Nuclear PDFs at the LHC

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Outline

- [Introduction]
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- nPDFs from lA DIS and DY data
- nPDFs from Neutrino DIS data
- Conclusions

Introduction

Nuclear PDF (nPDF)

- Information on hadronic structure

- Essential for hard processes in hadronic collisions
  - Deep inelastic scattering (DIS): l-A, ν-A
  - Drell-Yan (DY): $A + B \rightarrow \ell^+ + \ell^-$
  - Jets, Photons, Hadrons at large p_T, Heavy Quarks, ...

    in p-A, A-A, (γ-A, e-A) collisions

- Provide nuclear corrections for global analyses of proton PDFs

Theoretical Basis: Factorization

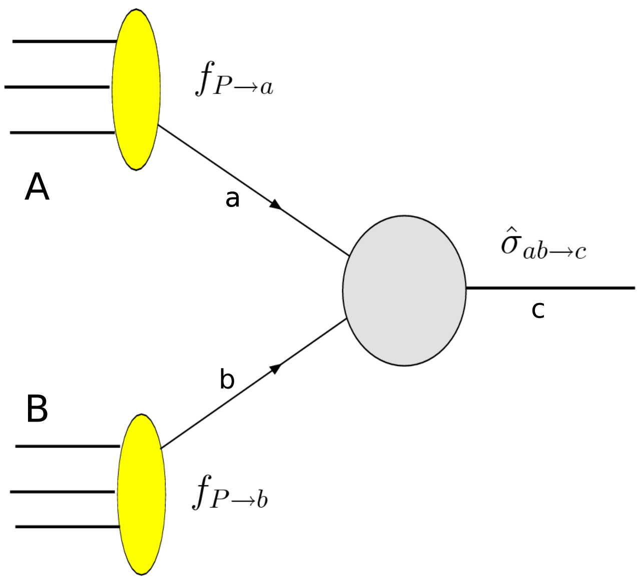
- Factorization theorems
  - provide (field theoretical) definitions of PDFs
  - make a statement about the error

- PDFs and predictions for observables+uncertainties **refer to this standard pQCD framework**

- There might be breaking of QCD factorization, deviations from DGLAP evolution, ...

Still need solid understanding of standard framework to establish deviations!

Factorization



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

From experiment

Calculable from theoretical model

Parton Distribution Functions (PDFs) $f_{A\to a}(x, \mu^2)$

- Universal, non-perturbative
- Describe the structure of hadrons
- Obey DGLAP evolution equations

The hard part $\hat{\sigma}_{ab\to c}(\mu^2)$

- Free of short distance scales
- Calculable in perturbation theory
- Depends on the process

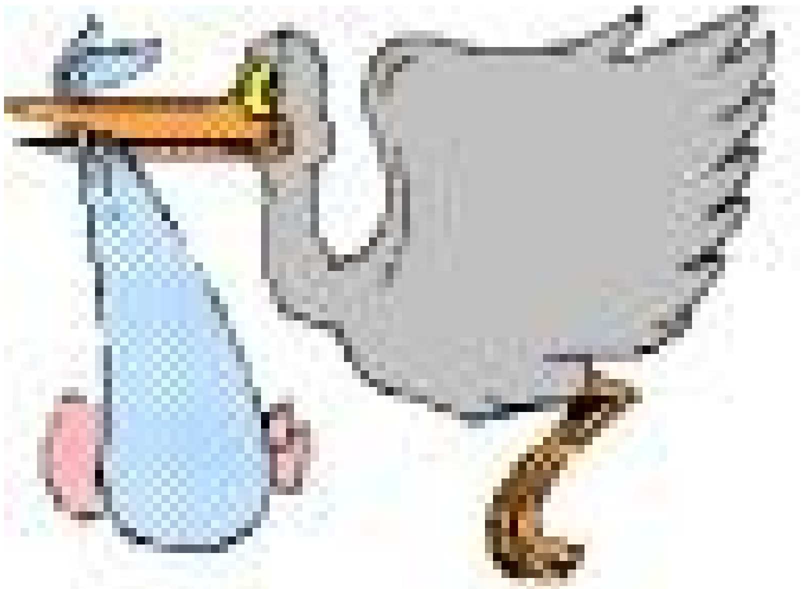
Predictive Power

Universality: same PDFs/FFs enter different processes:

- DIS: $$F_2^A(x,Q^2) = \sum_i \left[f_i^A \otimes C_{2,i}\right](x,Q^2)$$
- DY: $$\sigma_{A+B\to\ell^+ +\ell^- +X} = \sum_{i,j} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to\ell^+ +\ell^- +X}$$
- A+B -> H + X: $$\sigma_{A+B\to H+X} = \sum_{i,j,k} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to k+X} \otimes D_k^H$$
- Predictions for unexplored kinematic regions and for your favorite new physics process

Introduction to global analyses of PDFs

Where do PDFs come from?



General Remarks

- PDFs are non-perturbative objects
- Lattice: calculate moments of certain PDFs. Not yet precise enough even for the proton
- Only possibility: extract PDFs from exp. data (scale dependence is of course perturbative)
- Many different PDF flavors: need as many different observables as possible to disentangle and constrain them ('global')

Global Analysis: General Procedure

1.) Parameterize x-dependence of PDFs at input scale Q_0:

$$f(x,Q_0)=A_0 x^{A_1}(1-x)^{A_2} P(x;A_3,\ldots);\, f=u_v,d_v,g,\bar{u},\bar{d},s,\bar{s}$$

2.) Evolve from Q_0 --> Q by solving the DGLAP evolution equations
--> f(x,Q)

3.) Define suitable Chi^2 function and minimize w.r.t. fit parameters

$$\chi^2_{global}[A_i]=\sum_n w_n \chi^2_n;\, \chi^2_n=\sum_I \left(\frac{D_{nI}-T_{nI}}{\sigma_{nI}}\right)^2$$

Sum over experiments

Sum over data points

weights: default=1, allows to emphasize certain data sets

PDF Uncertainties

Sources:

- Experimental Errors to be propagated to the PDFs
- Theoretical Uncertainties
- Details of the Global Fits
- Inconsistencies in the use of the PDFs/application of the theoretical framework

There are known Unknowns ...

Errors of experimental data

Methods: to propagate exp. errors to PDFs

- **Hesse Matrix**
  - Eigenvector PDFs
  - Quadratic approximation
  - Simple computation of correlations
- **Lagrange Multipliers**
  - No quadratic approximation
  - Time consuming
- **Monte Carlo Methods**
  - generate N data samples by varying data within errors
  - N fits to the N samples -> Estimate uncertainty

Hessian method:

Assume only one fit parameter a --> Expand $\chi^2(a)$ around Minimum a_0

$$\chi^2(a)=\chi^2(a_0)+\frac{1}{2}\chi^{2''}(a_0)(a-a_0)^2+\ldots$$

Eigenvalue of Hessian 'matrix'

Determine Tolerance T <--> 1-sigma uncertainty: $T=\Delta\chi^2$

--> 1-σ uncertainty range for parameter a such that:

$$\chi^2(a)=\chi^2(a_0)+\Delta\chi^2 \Rightarrow \Delta a=T\sqrt{2/\chi^{2''}(a_0)}$$

--> best fit PDF: a_0 , two 'Eigenvector' PDFs: $a_0+\Delta a, a_0-\Delta a$

1-σ uncertainty for Observable X:

$$\Delta X=\frac{X(PDF[a_0+\Delta a])-X(PDF[a_0-\Delta a])}{2}\propto\Delta a\propto T$$

Generalization to n parameters: add in quadrature

Details of a global analysis

'Internal choices':

- **Choice/Weight of data sets** used
- **Assumptions on PDFs** (replace uncertainty!)
- Choice of Nuclear corrections to be applied to data taken with nuclear targets (D, Fe)
- Estimate/Choice of tolerance T corresponding to 1-sigma uncertainties
- Choice of the input scale
- Choice of the functional form of the PDFs at the input scale
- Scale evolution: x-space or n-space, spurious terms, soft-gluon resummation (evolution)

Details of a global analysis

'Public choices':

- Perturbative Order (LO, NLO, NNLO)
- Parameters: mc, mb, alphas(Mz)
- Factorization Scheme
- Heavy Flavour Scheme
- Central Factorization/Renormalization Scales
- Include?
  - Resummations (hard part)
  - Target Mass Corrections (TMC), Higher Twist
  - QED-effects

Remarks:

- 'Public choices' are choices also to be made by the user of the PDFs.

- For each public choice need in principle consistent set of PDFs

- Note: **Changes in the “details” may lead to results which lie outside previous error bands!**

- Certain items on the list become relevant due to the ever increasing demand for precision

Conclusion: Useful and necessary to have several different global analyses of PDFs.

Inconsistencies

Examples:

- Use NLO PDFs with LO cross sections
- Use LO PDFs with NLO cross sections
- Use different schemes for PDFs and hard scattering cross sections
- Use different mc, mb, alphas than utilized in the global fit
- Use intrinsic k_T

nPDFs from lA DIS and DY data

Work in collaboration with:

- People from Grenoble: K. Kovarik, J. Y. Yu, IS
- CTEQ-members: F. Olness (SMU), J. Morfin (FNAL),
  J. Owens (FSU), C. Keppel (JLAB)

arXiv:0907.2357

nPDFs from lA DIS and DY data

- Global analyses of nPDF:
  - **HKN'07** [PRC76(2007)065207]
    LO,NLO,error PDFs,chi^2/dof = 1.2
  - **EPS'09** [JHEP0904(2009)065]
    LO,NLO,error PDFs, chi^2/dof = 0.8
  - **DS'04** [PRD69(2004)074028]
    first NLO analysis, 'semi-global', no error PDFs, chi^2/dof = 0.76
- Based on lA DIS+DY data
  (EPS'09 uses also inclusive pi^0 data at midrap. from d+Au and p+p coll. at RHIC)
- In our analysis use same data sets as HKN'07 (up to cuts)

	R	Nucleus	Experiment	EPS09	HKN07	DS04
DIS		D/p	NMC		O	
	A/D	4He	SLAC E139	O	O	O
			NMC95	O (5)	O	O
		Li	NMC95	O	O	
		Be	SLAC E139	O	O	O
		C	EMC-88, 90		O	
			NMC 95	O	O	O
			SLAC E139	O	O	O
			FNAL-E665		O	
		N	BCDMS 85		O	
			HERMES 03		O	
		Al	SLAC E49		O	
			SLAC E139	O	O	O
		Ca	EMC 90		O	
			NMC 95	O	O	O
			SLAC E139	O	O	O
			FNAL-E665		O	
		Fe	SLAC E87		O	
			SLAC E139	O (15)	O	O
			SLAC E140		O	
			BCDMS 87		O	
		Cu	EMC 93	O	O	
		Kr	HERMES 03		O	
		Ag	SLAC E139	O	O	O
		Sn	EMC 88		O	
		Au	SLAC E139	O	O	O
			SLAC E140		O	
		Pb	FNAL-E665		O	
	A/C	Be	NMC 96	O	O	O
		Al	NMC 96	O	O	O
		Ca	NMC 95		O	
			NMC 96	O	O	O
		Fe	NMC 96	O	O	O
		Sn	NMC 96	O (10)	O	O
		Pb	NMC 96	O	O	O
	A/Li	C	NMC 95	O	O	
		Ca	NMC 95	O	O	
DY	A/D	C	FNAL-E772	O	O	O
		Ca		O (15)	O	O
		Fe		O (15)	O	O
		W		O (10)	O	O
	A/Be	Fe	FNAL E866	O	O	
		W		O	O	
π pro	dA/pp	Au	RHIC-PHENIX	O (20)		

Table from Hirai et al, arXiv:0909.2329

General conclusion: see H. Paukkunen, Talk at DIS'09

Excellent agreement between NLO pQCD and the lA DIS, DY, and pi^0 data in the kinematical range $0.005 < x < 1,\ m_c{}^2 < Q^2 < 150\, GeV^2$ is found.

Factorization theorem in hard nuclear processes seems to work well.

Two up-to-date sets including PDF uncertainties (HKN'07, EPS'09) ready for use at LHC.

Why yet another set of nPDF?

- Generally, the more global analyses available the better since quite a lot of physical assumptions and technical details enter the game.
  (Note that PDF error bands tend to underestimate the true error.)

- Want close connection to the CTEQ proton analysis. Use nPDF to calculate nuclear correction factors in a flexible way (Observable and Q^2 dependent).

- Work has been triggered by our analysis of Neutrino DIS data (see below).

Global fit package

- CTEQ global fit package extended:
  - handle various nuclear targets
  - included new observables:
    - structure function ratios: $F_2^A(x,Q^2)/F_2^{A'}(x,Q^2)$
    - ratio of DY cross sections: $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$
    - neutrino cross sections
  - included all the relevant data:
    - l-A DIS, DY
    - NuTeV (iron), CHORUS (lead)
  - modeled the A-dependence of our fit parameters

- Use same framework as in CTEQ6M proton fit:
  - $Q_0 = m_c = 1.3$ *GeV*, m_b = *4.5 GeV*, $\alpha_s(M_Z)=0.118$
  - Heavy quark treatment: ACOT scheme
  - Functional form for bound proton PDFs same as for free proton PDFs: (restrict x to 0<x<1)

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

(bound neutron PDFs by iospin symmetry)

- simple A-dependence: (reduces to proton for A=1)

$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right), \quad k = \{1,\ldots,5\}\,.$$

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

- Standard cuts: Q>2 GeV, W>3.5 GeV

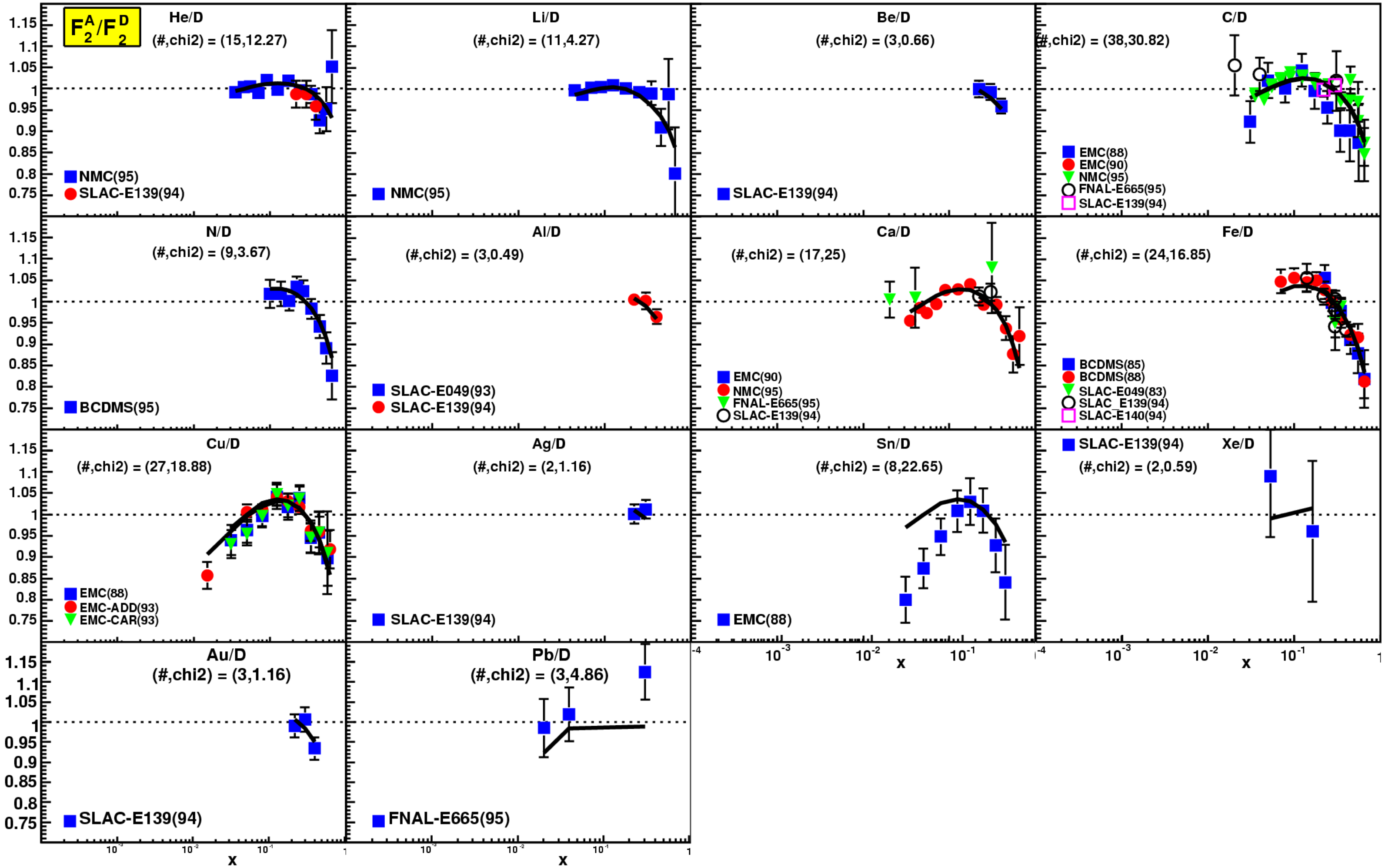
Some results

arXiv:0907.2357

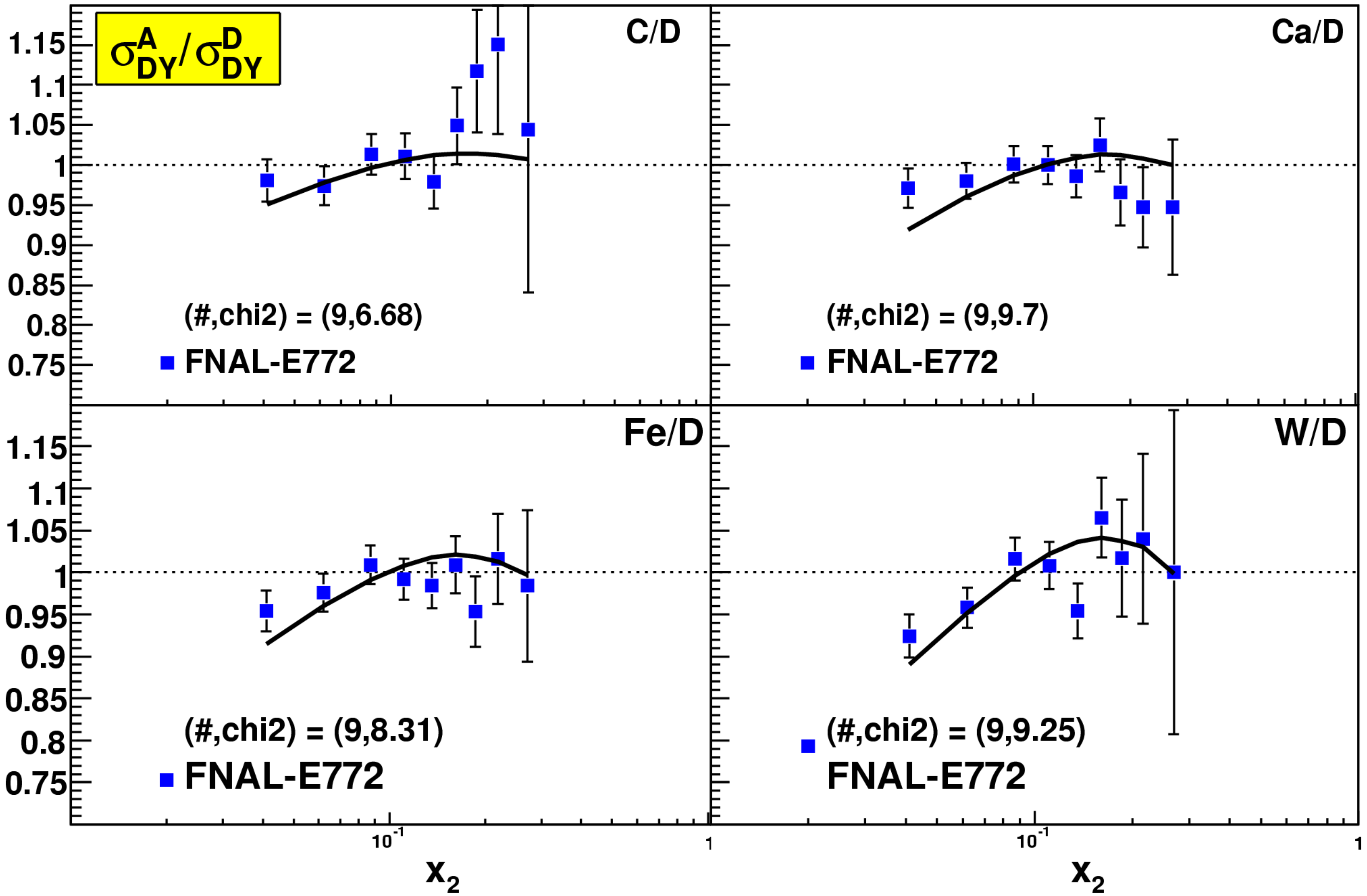
- 708 (1233) data points after (before) cuts
- 32 free paramters; 675 d.o.f.
- overall $\chi^2 / dof = 0.95$
- individually:
  - for $F_2{}^A / F_2{}^D$: $\chi^2 / pt = 0.92$
  - for $F_2{}^A / F_2{}^{A'}$: $\chi^2 / pt = 0.69$
  - for DY: $\chi^2 / pt = 1.08$

- **Our simple approach works!**

Fit to nuclear DIS data



Fit to Nuclear DY data

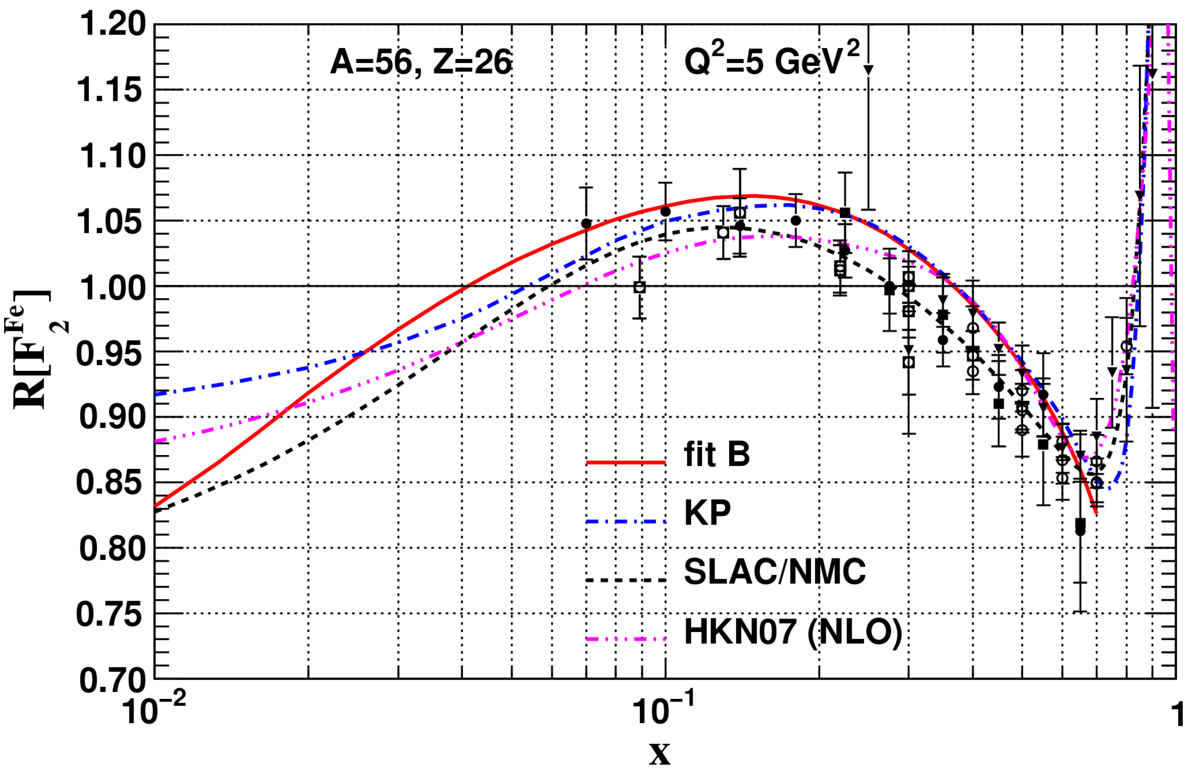


Nuclear correction factor R

$$R[\mathcal{O}] = \frac{O[\text{nuc.PDF}]}{O[\text{freePDF}]}$$

Use nPDF from our fit of lA DIS and DY data.

Results are compatible!



Next steps

- Error PDFs

- Try to relax cuts on Q^2 and W to study problematic large-x region
  - Target mass correction (TMC) [see arXiv:0709.1775]
  - Higher twist contributions
  - nPDF not zero at x=1 (but our functional forms vanish)
  - soft gluon resummation
  - resonances at low W, quark-hadron duality

see C. Keppel, Talk at DIS'09

nPDFs from neutrino DIS data

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PRD77(2008)054013

Why neutrino DIS?

- **Flavor separation:**
  Neutrino sfs depend on different combinations of PDFs

- **Dimuon production:**
  - Main source of information on the strange sea
  - Large uncertainty on s(x) has significant influence on the W and Z benchmark processes at LHC

- **Data interesting for proton PDF and nPDF**

- **For proton PDF: need nuclear corrections!**

Why neutrino DIS?

- **LBL precision neutrino experiments:**
  Need good understanding of ν-A cross sections (A=Oxygen, Carbon)

- **EW precision measurements:**
  Paschos-Wolfenstein: extraction of $\sin^2\theta_W$

Analysis of NuTeV data

- NuTeV cross section data
  - more than 1000 neutrino cross section data
  - more than 1000 anti-neutrino cross section data
  - correlated errors, radiative corrections, with and w/ o/ isoscalar corrections
- NuTeV/CCFR dimuon data (172 pts) to fix s(x) PDF
- Idea: Analyse iron data only (iron neutrino data)
  - Advantage: no A-dependence needs to be modeled
  - Only 2 Observables: not all PDFs constrained Need to be careful.

Analysis of NuTeV data -cont.-

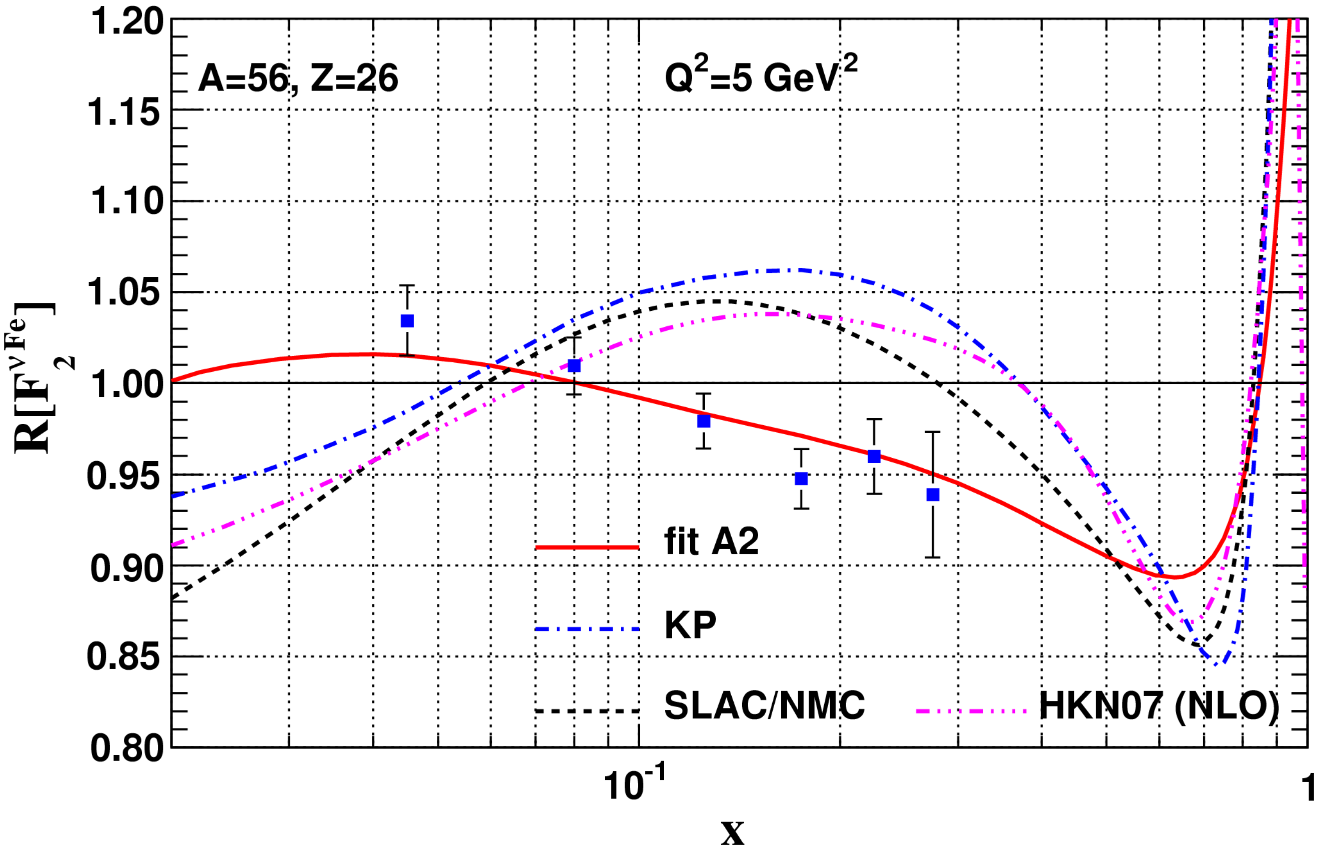
- Assumptions
  - Gluon PDF not constrained: Fix gluon to free proton gluon (supported by result of DS'04)
  - Assume corrections to dbar similar to corrections to ubar at moderate and small x

- 'Perform regression analysis' where only one parameter is left free at a time

- Band of fits with similar χ^2/dof

Nuclear correction factors for F_2(iron)

Are nuclear corrections in charged-lepton and neutrino DIS different?



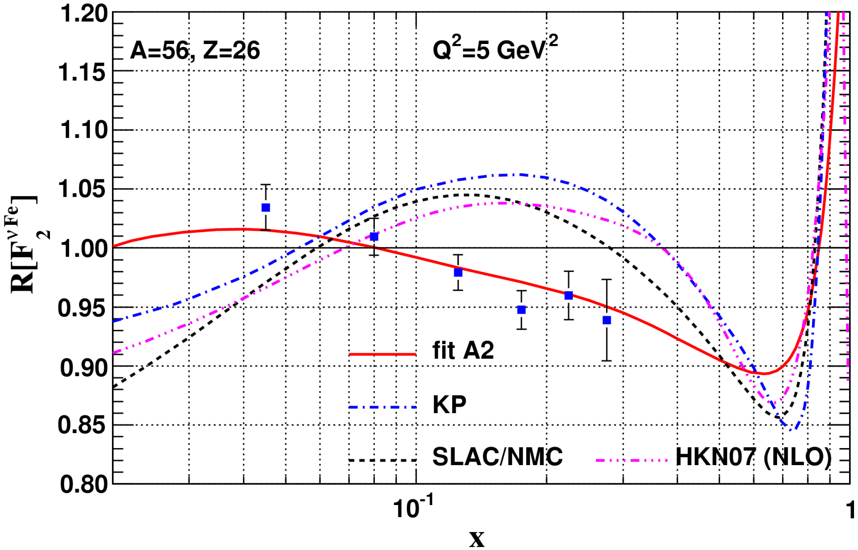
Note that the correction factors for different observables are expected to differ!

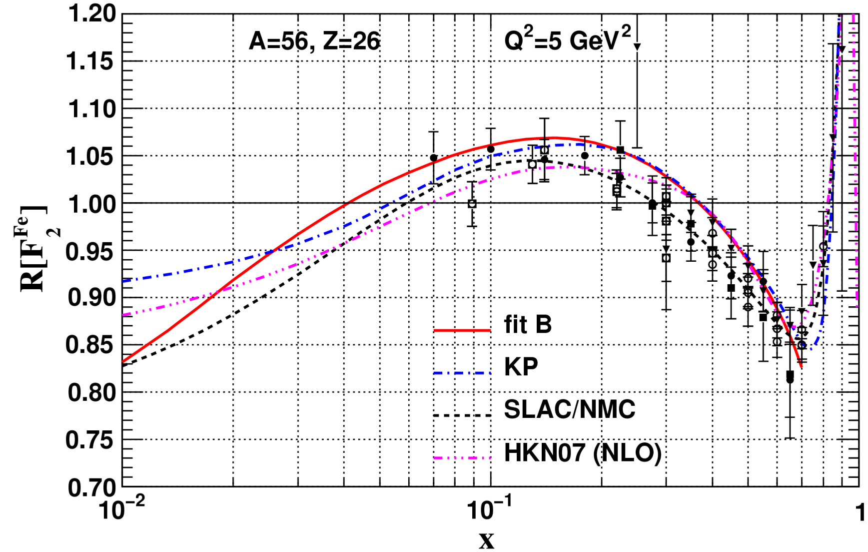
Correction factor for F_3 could be different!

NuSOnG can study these issues and test the universality of the NPDFs! **VERY IMPORTANT**

arXiv: 0906.3563, 0803.0354

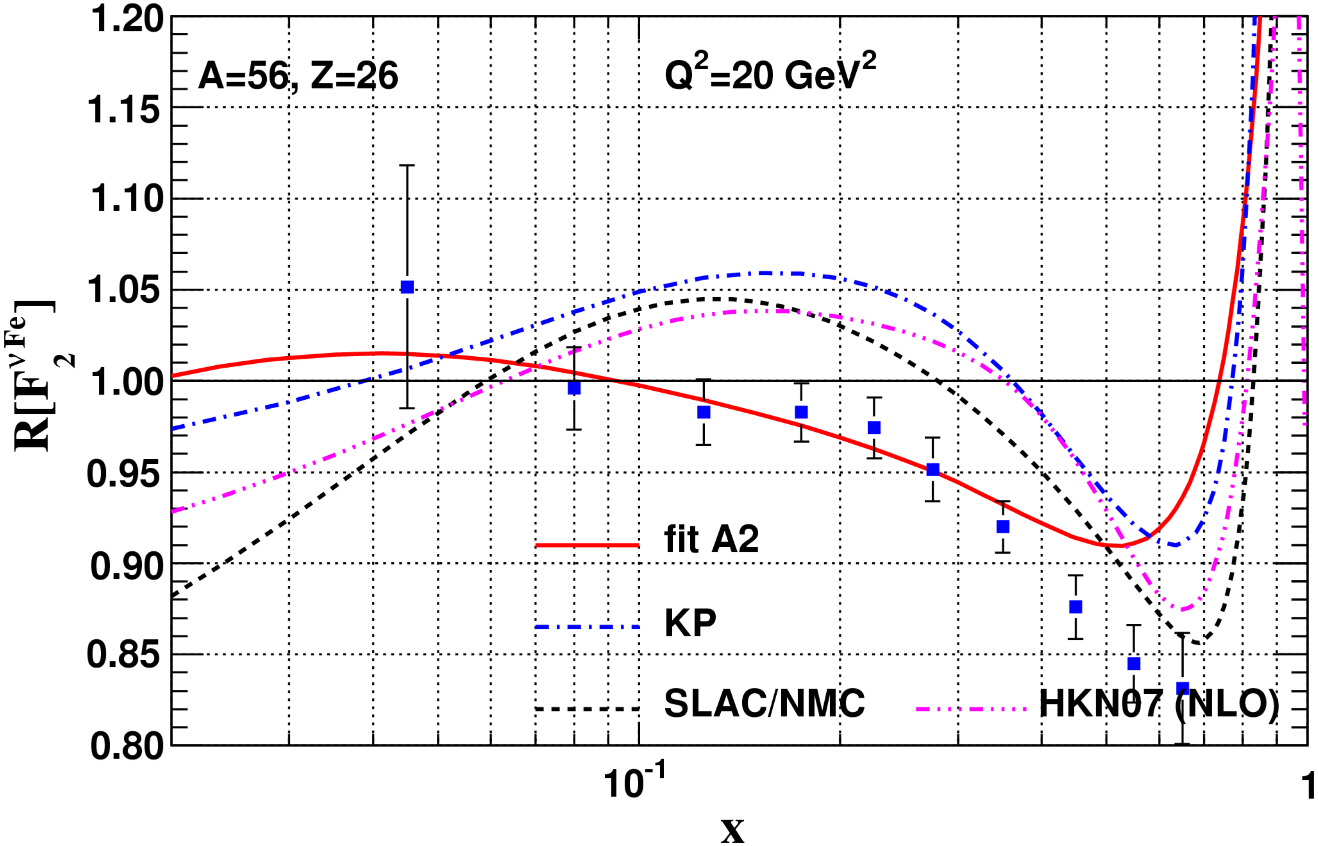
Current picture





IS there a compromise fit?
A better flavor decomposition?

Need global analysis of l-A DIS + DY + nu-A DIS for definite conclusions!



A=56, Z=26
Q^2=20 GeV^2
fit A2
KP
SLAC/NMC
HKN07 (NLO)
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
$R[F_2^{\nu Fe}]$
10^{-1}
1
x

Conclusions

- A new set of nPDFs is on the way. Extension of the CTEQ fitting framework.

- Results for neutrino-iron DIS have triggered a lot of interest. Need fully global analysis

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