Nuclear Parton Distributions

(concentrating on nCTEQ)

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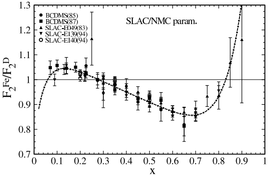
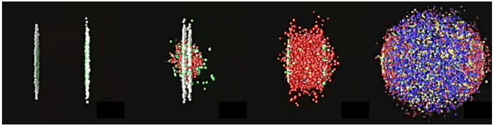
Outline

Motivations: Why do we need nuclear PDFs?

- What are PDFs of bound protons/neutrons?



- Heavy ion collisions in LHC and RHIC



- Differentiate flavors in free-proton PDFs (e.g. strange)

charged lepton DIS

$$F_2^{l^\pm} \sim \left(\tfrac{1}{3}\right)^2 [d+s] + \left(\tfrac{2}{3}\right)^2 [u+c]$$

neutrino DIS

$$F_2^{\nu} \sim \left[d + s + \bar{u} + \bar{c}\right]$$
$$F_2^{\bar{\nu}} \sim \left[\bar{d} + \bar{s} + u + c\right]$$
$$F_3^{\nu} \sim 2\left[d + s - \bar{u} - \bar{c}\right]$$
$$F_3^{\bar{\nu}} \sim 2\left[u + c - \bar{d} - \bar{s}\right]$$

Motivations: differentiate flavors in proton PDFs

- To differentiate flavors we need to probe different linear combinations of PDFs

charged lepton DIS

$$F_2^{l^\pm} \sim \left(\tfrac{1}{3}\right)^2 [d+s] + \left(\tfrac{2}{3}\right)^2 [u+c]$$

neutrino DIS

$$F_2^{\nu} \sim \left[d+s+\bar{u}+\bar{c}\right]$$
$$F_2^{\bar{\nu}} \sim \left[\bar{d}+\bar{s}+u+c\right]$$

$$F_3^{\nu} \sim 2\left[d+s-\bar{u}-\bar{c}\right]$$
$$F_3^{\bar{\nu}} \sim 2\left[u+c-\bar{d}-\bar{s}\right]$$

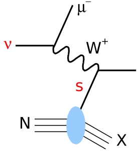
- Neutrino data gives access to different flavor combinations.
- Can be done only with heavy nuclear targets.
- Depend on nuclear corrections.

Motivations: proton Strange PDF

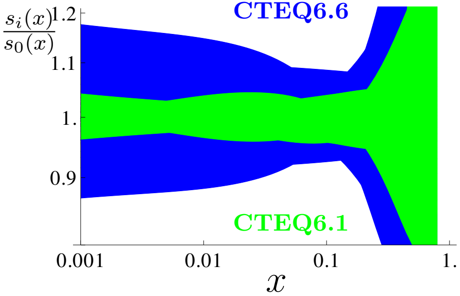
Before `CTEQ6.6` proton PDFs it was assumed
P. Nadolsky et al. PRD 78, 013004 (2008), `arXiv:0802.0007`

$$s(x) = \bar{s}(x) \sim \kappa\, \frac{\bar{u}(x) + \bar{d}(x)}{2}, \qquad \kappa = \frac{1}{2}$$

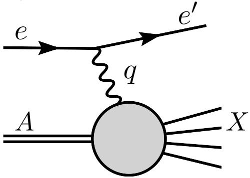
- Underestimating s PDF uncertainty, as $\bar{u}$, $\bar{d}$ are much better constrained.
- Neutrino-nucleon dimuon data (CCFR, NuTeV)



allowed to fit s PDF independently of $\bar{u}$, $\bar{d}$ sea.



Variables: DIS of nuclear target $eA \to e'X$



- DIS variables in case on nucleons in nucleus $\begin{cases} Q^2 \equiv -q^2 \\ x_A \equiv \frac{Q^2}{2\,p_A \cdot q} \end{cases}$
    - p^A – nucleus momentum
    - $x_A \in (0,1)$ – analog of Bjorken variable (fraction of the nucleus momentum carried by a nucleon)

- Analogue variables for partons:
    - $p_N = \frac{p_A}{A}$ – *average* nucleon momentum
    - $x_N \equiv \frac{Q^2}{2\,p_N \cdot q} = A\,x_A$ – parton momentum fraction with respect to the avarage nucleon momentum p_N
    - $x_N \in (0, A)$ – parton can carry more than the average nucleon momentum p_N.

Assumptions entering the nuclear PDF analysis

1. **Factorization** & DGLAP evolution
   - allow for definition of **universal PDFs**
   - make the formalism **predictive**
   - needed even if it is broken
2. Isospin symmetry $\begin{cases} u^{n/A}(x) = d^{p/A}(x) \\ d^{n/A}(x) = u^{p/A}(x) \end{cases}$
3. The *bound proton* PDFs have the *same evolution equations* and sum rules as the free proton PDFs *provided we neglect any contributions from the region* $x > 1$ (which is expected to have negligible contribution [PRC 73, 045206 (2006), `arXiv:hep-ph/0509241`])

Then observables $\mathcal{O}^A$ can be calculated as:

$$\mathcal{O}^A = Z\,\mathcal{O}^{p/A} + (A - Z)\,\mathcal{O}^{n/A}$$

With the above assumptions we can use the free proton framework to analyze nuclear data

Schematics of Global Analysis

1. Parametrize PDFs at low initial scale $\mu = Q_0 = 1.3\text{GeV}$:

$$f(x, Q_0) = f(x; a_0, a_1, \dots) = a_0 x^{a_1}(1-x)^{a_2} P(x; a_3, \dots)$$

2. Use DGLAP equation to evolve $f(x, \mu)$ from $\mu = Q_0$ to $\mu = Q_{\text{max}}$.
3. Define and minimize appropriate χ^2 function (with respect to parameters $a_0, a_1, \dots$)

$$\chi^2(\{a_i\}) = \sum_{\text{experiments}} w_n \chi_n^2(\{a_i\})$$

$$\chi_n^2(\{a_i\}) = \sum_{\text{data points}} \left(\frac{\text{data} - \text{theory}(\{a_i\})}{\text{uncertainty}} \right)^2$$

(by default $w_n = 1$)

Uncertainties in global analysis

- **Experimental errors** (included in PDFs error analysis)
- **Theoretical uncertainties** (not included)
- **"Details"** of Global Fits
  (e.g. parametrization, HF schemes; hard to estimate not included)

Propagating experimental errors to PDFs:

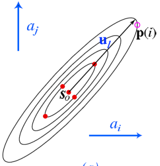
- Hessian Method
  - Eigenvector PDFs
  - Quadratic approximation
  - Simple computation of correlations
- Lagrange Multipliers
- Monte Carlo Methods

Hessian method

[JHEP 07 (2002) 012, arXiv:hep-ph/0201195]

- **Expand** χ^2 function around minimum, $\{a_i^0\}$,

$$\chi^2 = \chi_0^2 + \sum_{ij} \frac{1}{2}(a_i - a_i^0)(a_j - a_j^0)\left(\frac{\partial^2 \chi^2}{\partial y_i \partial y_j}\right)_0$$



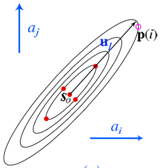
(a)
Original parameter basis

Hessian method

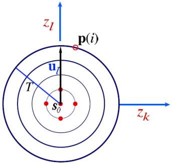
[JHEP 07 (2002) 012, arXiv:hep-ph/0201195]

- **Expand** χ^2 function around minimum, $\{a_i^0\}$, and **diagonalize**

$$\chi^2 = \chi_0^2 + \sum_{ij} \frac{1}{2}(a_i - a_i^0)(a_j - a_j^0)\left(\frac{\partial^2 \chi^2}{\partial y_i \partial y_j}\right)_0 = \chi_0^2 + \sum_i z_i^2$$



(a)
Original parameter basis



(b)
Orthonormal eigenvector basis

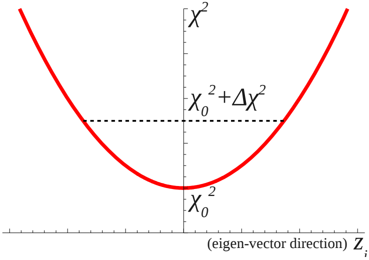
Hessian method

[JHEP 07 (2002) 012, arXiv:hep-ph/0201195]

- **Expand** χ^2 function around minimum, $\{a_i^0\}$, and **diagonalize**

$$\chi^2 = \chi_0^2 + \sum_{ij} \frac{1}{2}(a_i - a_i^0)(a_j - a_j^0)\left(\frac{\partial^2 \chi^2}{\partial y_i \partial y_j}\right)_0 = \chi_0^2 + \sum_i z_i^2$$

- Choose tolerance criteria $\Delta\chi^2 = \chi^2 - \chi_0^2$ value (defining 1-σ uncertainty),
  - ideal case $\Delta\chi^2 = 1$
  - realistic global analysis $\Delta\chi^2 \sim 1 - 100$



Hessian method

[JHEP 07 (2002) 012, arXiv:hep-ph/0201195]

- **Expand** χ^2 function around minimum, $\{a_i^0\}$, and **diagonalize**

  $$\chi^2 = \chi_0^2 + \sum_{ij} \frac{1}{2}(a_i - a_i^0)(a_j - a_j^0)\left(\frac{\partial^2\chi^2}{\partial y_i \partial y_j}\right)_0 = \chi_0^2 + \sum_i z_i^2$$

- Choose tolerance criteria $\Delta\chi^2 = \chi^2 - \chi_0^2$ value (defining 1-σ uncertainty),
  - ideal case $\Delta\chi^2 = 1$
  - realistic global analysis $\Delta\chi^2 \sim 1 - 100$
- Construct error PDFs corresponding to each eigenvector direction:

  $$f_i^{\pm} = f(\{z_i\}) = f(0, \ldots, z_i = \pm\sqrt{\Delta\chi^2}, \ldots, 0)$$
  $$z_i = \pm\sqrt{\Delta\chi^2}$$

- Calculate errors of observable X:

  $$\Delta X = \frac{1}{2}\sqrt{\sum_i \left[X(f_i^+) - X(f_i^-)\right]^2}$$

Differences with the free-proton PDFs

- Different data sets – much less data:
  - Less data $\rightarrow$ less constraining power $\rightarrow$ more assumptions (fixing) about a_i parameters
  - **Assumptions replace uncertainities!**
- Parametrization

Outline

Available nuclear PDFs

- **Multiplicative nuclear correction factors**

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A)\ f_i^{free\ proton}(x_N, \mu_0)$$

  - Hirai, Kumano, Nagai [PRC 76, 065207 (2007), `arXiv:0709.3038`]
  - Eskola, Paukkunen, Salgado [JHEP 04 (2009) 065, `arXiv:0902.4154`]
  - de Florian, Sassot, Stratmann, Zurita [PRD 85, 074028 (2012), `arXiv:1112.6324`]

- **Native nuclear PDFs**
  - `nCTEQ` [PRD 80, 094004 (2009), `arXiv:0907.2357`]

$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

$$f_i(x_N, A = 1, \mu_0) \equiv f_i^{free\ proton}(x_N, \mu_0)$$

HKN framework [PRC 76, 065207 (2007), arXiv:0709.3038]

- LO & NLO PDFs with errors
- Error PDFs produced with *Hessian method*
- Parametrization (Q_0=1GeV)

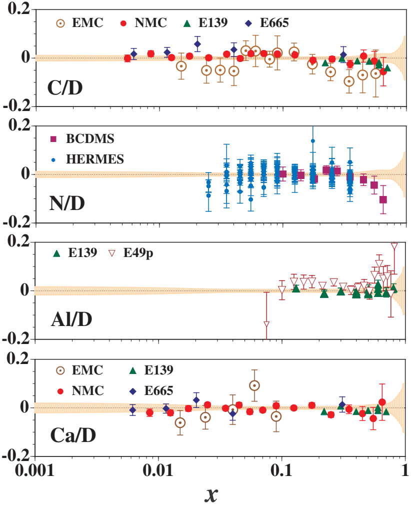
$$f_i^{p/A}(x_N, Q_0) = R_i^A(x_N, Q_0)\, f_i^p(x_N, Q_0), \qquad\qquad i = u_v, d_v, g, \text{sea}$$

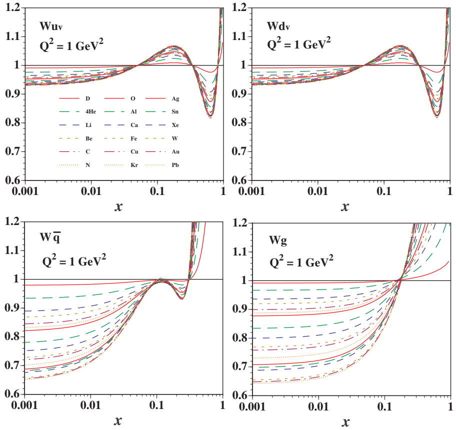
$$R_i(x, Q_0, A) = 1 + \left(1 - \tfrac{1}{A^\alpha}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$

- MRST 1998 free proton baseline
- Neglects $x_N > 1$
- Data: DIS & DY

HKN framework [PRC 76, 065207 (2007), arXiv:0709.3038]

- NLO fit: $\chi^2/dof = 1.21$





EPS09 framework [JHEP 04 (2009) 065, arXiv:0902.4154]

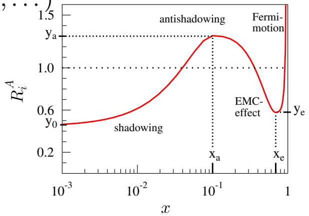
- LO & NLO PDFs with errors
- Error PDFs produced with *Hessian method*
- Parametrization (Q_0=1.3GeV)

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A, Z)\, f_i(x_N, \mu_0), \qquad i = \text{valence}, s, g$$

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

A-dependence of fitting parameters ($d_i = a_i, b_i, \ldots$)

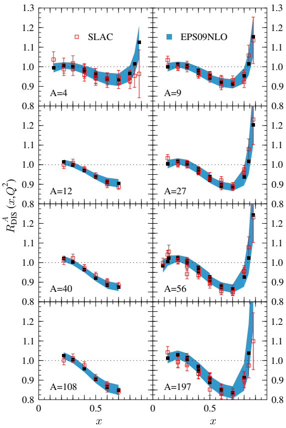
$$d_i^A = d_i^{A_{ref}} \left(\frac{A}{A_{ref}}\right)^{p_{d_i}}$$

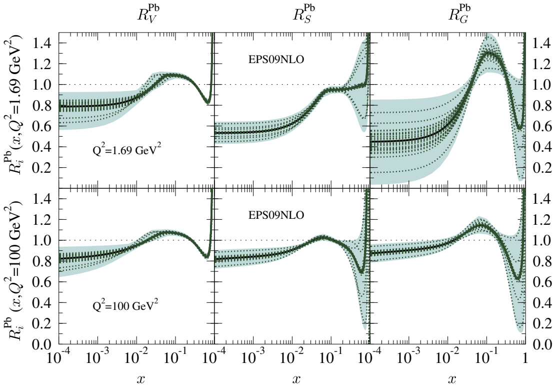


- CTEQ6.1M free proton baseline
- Neglects $x_N > 1$
- Data: DIS, DY, π^0 @ RHIC

EPS09 framework [JHEP 04 (2009) 065, arXiv:0902.4154]

- NLO fit: $\chi^2/dof = 0.79$





DSSZ framework [PRD 85, 074028 (2012), arXiv:1112.6324]

- NLO PDFs with errors
- Error PDFs produced with *Hessian method*
- Parametrization (Q_0=1GeV)

$$f_i^{p/A}(x_N, Q_0) = R_i^A(x_N, Q_0)\, f_i^p(x_N, Q_0), \qquad i = \text{valence}, s, g$$

$$R_v^A(x, Q_0) = \epsilon_1 x^{\alpha_1}(1-x)^{\beta_1}\left[1 + \epsilon_2(1-x)^{\beta_2}\right]\left[1 + a_v(1-x)^{\beta_3}\right]$$
$$R_s^A(x, Q_0) = R_v^A(x, Q_0)\frac{\epsilon_s}{\epsilon_1}\frac{1 + a_s x^{\alpha_s}}{1 + a_s}$$
$$R_g^A(x, Q_0) = R_v^A(x, Q_0)\frac{\epsilon_g}{\epsilon_1}\frac{1 + a_g x^{\alpha_g}}{1 + a_g}$$

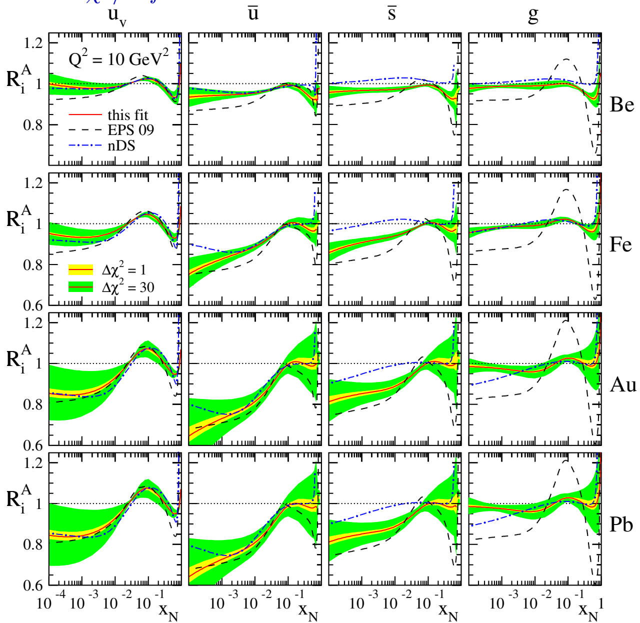
A-dependence of fitting parameters ($\xi = \alpha_v, \alpha_s, \dots$)

$$\xi = \gamma_\xi + \lambda_\xi A^{\delta_\xi}$$

- MSTW 2008 free proton baseline
- Neglects $x_N > 1$
- Data: DIS, DY, π^0 @ RHIC, Neutrino DIS

DSSZ framework [PRD 85, 074028 (2012), arXiv:1112.6324]

- NLO fit: $\chi^2/dof = 0.99$



nCTEQ framework [PRD 80, 094004 (2009), arXiv:0907.2357]

- Functional form of the bound proton PDF same as for the free proton (CTEQ6M, x restricted to $0 < x < 1$)

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}, \qquad i = u_v, d_v, g, \ldots$$
$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} + (1+c_3 x)(1-x)^{c_4}$$

- A-dependent fit parameters (reduces to free proton for $A = 1$)

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

- PDFs for nucleus (A, Z)

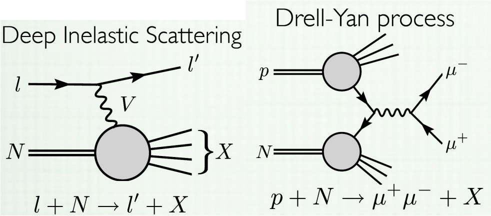
$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A-Z}{A} f_i^{n/A}(x, Q)$$

(bound neutron PDF $f_i^{n/A}$ by isospin symmetry)

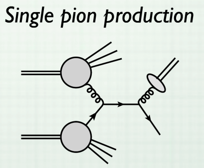
Data sets

- NC DIS & DY

CERN BCDMS & EMC & NMC
N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)
FNAL E-665
N = (D, C, Ca, Pb, Xe)
DESY Hermes
N = (D, He, N, Kr)
SLAC E-139 & E-049
N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)
FNAL E-772 & E-886
N = (D, C, Ca, Fe,W)



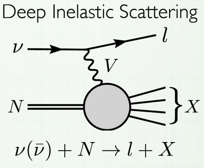
- Single pion production (not yet included)



RHIC - PHENIX & STAR

N = Au

- Neutrino (to be included later)



CHORUS CCFR & NuTeV

N = Pb N = Fe

nCTEQ fits

Fit properties:

- fit @NLO
- $Q_0 = 1\text{GeV}$
- using ACOT heavy quark scheme
- kinematical cuts: $Q > 2\text{GeV}$, $W > 3.5\text{GeV}$
- 708 (1233) data points after (before) cuts
- 17 free parameters
  - 7 gluon
  - 8 valence
  - 2 sea
- $\chi^2/\text{dof} = 0.87$

Error analysis:

- use Hessian method

$$\chi^2 = \chi_0^2 + \frac{1}{2} H_{ij}(a_i - a_i^0)(a_j - a_j^0)$$

$$H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}$$

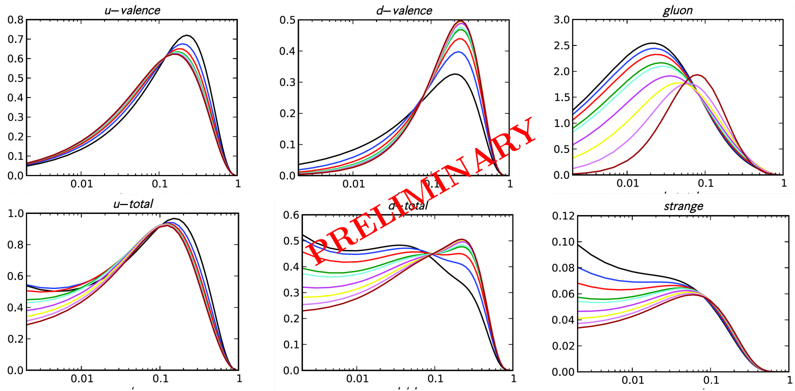
- tolerance $\Delta\chi^2 = 35$ (every nuclear target within 90% C.L.)
- eigenvalues span 10 orders of magnitude → require numerical precision
- use noise reducing derivatives

nCTEQ RESULTS
(preliminary)

nCTEQ results

A-dependence of bound proton PDFs

$$x\, f_i^A(x,Q) \qquad A = (1, 2, 4, 9, 12, 27, 56, 108, 207)$$

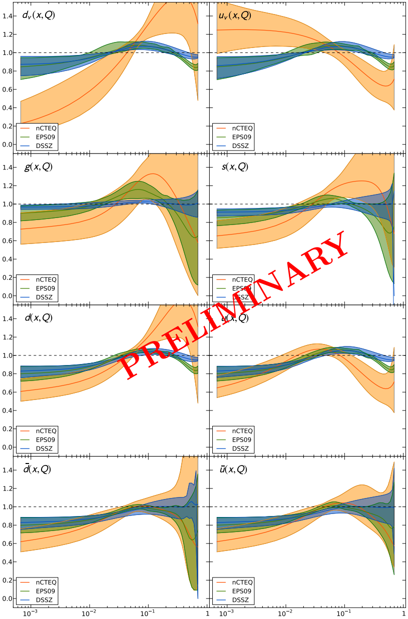


nCTEQ results

Nuclear correction factors
($Q = 10\text{GeV}$)

$$R_i(Pb) = \frac{f_i^{Pb}(x,Q)}{f_i^p(x,Q)}$$

- different solution for d-valence & u-valence compared to EPS09 & DSSZ
- sea quark nuclear correction factors similar to EPS09
- nuclear correction factors depend largely on underlying proton baseline

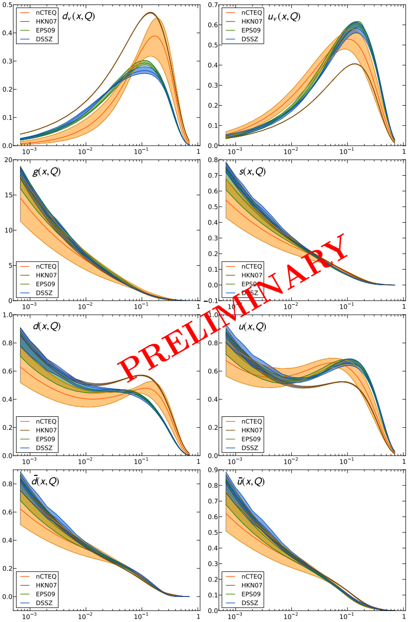


nCTEQ results

Nuclear PDFs ($Q = 10\text{GeV}$)

$$x\, f_i^{Pb}(x, Q)$$

- nCTEQ d-valence & u-valence solution between HKN07 & EPS09
- nCTEQ features larger uncertainties than previous nPDFs
- better agreement between different groups (nPDFs don't depend on proton baseline)



nCTEQ vs. EPS09

nCTEQ

$$x u_v^{p/A}(Q_0) = x^{c_1^u}(1-x)^{c_2^u} e^{c_3^u x}(1+e^{c_4^u} x)^{c_5^u}$$

$$x d_v^{p/A}(Q_0) = x^{c_1^d}(1-x)^{c_2^d} e^{c_3^d x}(1+e^{c_4^d} x)^{c_5^d}$$

$$c_k^{u_v} = c_{k,0}^{u_v} + c_{k,1}^{u_v}\left(1 - A^{-c_{k,2}^{u_v}}\right)$$

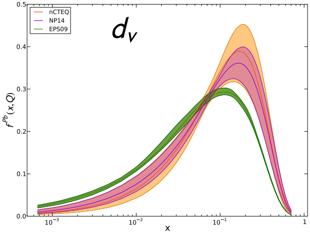
$$c_k^{d_v} = c_{k,0}^{d_v} + c_{k,1}^{d_v}\left(1 - A^{-c_{k,2}^{d_v}}\right)$$

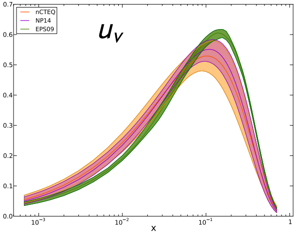
EPS09

$$u_v^{p/A}(Q_0) = R_v(x, A, Z)\, u(x, Q_0)$$

$$d_v^{p/A}(Q_0) = R_v(x, A, Z)\, d(x, Q_0)$$

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





we set:

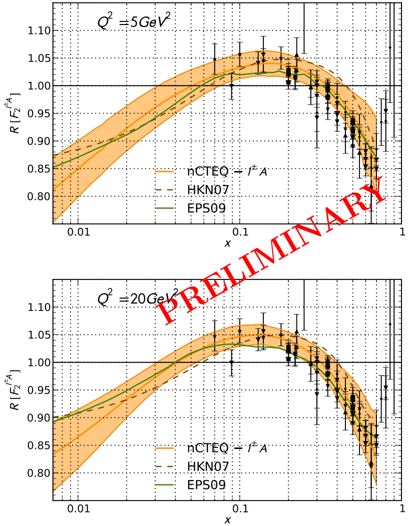
$$\begin{cases} c_1^{d_v} = c_1^{u_v} \\ c_2^{d_v} = c_2^{u_v} \end{cases}$$

nCTEQ results

Structure function ratio

$$R = \frac{F_2^{Fe}(x,Q)}{F_2^{D}(x,Q)}$$

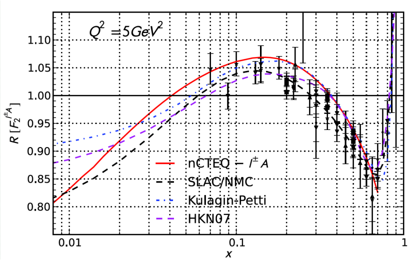
- good data description
- despite different u-valence & d-valence ratios are similar to EPS09



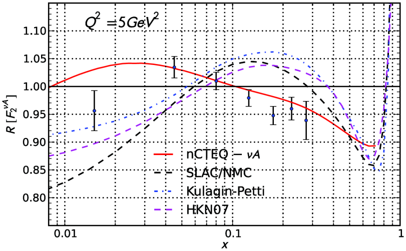
Compatibility of nuclear corrections for νA and $l^{\pm}A$ DIS

PRL106, 122301 (2011), `arXiv:1012.0286`
PRD80, 094004 (2009), `arXiv:0907.2357`

Fit to $l^{\pm}A$ DIS and DY data
$\chi^2/\mathrm{dof} = 0.89$

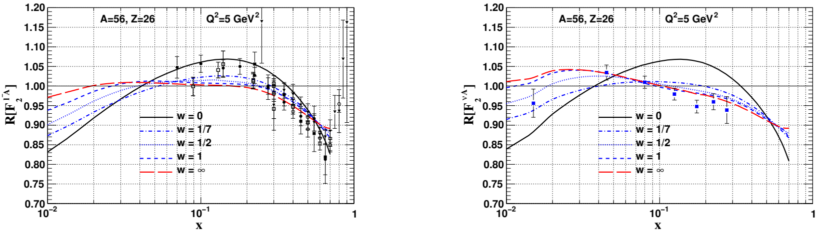


Fit to νA DIS data only
$\chi^2/\mathrm{dof} = 1.33$



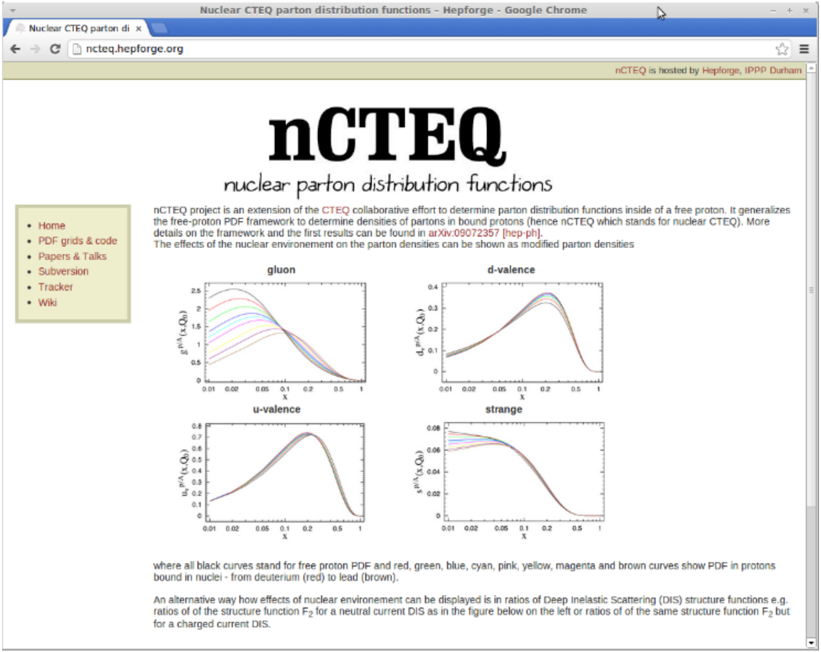
Compatibility of nuclear corrections for νA and $l^{\pm}A$ DIS

PRL106, 122301 (2011), arXiv:1012.0286
PRD80, 094004 (2009), arXiv:0907.2357



w	$l^{\pm}A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
0	708	638 (0.90)	-	-	638 (0.90)
1/7	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
1/2	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
1	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
∞	-	-	3134	4192 (1.33)	4192 (1.33)

$$\chi^2 = \sum_{l^{\pm}A \text{ data}} \chi_i^2 + \sum_{\nu A \text{ data}} w\chi_i^2, \qquad w = \{0, \tfrac{1}{7}, \tfrac{1}{2}, 1, \infty\}$$


Nuclear CTEQ parton distribution functions - Hepforge - Google Chrome
Nuclear CTEQ parton di
ncteq.hepforge.org
nCTEQ is hosted by Hepforge, IPPP Durham
nCTEQ
nuclear parton distribution functions
Home
PDF grids & code
Papers & Talks
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nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). More details on the framework and the first results can be found in arXiv:09072357 [hep-ph].
The effects of the nuclear environement on the parton densities can be shown as modified parton densities
gluon
d-valence
u-valence
strange
x
where all black curves stand for free proton PDF and red, green, blue, cyan, pink, yellow, magenta and brown curves show PDF in protons bound in nuclei - from deuterium (red) to lead (brown).
An alternative way how effects of nuclear environement can be displayed is in ratios of Deep Inelastic Scattering (DIS) structure functions e.g. ratios of of the structure function F2 for a neutral current DIS as in the figure below on the left or ratios of of the same structure function F2 but for a charged current DIS.

Summary

- We have first nCTEQ error PDFs (still preliminary)
- nCTEQ PDFs features larger (more realistic) uncertainties.

- LHC $p\ Pb$ data will allow to further constrain nPDFs (first need a proton baseline with LHC data).
- Nuclear component important not only for heavy ion collisions, but also for flavor differentiation, especially for s-quark distribution (which is important for LHC W/Z benchmark processes).

Summary

- Plans for future:
  - finish current analysis;
  - redo analysis of neutrino nuclear corrections;
  - include new data (LHC, JLAB, Minerνa, ???);
  - high x region, deuterium nuclear corrections, higher twist effects – CJ collaboration in JLAB;
  - unified framework to fit both free proton and nuclear PDFs;
  - different methods for minimizing and estimating errors;

BACKUP SLIDES

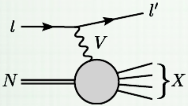
NEUTRINO DIS

K. Kovařík, DIS2013

- Experiments included in the analysis

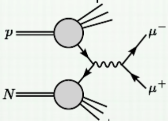
Charged lepton

Deep Inelastic Scattering



$l + N \to l' + X$

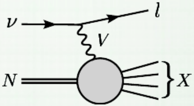
Drell-Yan process



$p + N \to \mu^+\mu^- + X$

Neutrino

Deep Inelastic Scattering



$\nu(\bar{\nu}) + N \to l + X$

CERN BCDMS & EMC & NMC
$N = (\mathrm{D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W})$

FNAL E-665
$N = (\mathrm{D, C, Ca, Pb, Xe})$

DESY Hermes
$N = (\mathrm{D, He, N, Kr})$

SLAC E-139 & E-049
$N = (\mathrm{D, Ag, Al, Au, Be, C, Ca, Fe, He})$

FNAL E-772 & E-886
$N = (\mathrm{D, C, Ca, Fe, W})$

CHORUS
$N = \mathrm{Pb}$

CCFR & NuTeV
$N = \mathrm{Fe}$

1233 data points (708 after cuts)

3832 data points (3134 after cuts)

nCTEQ

- NPDF fit properties:
  - we fit nuclear data with NLO QCD predictions
  - we include heavy quark effects (ACOT)
  - applied standard CTEQ kinematical cuts **Q>2GeV & W>3.5GeV**

- NPDF fit results:
  - 708 (1233) data points after (before) cuts
  - 17 free parameters - 691 degrees of freedom
  - overall χ^2/dof = 0.87
  - individually for different data subsets
    - for F_2^A/F_2^D χ^2/pt = 0.80
    - for $F_2^A/F_2^{A'}$ χ^2/pt = 0.51
    - for $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$ χ^2/pt = 0.85

F_2^A/F_2^D : Observable	Experiment	# data
D	NMC-97	275
He/D	SLAC-E139	18
	NMC-95,re	16
	Hermes	92
Li/D	NMC-95	15
Be/D	SLAC-E139	17
C/D	EMC-88	9
	EMC-90	2
	SLAC-E139	7
	NMC-95,re	16
	NMC-95	15
	FNAL-E665-95	4
N/D	BCDMS-85	9
	Hermes	92
Al/D	SLAC-E049	18
	SLAC-E139	17
Ca/D	EMC-90	2
	SLAC-E139	7
	NMC-95,re	15
	FNAL-E665-95	4
Fe/D	BCDMS-85	6
	BCDMS-87	10
	SLAC-E049	14
	SLAC-E139	23
	SLAC-E140	6
Cu/D	EMC-88	9
	EMC-93(addendum)	10
	EMC-93(chariot)	9
Kr/D	Hermes	84
Ag/D	SLAC-E139	7
Sn/D	EMC-88	8
Xe/D	FNAL-E665-92	4
Au/D	SLAC-E139	18
Pb/D	FNAL-E665-95	4
Total:		862

$F_2^A/F_2^{A'}$: Observable	Experiment	# data
Be/C	NMC-96	15
Al/C	NMC-96	15
Ca/C	NMC-95	20
	NMC-96	15
Fe/C	NMC-95	15
Sn/C	NMC-96	144
Pb/C	NMC-96	15
C/Li	NMC-95	20
Ca/Li	NMC-95	20
Total:		279

$\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$: Observable	Experiment	# data
C/D	FNAL-E772-90	9
Ca/D	FNAL-E772-90	9
Fe/D	FNAL-E772-90	9
W/D	FNAL-E772-90	9
Fe/Be	FNAL-E866-99	28
W/Be	FNAL-E866-99	28
Total:		92

K. Kovařík, DIS2013

Karlsruhe Institute of Technology

nCTEQ

- NPDF Hessian analysis:

$$\chi^2 = \chi_0^2 + \frac{1}{2} H_{ij}(a_i - a_i^0)(a_j - a_j^0) \qquad H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}$$

- 17 free parameters - 7 gluon parameters
  - 8 valence parameters
  - 2 sea parameters
- Eigenvalues span 10 orders of magnitude → numerical precision required
- Use improved derivatives - less sensitive to noise

$$\frac{\partial f}{\partial x} = \frac{f_1 - f_{-1}}{2h} \quad \to \quad \frac{f_1 - f_{-1} + 2(f_2 - f_{-2}) + 3(f_3 - f_{-3})}{28h}$$

$$\to \quad \frac{f_1 - f_{-1} + 2(f_2 - f_{-2}) + 3(f_3 - f_{-3}) + 4(f_4 - f_{-4}) + 5(f_5 - f_{-5})}{110h}$$

central differences

noise robust Lanczos 3, 5-point derivative

- $\Delta\chi^2 = 35$ determined so that every nuclear target is described within 90% C.L.

K. Kovařík, DIS2013

Karlsruhe Institute of Technology

Compatibility of nuclear corrections for νA and $l^{\pm}A$ DIS

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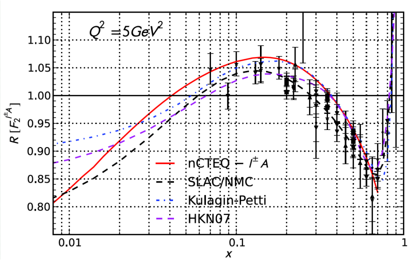

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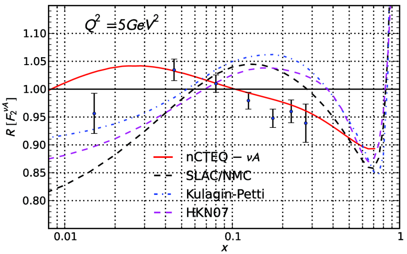

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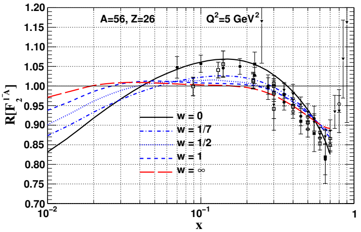
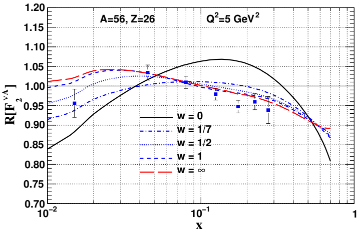
PRD80, 094004 (2009), arXiv:0907.2357





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1/7	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
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$$\chi^2 = \sum_{l^{\pm}A \text{ data}} \chi_i^2 + \sum_{\nu A \text{ data}} w\chi_i^2, \qquad w = \{0, \tfrac{1}{7}, \tfrac{1}{2}, 1, \infty\}$$

Compatibility of nuclear corrections for νA and $l^{\pm}A$ DIS

- It was argued in the literature that νA DIS data is compatible with $l^{\pm}A$ data:

  Paukkunen, Salgado, JHEP **07**, 32 2010, `arXiv:1004.3140`

  de Florian, Sassot, Stratmann, Zurita, PRD85, 074028 (2012), `arXiv:1112.6324`

- However these results were obtained using **uncorrelated errors** for NuTeV experiment, which were crucial for the `nCTEQ` conclusions PRL106, 122301 (2011).

w	$l^{\pm}A$	χ^2(/pt)	νA	χ^2(/pt)	total χ^2(/pt)
1-corr	708	736 (1.04)	3134	4246 (1.36)	4983 (1.30)
1-uncorr	708	809 (1.14)	3110	3115 (1.00)	3924 (1.02)

Compatibility of nuclear corrections for νA and $l^{\pm}A$ DIS

- Recent paper
  Paukkunen, Salgado, PRL110, 212301 (2013), arXiv:1302.2001
  suggests a method to renormalize the NuTeV data so that the tension between νA and $l^{\pm}A$ data sets are removed

  Instead of looking at the ratio of cross-sections $R^{\nu}(x,y,E) \equiv \frac{\sigma^{\nu}_{\text{exp}}(x,y,E)}{\sigma^{\nu}_{\text{CTEQ6.6}}(x,y,E)}$

  they suggest considering

$$\overline{R}^{\nu}(x,y,E) \equiv \frac{\sigma^{\nu}_{\text{exp}}(x,y,E)/I^{\nu}_{\text{exp}}(E)}{\sigma^{\nu}_{\text{CTEQ6.6}}(x,y,E)/I^{\nu}_{\text{CTEQ6.6}}(E)}$$

  where

$$I^{\nu}_{\text{exp}}(E) \equiv \sum_{i \in \text{fixed } E} \sigma_{\text{exp},i}(x,y,E) \times B_i(x,y)$$

  $B_i(x,y)$ is size of the experimental (x,y)-bin

- However this analysis still **do not** take into account correlated errors provided by NuTeV collaboration.

NEUTRINO DIS

K. Kovařík, DIS2013

- Analysis of fits with neutrino DIS (uncorrelated errors)

w	$l^{\pm}A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
1-corr	708	736 (1.04)	3134	4246 (1.36)	4983 (1.30)
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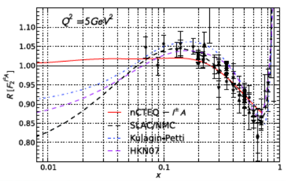
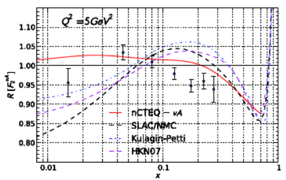
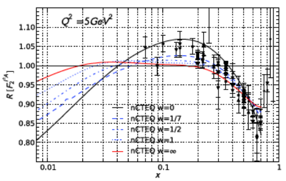
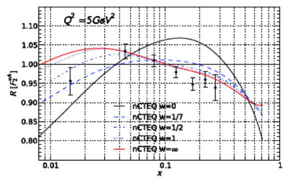
uncorrelated errors





correlated errors





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DS04 framework

De Florian, Sassot, PRD 69, 074028 (2004)
arXiv:hep-ph/0311227

- Parametrization (GRV98 baseline, FFNS, $Q_0^2 = 0.4\mathrm{GeV}^2$)

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

allows for $0 < x_N < A$

- Weight functions W_i parameterize nuclear effects for *valence*, *sea* and *gluon*

$$\begin{aligned} W_v(y, A, Z) &= A\left[a_v \delta(1-\epsilon_v - y) + (1-a_v)\delta(1-\epsilon_{v'} - y)\right] \\ &\quad + n_v \left(\frac{y}{A}\right)^{\alpha_v} \left(1-\frac{y}{A}\right)^{\beta_v} + n_s \left(\frac{y}{A}\right)^{\alpha_s} \left(1-\frac{y}{A}\right)^{\beta_s} \\ W_s(y, A, Z) &= A\delta(1-y) + \frac{a_s}{N_s}\left(\frac{y}{A}\right)^{\alpha_s} \left(1-\frac{y}{A}\right)^{\beta_s} \\ W_g(y, A, Z) &= A\,\delta(1-y) + \frac{a_g}{N_g}\left(\frac{y}{A}\right)^{\alpha_g} \left(1-\frac{y}{A}\right)^{\beta_g} \end{aligned}$$

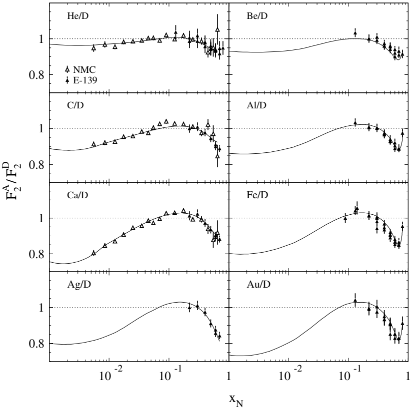
- Nuclear structure functions are defined as usual

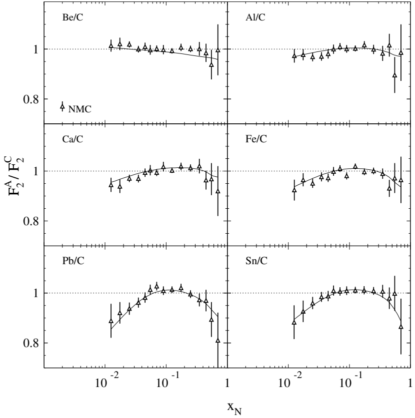
$$A\,F_2^A(x, Q^2) = Z\,F_2^{p/A}(x, Q^2) + (A-Z)\,F_2^{n/A}(x, Q^2)$$

✓ *In principle* takes into account $x > 1$ region.
✓ Convenient for working in Mellin space.
? Unfortunately in the actual grids $0 < x < 1$, and sum rules are consistent with $(0, 1)$ range.

DS04 framework

DS04 feature very good data description (DIS, DY, 420 data points) with $\chi^2/ndof = 0.76$





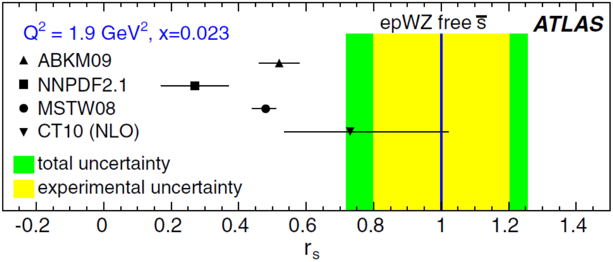
ATLAS strange measurement

ATLAS has used W/Z production to infer constraints on the strange quark distribution (2010 data, 35pb^{-1})

G. Aad et al. (ATLAS Collaboration) Phys. Rev. Lett. 109, 012001 (2012), arXiv:1203.4051

for $Q^2 = 1.9$ GeV^2 and $x = 0.023$:

$$r_s = 0.5(s+\bar{s})/\bar{d} = 1.00^{+0.25}_{-0.28}$$

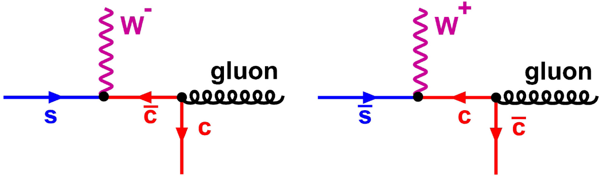


CMS Wc final states measurement

CMS measured ratios of cross-sections using 36pb^{-1} of data
CMS-PAS-EWK-11-013

arXiv:1310.1138

$$R_c^{\pm} = \frac{\sigma(W^+\bar{c})}{\sigma(W^-c)} = 0.92 \pm 0.19(stat.) \pm 0.04(sys.)$$



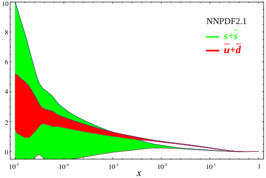
see also:

W. J. Stirling, E. Vryonidou, Phys. Rev. Lett. 109, 082002 (2012),

`arXiv:1203.6781`

Motivations: proton Strange PDF

- large proton *s*-quark PDF uncertainty:



- much more important in LHC than in Tevatron
  - heavy quarks contributions more important
  - larger rapidity range
  - high energy $\rightarrow$ probes PDFs at small x