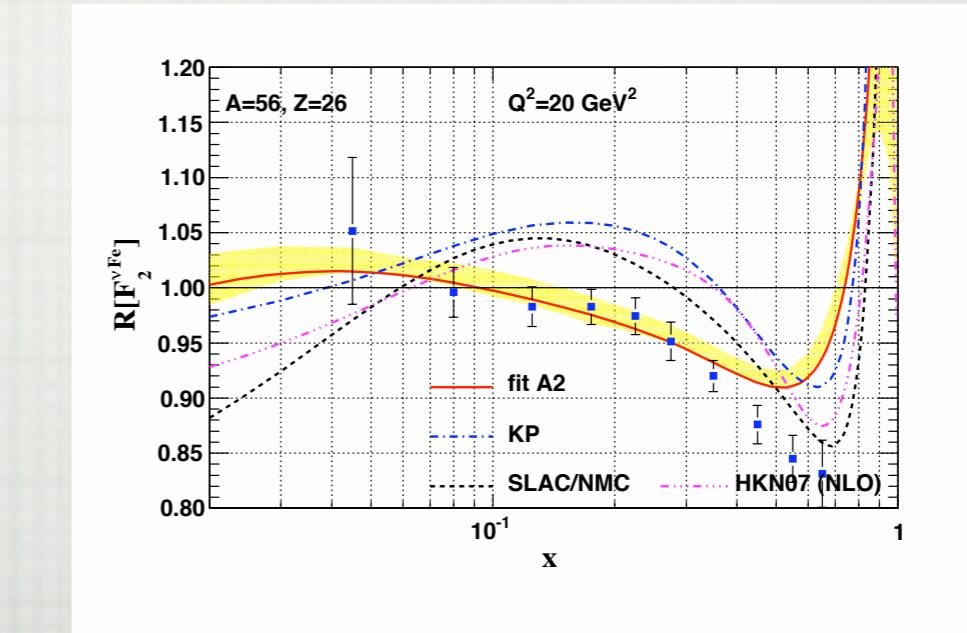
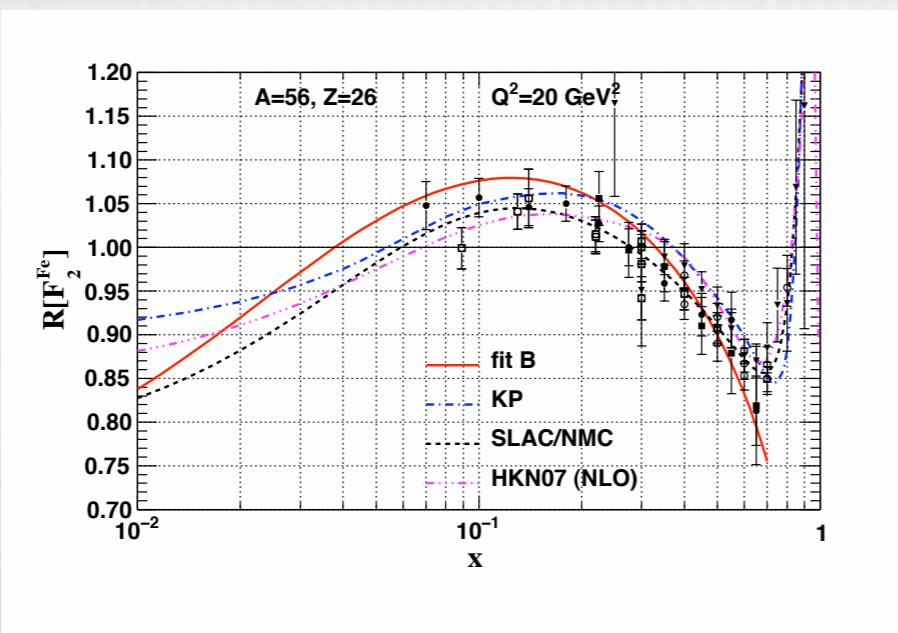
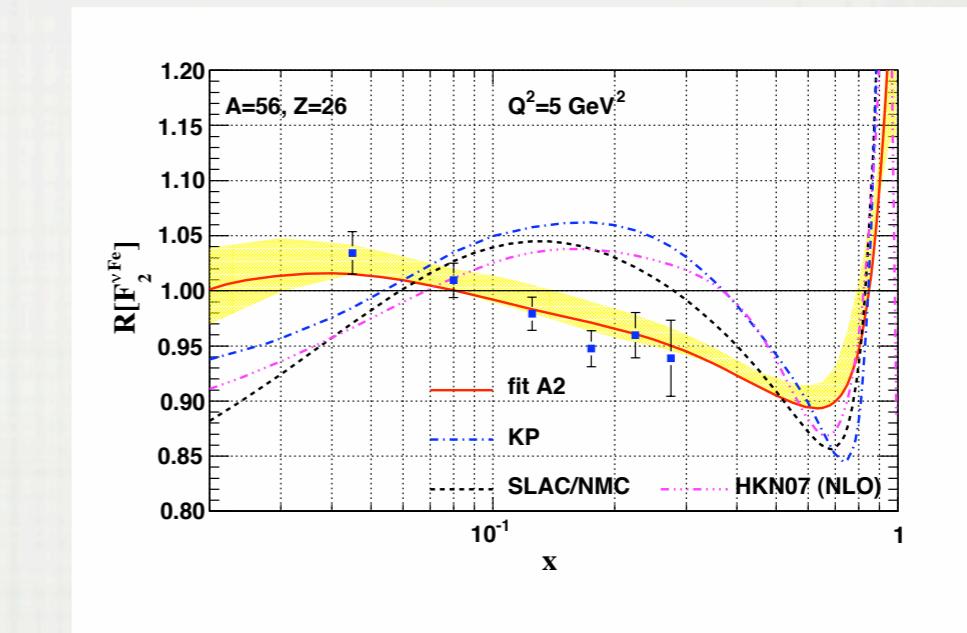
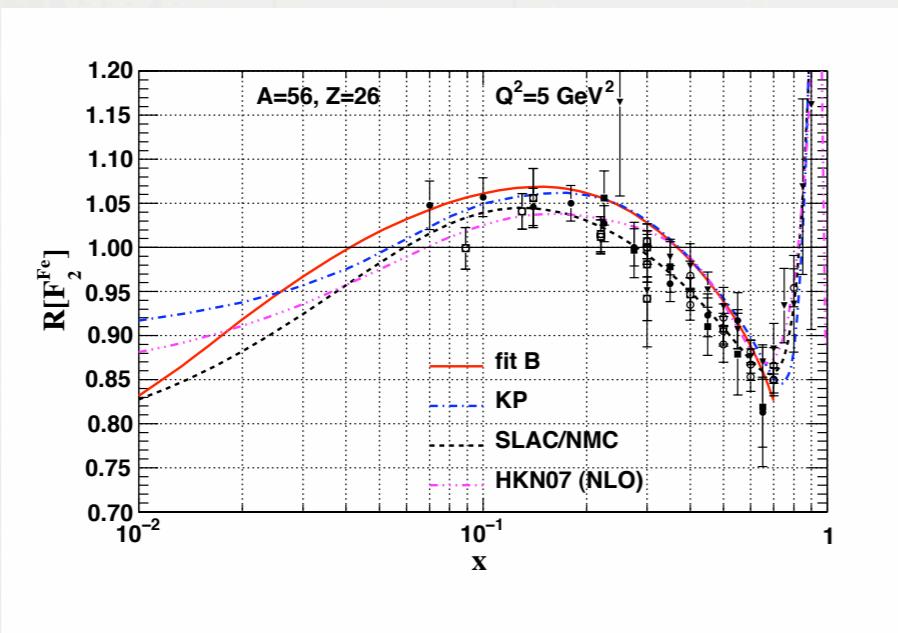
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RESULTS

- Comparison of iron F_2 from neutrino and charged lepton DIS

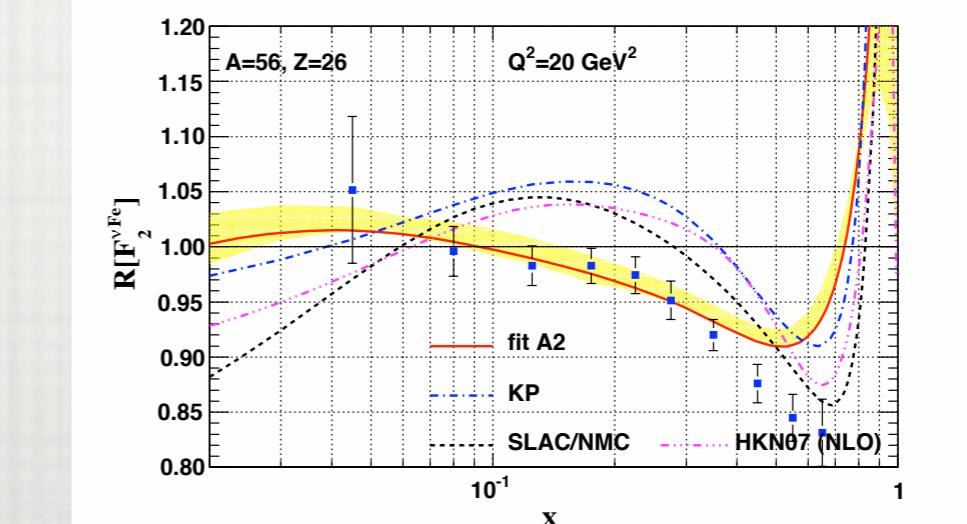
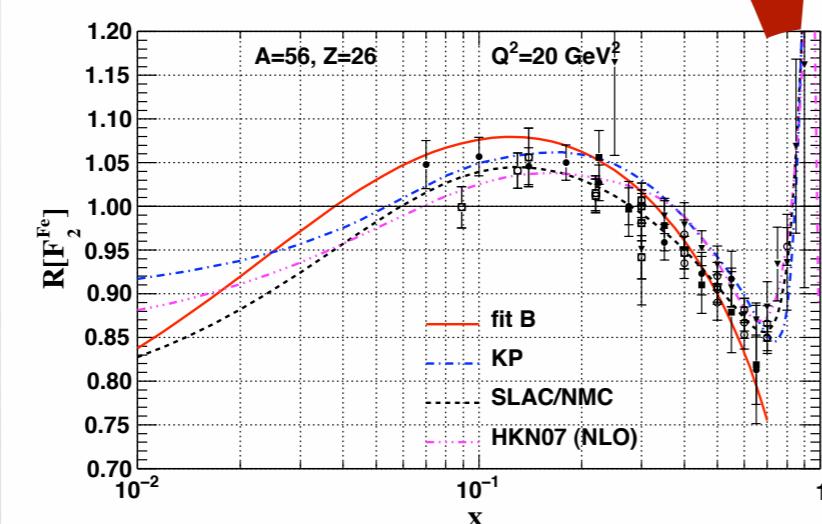
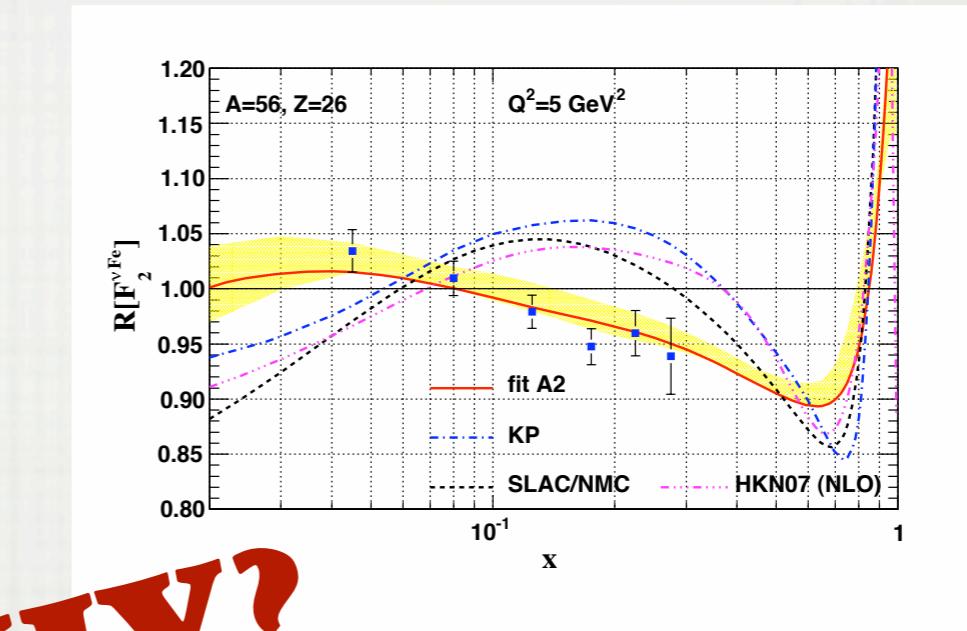
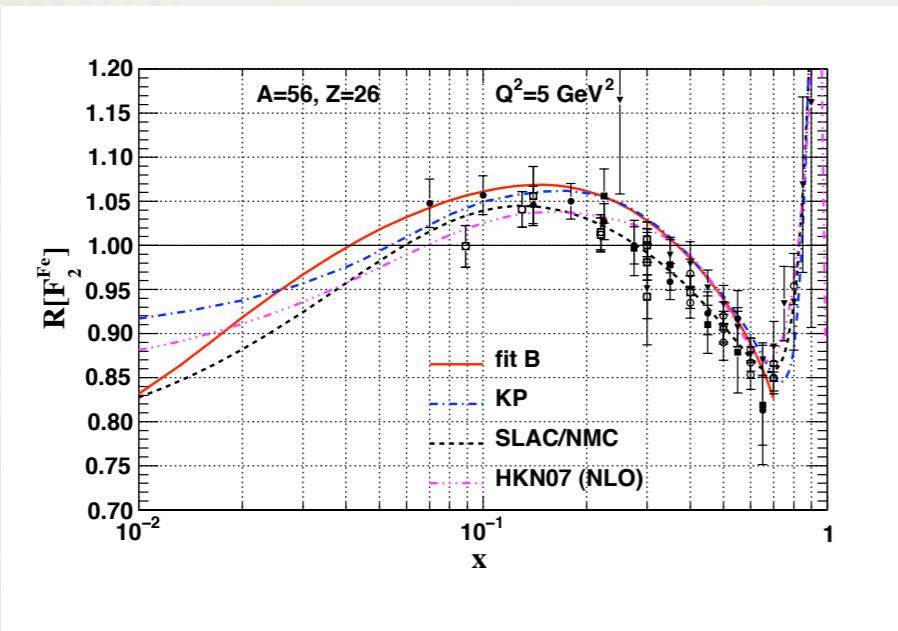
$$R[F_2^{Fe}] = F_2^{Fe}/F_2^D$$



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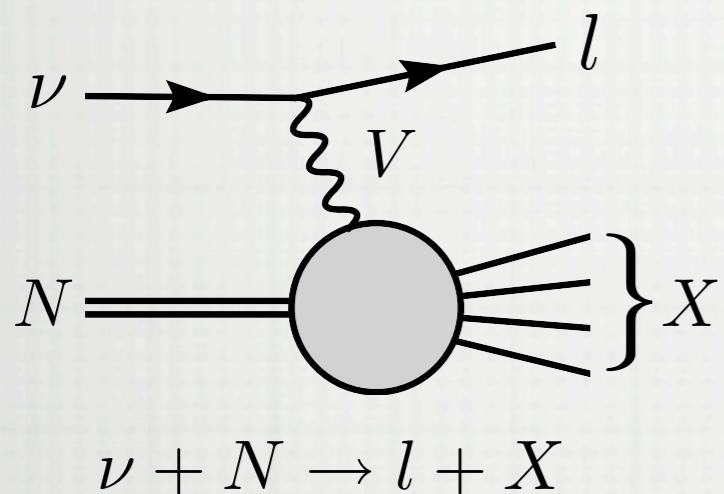
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WHY?

OUTLOOK

- Re-analyze neutrino data within the same framework as for charged lepton
- Neutrino DIS data



NuTeV & di-muon	$N = \text{Fe}$	$\rightarrow 2310$ data points
CHORUS	$N = \text{Pb}$	$\rightarrow 824$ data points
All charged lepton DIS & Drell-Yan data		
		$\rightarrow 708$ data points

- Challenges in combining the neutrino & charged lepton data
 - deal with the disparity of number of data points - assigning weights to neutrino data
 - neutrino DIS data only with 2 heavy nuclei - insufficient to get a reliable A-dependance
 - do all neutrino data show the different behavior or only NuTeV ?

OUTLOOK

VERY PRELIMINARY

- Properties of neutrino fits

- CHORUS data are in good agreement with the charged lepton data

combined: $\chi^2/\text{pt}=1.03$

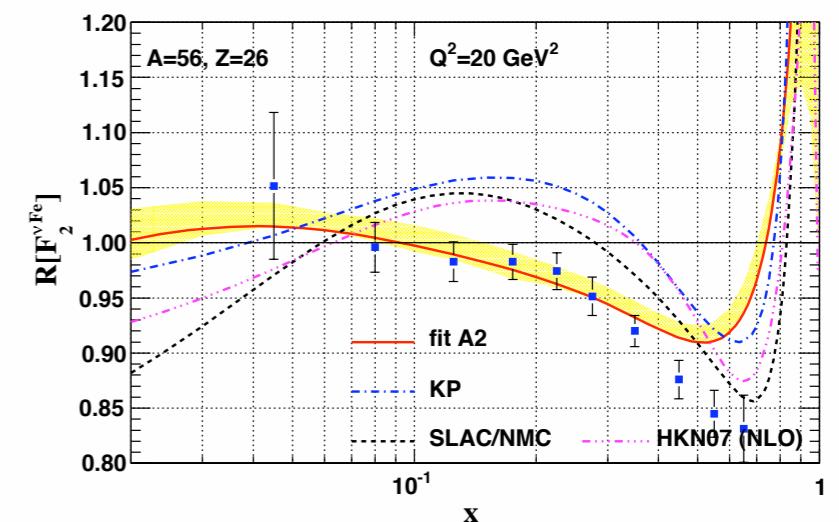
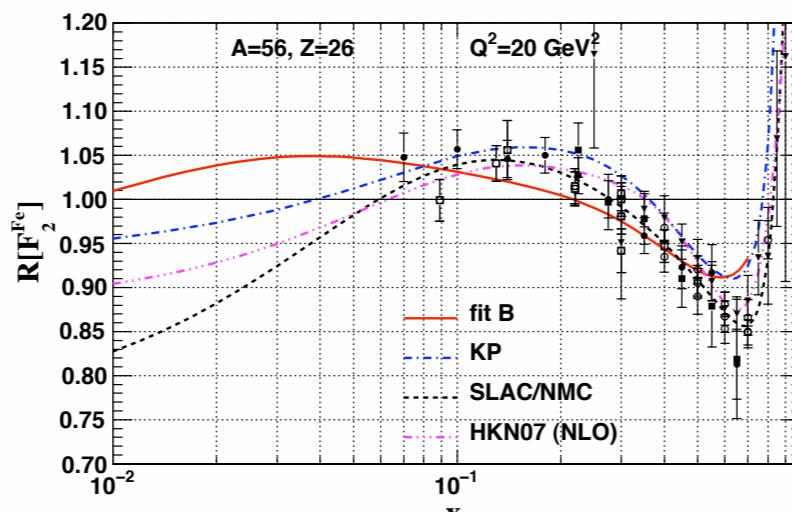
- NuTeV data difficult to fit alone or together with the charged lepton data

alone: $\chi^2/\text{pt}=1.35$

combined: $\chi^2/\text{pt}=1.33$

- Neutrino data dominate the combined fit without re-weighting - final result depend from the weight chosen

only NuTeV



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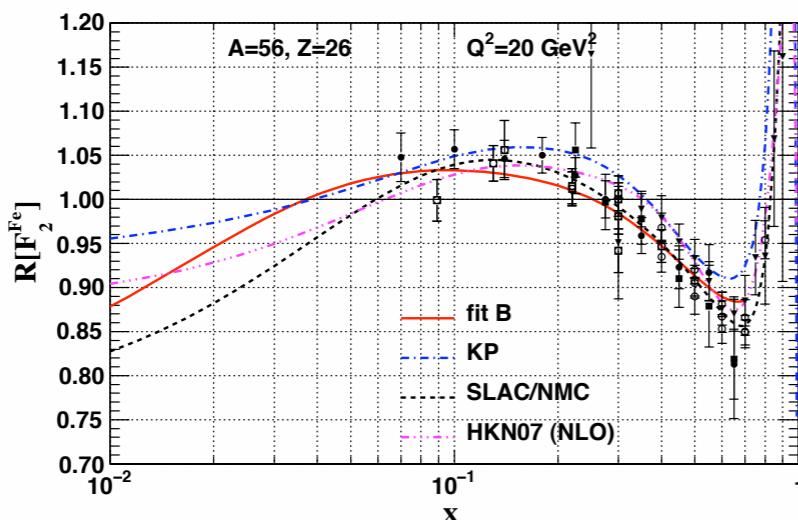
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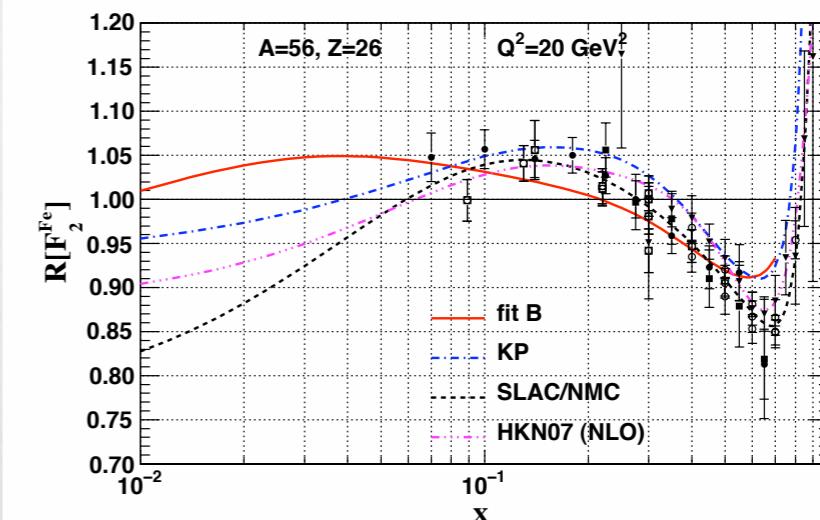
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combined neutrino & charged lepton (weight = 1/2)



only NuTeV

CONCLUSIONS

- ➊ Global nuclear CTEQ fit is able to describe the charged lepton data well
 - hope to release a first public nPDF set in not so distant future
- ➋ Greatest challenges on the way to public nPDFs
 - relax kinematical cuts and fit Fermi motion peak in a natural way
 - error PDFs
 - find a way how to constrain the gluon - see Tzvetalina's talk
- ➌ Reconcile neutrino DIS with charged lepton DIS
 - find a natural weight for neutrino data sets
 - decide on the compatibility of data sets
 - if incompatible - what is the reason for different behavior of neutrinos (no shadowing)