

# Update on nCTEQ PDFs: nuclear PDF uncertainties and LHC applications

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## Outline:

- ▶ Motivations & Introduction
- ▶ Framework
- ▶ Results
- ▶ Comments on LHC  $W/Z$  measurements
- ▶ Summary

**in collaboration with:**

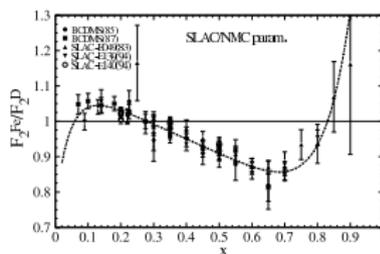
K. Kovařík, T. Ježo, F. I. Olness,  
I. Schienbein, J. Y. Yu, B. Clark,  
J. Owens, J. Morfin, C. Keppel

**DIS**2014

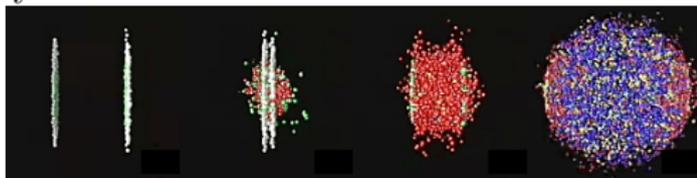
**Warsaw,  
28 April - 2 May 20  
14**

# 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**

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

**neutrino DIS**

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

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

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

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

# 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.  $x \in (0, 1)$  like in free-proton PDFs [instead of  $(0, A)$ ]

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

## ▶ Multiplicative nuclear correction factors

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

- ▶ 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]

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

- ▶ Functional form of the **bound proton PDF** same as for the free proton ( $\sim$ CTEQ61 [hep-ph/0702159],  $x$  restricted to  $0 < x < 1$ )

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

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

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

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

- ▶ 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**

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

**FNAL E-665**

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

**DESY Hermes**

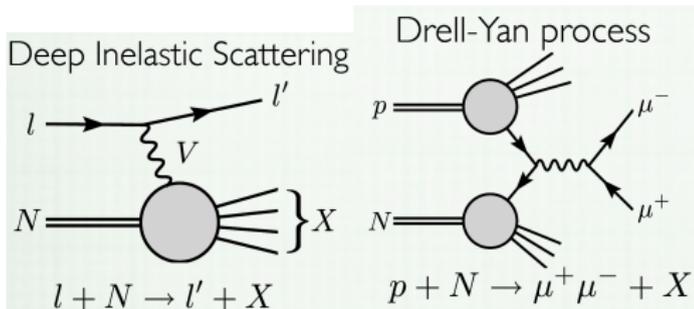
$N = (\text{D, He, N, Kr})$

**SLAC E-139 & E-049**

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

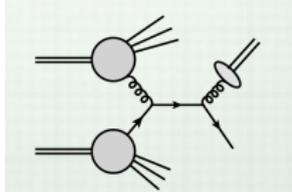
**FNAL E-772 & E-886**

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



## ▶ Single pion production (new)

*Single pion production*

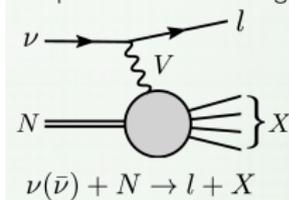


**RHIC - PHENIX & STAR**

$N = \text{Au}$

## ▶ Neutrino (to be included later)

Deep Inelastic Scattering



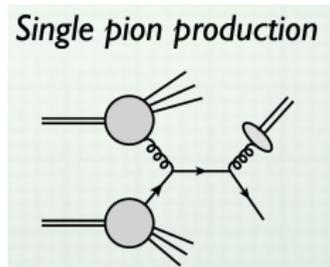
**CHORUS CCFR & NuTeV**

$N = \text{Pb}$   $N = \text{Fe}$

# Data sets: Single pion production

RHIC - PHENIX & STAR

( $N = \text{Au}$ )



PHENIX Collaboration:

[*Phys.Rev.Lett.* 98 (2007) 172302, [nucl-ex/0610036](#)]

STAR Collaboration:

[*Phys.Rev.* C81 (2010) 064904, [arXiv:0912.3838](#)]

► Theory calculation:

P. Aurenche, M. Fontannaz, J.-Ph. Guillet, B. A. Kniehl, M. Werlen  
[*Eur. Phys. J.* C13, 347-355, (2000), [arXiv:hep-ph/9910252](#)]

► Fragmentation functions:

J. Binnewies, Bernd A. Kniehl, G. Kramer  
[*Z. Phys.* C65 (1995) 471-480, [arXiv:hep-ph/9407347](#)]

# Fit details

## Fit properties:

- ▶ fit @NLO
- ▶  $Q_0 = 1.3\text{GeV}$
- ▶ using ACOT heavy quark scheme
- ▶ kinematical cuts:  $Q > 2\text{GeV}$ ,  
 $W > 3.5\text{GeV}$
- ▶ 708 (DIS & DY) + 32 (single  $\pi^0$ )  
= 740 data points after cuts
- ▶ 16 free parameters
  - ▶ 7 gluon
  - ▶ 7 valence
  - ▶ 2 sea
- ▶  $\chi^2 = 618$ , giving  $\chi^2/\text{dof} = 0.85$

## 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  $\rightarrow$  require numerical precision
- ▶ use noise reducing derivatives

# nCTEQ RESULTS

(preliminary)

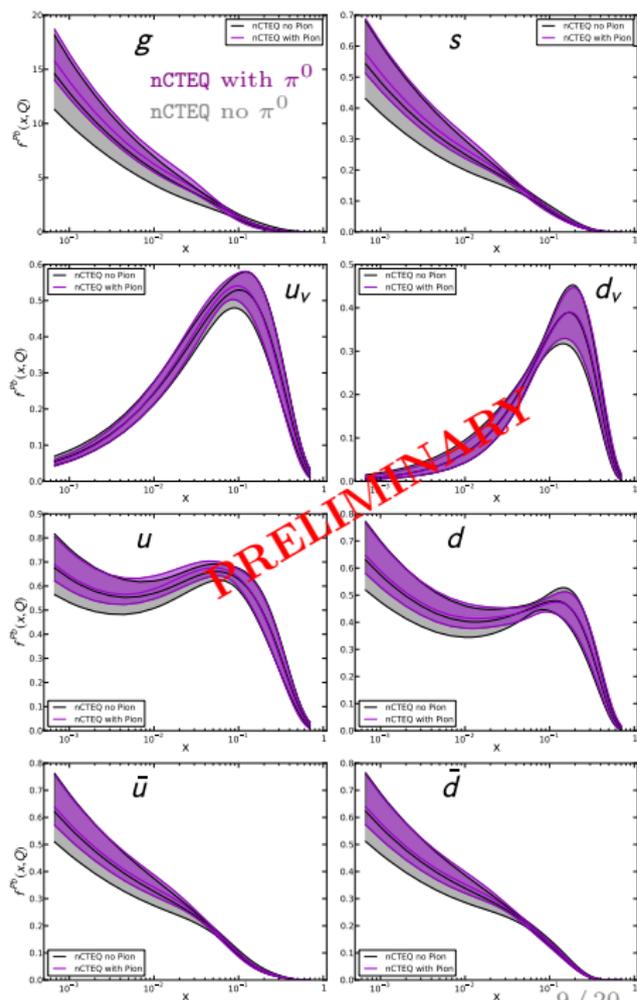
# nCTEQ results

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

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

Compare nCTEQ fits:

- ▶ with  $\pi^0$  data (violet)
- ▶ without  $\pi^0$  data (gray)



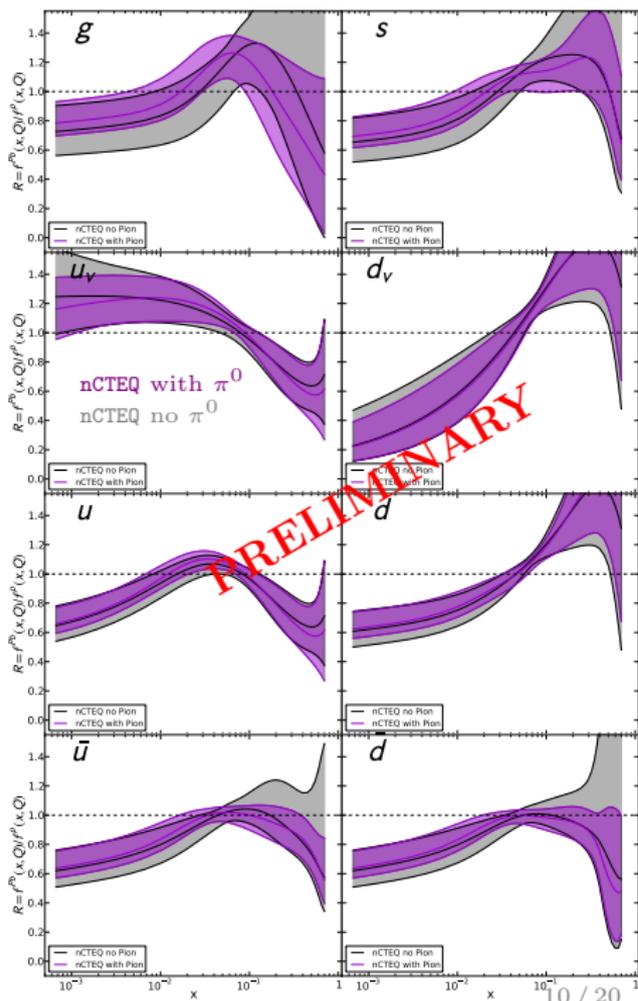
# nCTEQ results

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

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

Compare nCTEQ fits:

- ▶ with  $\pi^0$  data (violet)
- ▶ without  $\pi^0$  data (gray)

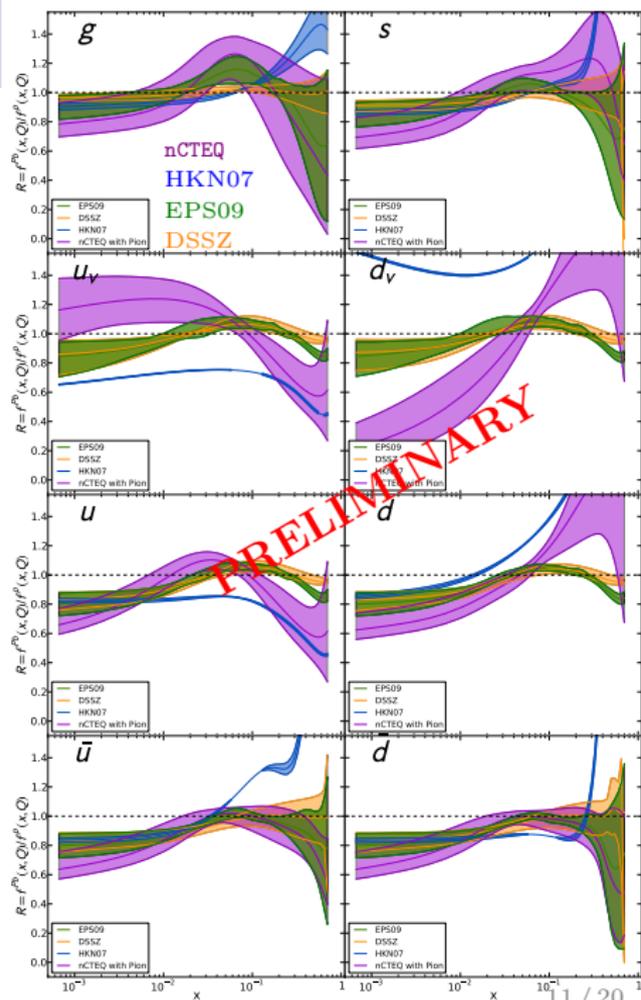


# nCTEQ results

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

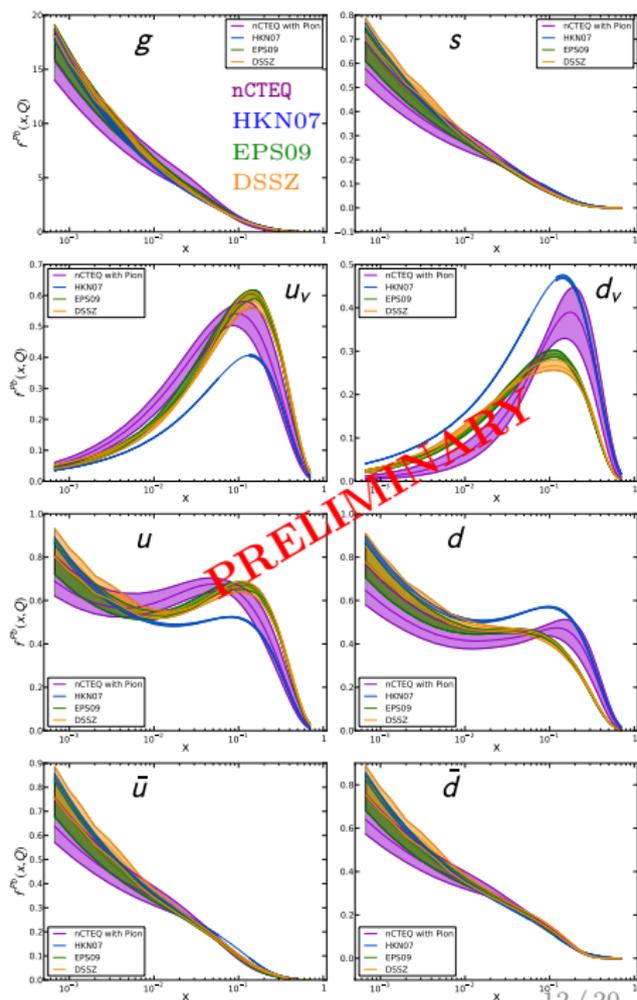


# nCTEQ results

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

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

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

$$c_k^{uv} = c_{k,0}^{uv} + c_{k,1}^{uv} (1 - A^{-c_{k,2}^{uv}})$$

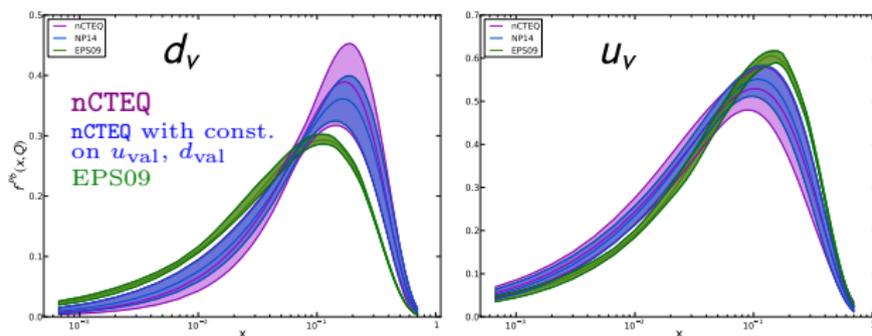
$$c_k^{dv} = c_{k,0}^{dv} + c_{k,1}^{dv} (1 - A^{-c_{k,2}^{dv}})$$

## EPS09

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

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

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



we set:

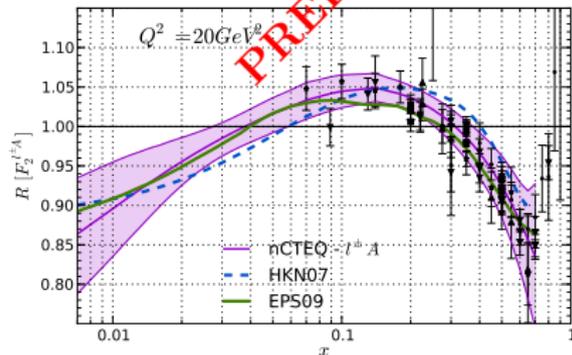
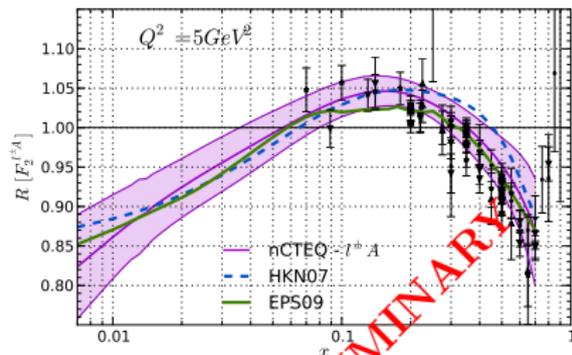
$$\begin{cases} c_1^{dv} = c_1^{uv} \\ c_2^{dv} = c_2^{uv} \end{cases}$$

# nCTEQ results: $F_2$ ratios

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

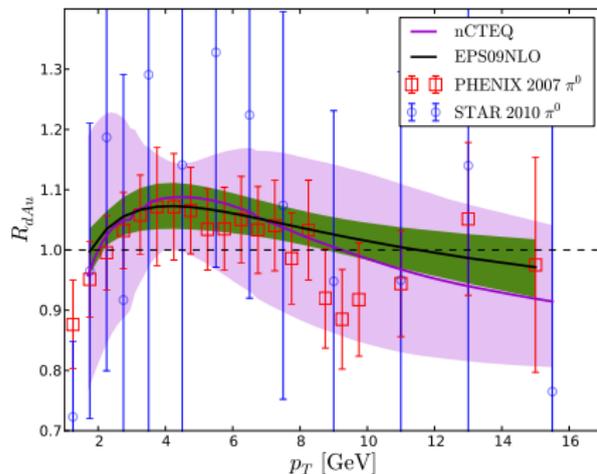


# nCTEQ results: $\pi^0$ production

## Pion production, ratio

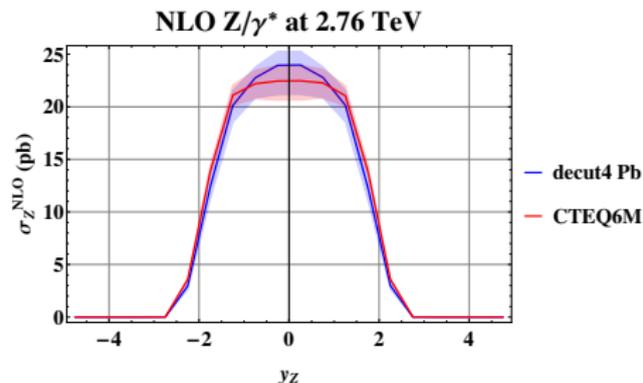
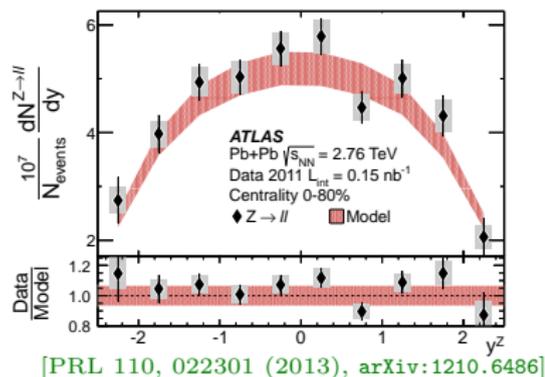
$$R_{dAu}^{\pi} = \frac{\frac{1}{2A} d^2 \sigma_{\pi}^{dAu} / dp_T dy}{d^2 \sigma_{\pi}^{pp} / dp_T dy}$$

- ▶ good data description, however big experimental uncertainties do not allow for strong constraints on PDFs
- ▶ despite different  $u$ -valence &  $d$ -valence ratios are similar to EPS09



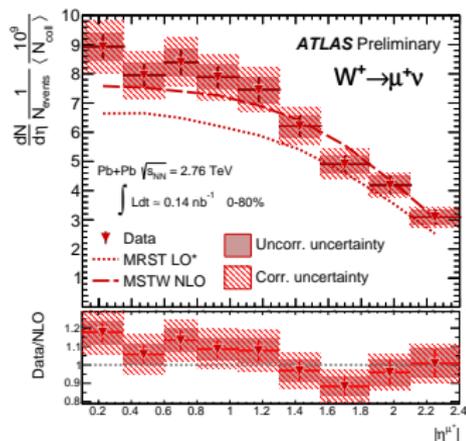
# What can we give/gain from LHC data?

Recent ATLAS results for  $W/Z$  production in *lead* collisions are analyzed using proton PDFs



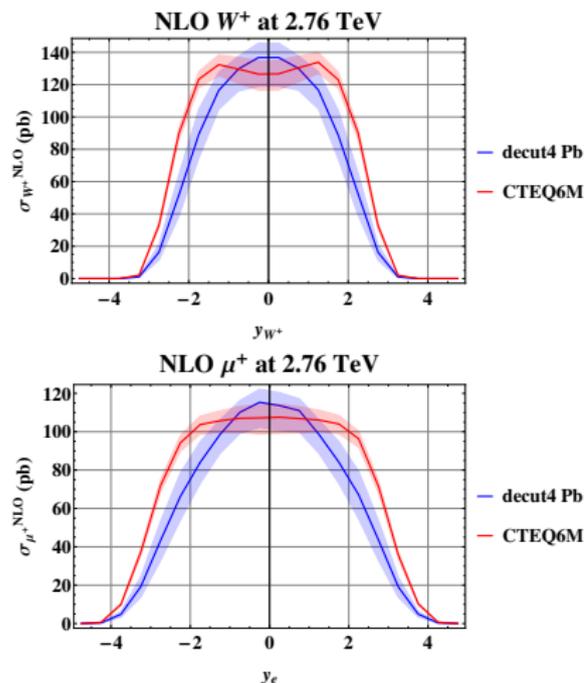
- ▶ No shape change for on-shell  $Z$  (and  $W^-$ ) rapidity when using free-proton or *lead* PDFs.
- ▶ The shapes of the lepton distributions for these bosons are also indistinguishable.

# What can we give/gain from LHC data?



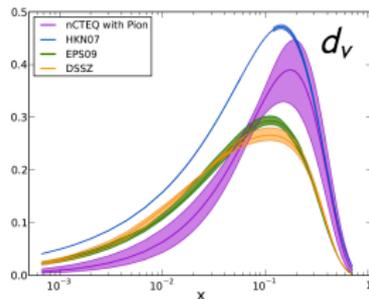
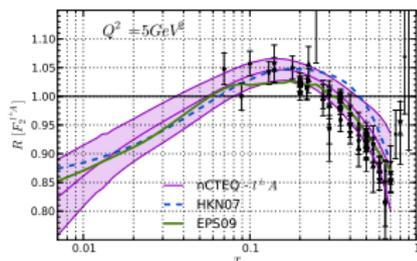
[ATLAS-CONF-2013-106]

- ▶ There is an observable shape change in for on-shell  $W^+$  production. The difference is up to 20 % in some regions of parameter space.
- ▶ These differences should be seen with higher statistics.



# Summary

- ▶ We have updated the nCTEQ error PDFs (still preliminary).
- ▶ nCTEQ PDFs features larger uncertainties but they are still underestimated.



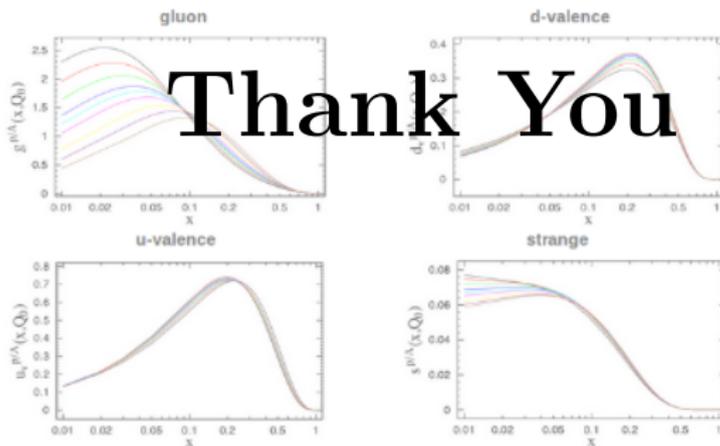
- ▶ To have reliable estimate of nuclear corrections we need more data (LHC *lead* run can help).
- ▶ Nuclear component important not only for heavy ion collisions, but also for the free-proton analysis.

# nCTEQ

## nuclear parton distribution functions

- Home
- PDF grids & code
- Papers & Talks
- Subversion
- Tracker
- Wiki

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 \[hep-ph\]](https://arxiv.org/abs/09072357). The effects of the nuclear environment on the parton densities can be shown as modified parton densities



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 environment can be displayed is in ratios of Deep Inelastic Scattering (DIS) structure functions e.g. ratios of the structure function  $F_2$  for a neutral current DIS as in the figure below on the left or ratios of the same structure function  $F_2$  but for a charged current DIS.

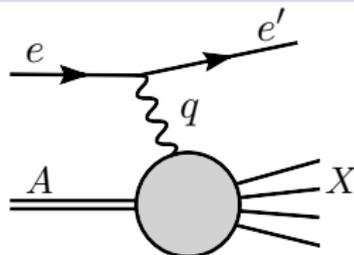
# BACKUP SLIDES

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

- ▶ DIS variables in case on nucleons

$$\text{in nucleus } \begin{cases} Q^2 \equiv -q^2 \\ x_A \equiv \frac{Q^2}{2p_A \cdot q} \end{cases}$$

- ▶  $p^A$  – 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
- ▶  $x_N \equiv \frac{Q^2}{2p_N \cdot q} = A x_A$  – parton momentum fraction with respect to the average nucleon momentum  $p_N$
- ▶  $x_N \in (0, A)$  – parton can carry more than the average nucleon momentum  $p_N$ .