

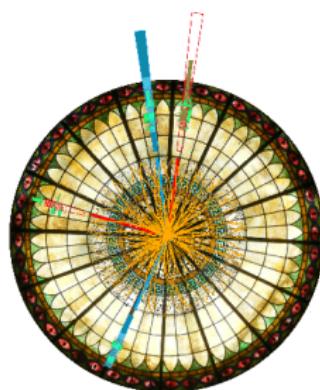
nCTEQ15 – Global analysis of nuclear parton distributions with uncertainties

**A. Kusina¹, K. Kovařík, T. Ježo, C. Keppel, J. Morfin,
F. I. Olness, J. Owens, I. Schienbein, J. Y. Yu**

¹Laboratoire de Physique Subatomique et de Cosmologie (LPSC)
53 Rue des Martyrs Grenoble, France

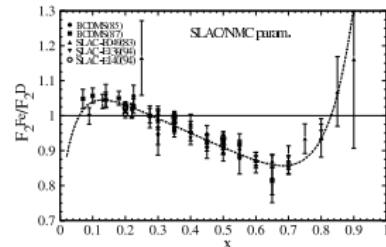
DIS 2015
XXIII International Workshop on
Deep-Inelastic Scattering and
Related Subjects

Dallas, Texas
April 27 – May 1, 2015

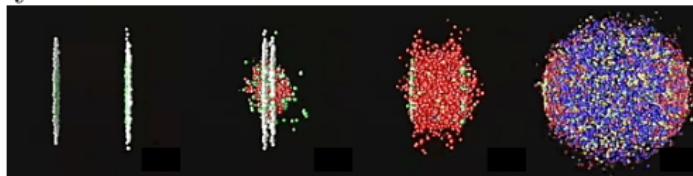


Motivations: Why do we need nuclear PDFs?

- ▶ 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

Available nuclear PDFs

- ▶ 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 $0 < x < 1$)

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

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

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

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

- ▶ 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 BC DMS & 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

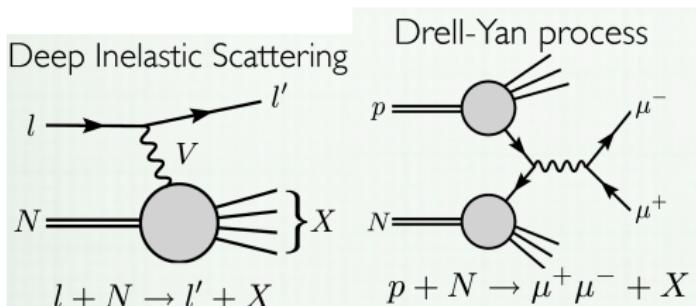
N = (D, He, N, Kr)

SLAC E-139 & E-049

N = (D, Ag, Al, Au, Be, C, Ca,
Fe, He)

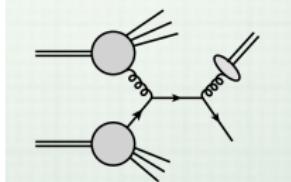
FNAL E-772 & E-886

N = (D, C, Ca, Fe, W)



► Single pion production (new)

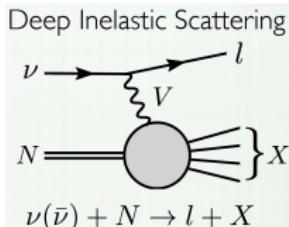
Single pion production



RHIC - PHENIX & STAR

N = Au

► Neutrino (to be included later)



CHORUS CCFR & NuTeV

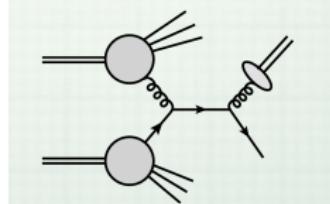
N = Pb N = Fe

Data sets: Single pion production

RHIC - PHENIX & STAR

(N = Au)

Single pion production



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
- ▶ kinematic cuts:
 $Q > 2\text{GeV}$, $W > 3.5\text{GeV}$
 $p_T > 1.7 \text{ GeV}$
- ▶ 708 (DIS & DY) + 32 (single π^0)
= 740 data points after cuts
- ▶ 16 free parameters
 - ▶ 7 gluon
 - ▶ 7 valence
 - ▶ 2 sea
- ▶ $\chi^2 = 611$, 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 → require numerical precision
- ▶ use noise reducing derivatives

Fit details

Kinematic cuts

Fit properties

- fit @ 1 GeV
- $Q_0 = \begin{cases} Q > 2 \text{ GeV} \\ W > 3.5 \text{ GeV} \end{cases}$
- using kinematics

$Q > 2\text{GeV}, W > 3.5\text{GeV}$

$p_T > 1.7 \text{ GeV}$

- 708 (DIS & DY) + 32 (single π^0)
= 740 data points after cuts

- 16 free parameters

- 7 gluon
- 7 valence
- 2 sea

- $\chi^2 = 611$, giving $\chi^2/\text{dof} = 0.85$

nCTEQ:

EPS: $Q > 1.3 \text{ GeV}$

HKN: $Q > 1 \text{ GeV}$

DSSZ: $Q > 1 \text{ GeV}$

Fit details

Kinematic cuts

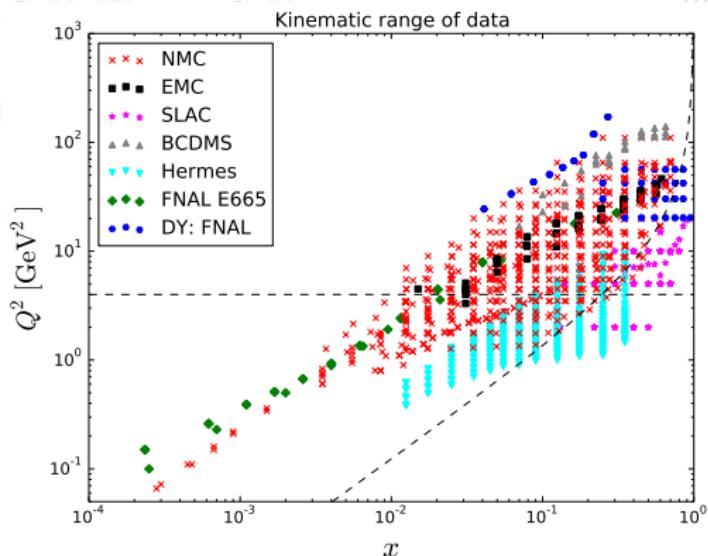
Fit properties

- fit @ $Q^2 > 2 \text{ GeV}$
- $Q_0 = 2 \text{ GeV}$
- using $W > 3.5 \text{ GeV}$
- kinematics: $Q > 2 \text{ GeV}$
- $p_T > 1 \text{ GeV}$
- 708 (1) = 740 data points
- 16 freedom degrees
- $\chi^2 = 16$
- $\chi^2 = 16$

EPS: $Q > 1.3 \text{ GeV}$

HKN: $Q > 1 \text{ GeV}$

DSSZ: $Q > 1 \text{ GeV}$



$\Delta\chi^2 = 35$ (every target within 90% C.L.)
es span 10 orders of
le \rightarrow require numerical
nCTEQ: 740 data points

EPS09: 929 data points

Fit details

Fit properties:

Hessian method

- ▶ choice of tolerance: $T = 35$
- ▶ quadratic approximation

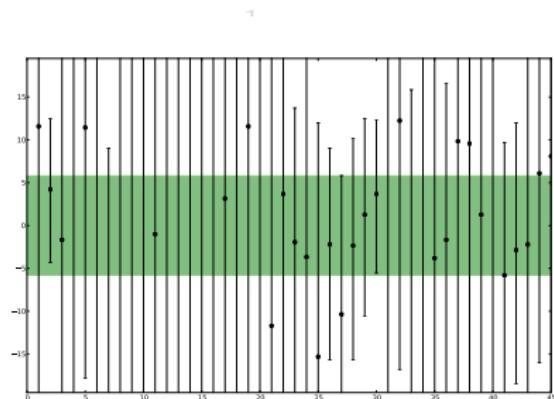
$Q > 2\text{GeV}$, $W > 3.5\text{GeV}$

$p_T > 1.7 \text{ GeV}$

- ▶ 708 (DIS & DY) + 32 (single π^0)
= 740 data points after cuts
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Error analysis:

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Fit details

Fit properties:

Hessian method

- ▶ choice of tolerance: $T = 35$
- ▶ quadratic approximation

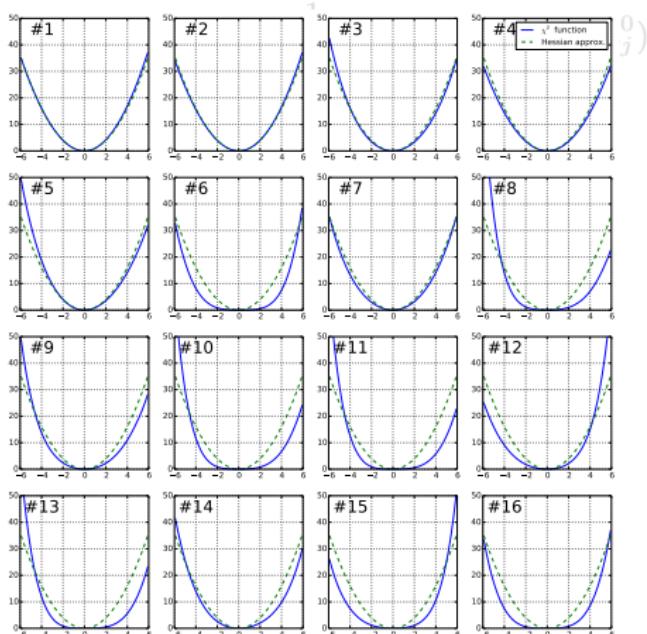
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Error analysis:

- ▶ use Hessian method



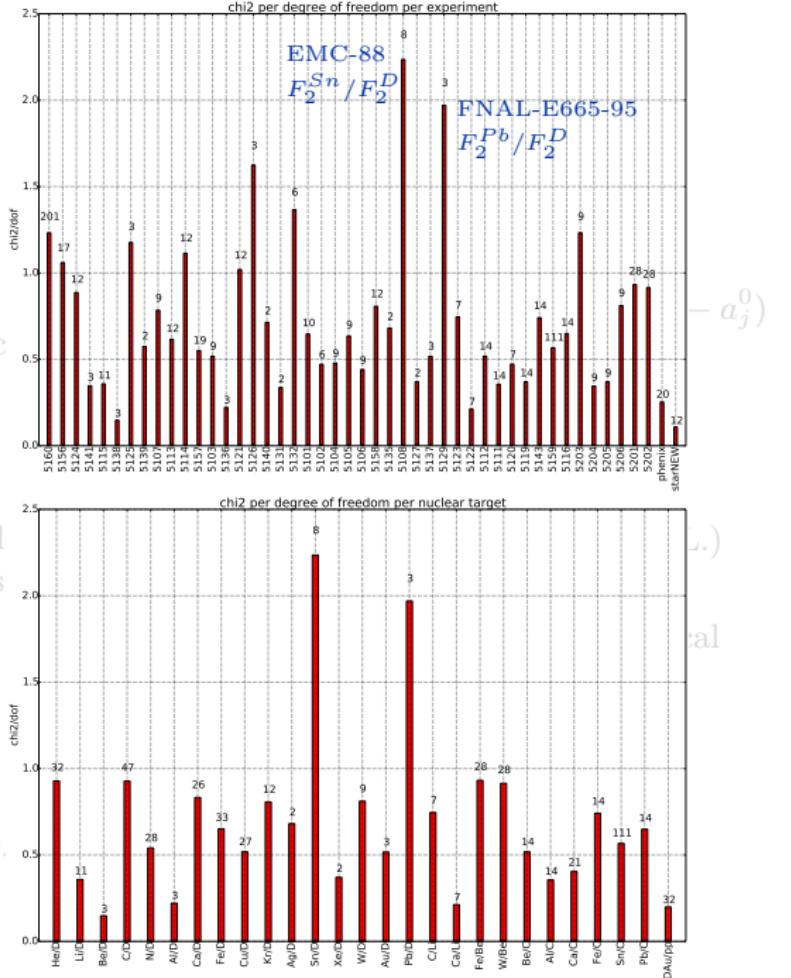
Fit details

Fit properties:

Fit quality

► $\chi^2/dof = 0.85$

- kinematic cuts:
 $Q > 2\text{GeV}$, $W > 3.5\text{GeV}$
 $p_T > 1.7 \text{ GeV}$
- 708 (DIS & DY) + 32 (singl)
= 740 data points after cuts
- 16 free parameters
 - 7 gluon
 - 7 valence
 - 2 sea
- $\chi^2 = 611$, giving $\chi^2/\text{dof} = 0.85$



nCTEQ RESULTS

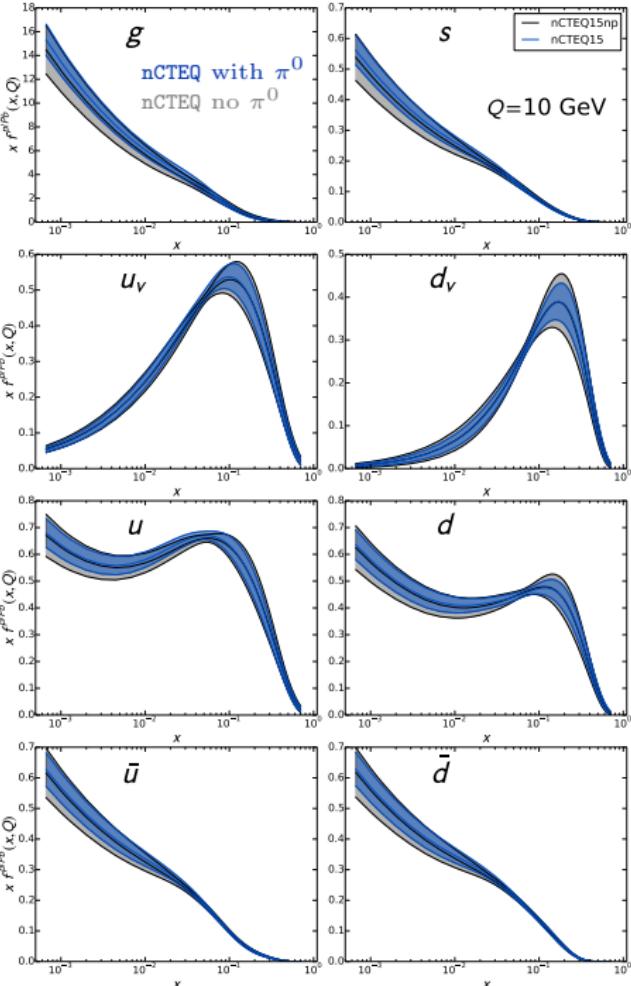
nCTEQ results

Nuclear PDFs ($Q = 10$ GeV)

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

Compare nCTEQ fits:

- ▶ nCTEQ15 with π^0 data
- ▶ nCTEQ15wp without π^0 data



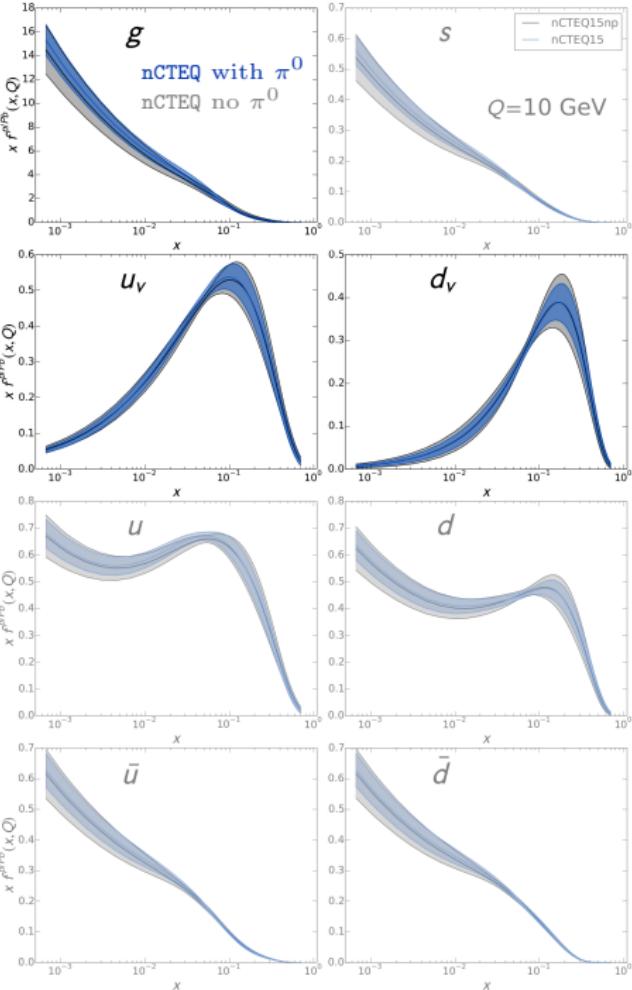
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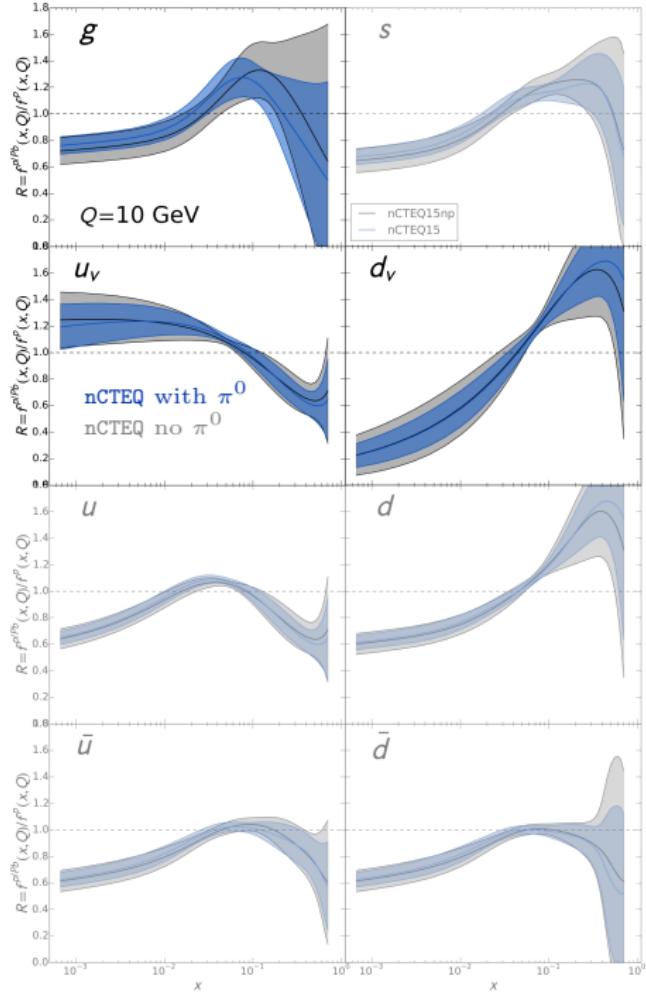
nCTEQ results

Nuclear correction factors
($Q = 10$ GeV)

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

Compare nCTEQ fits:

- ▶ nCTEQ15 with π^0 data
- ▶ nCTEQ15wp without π^0 data

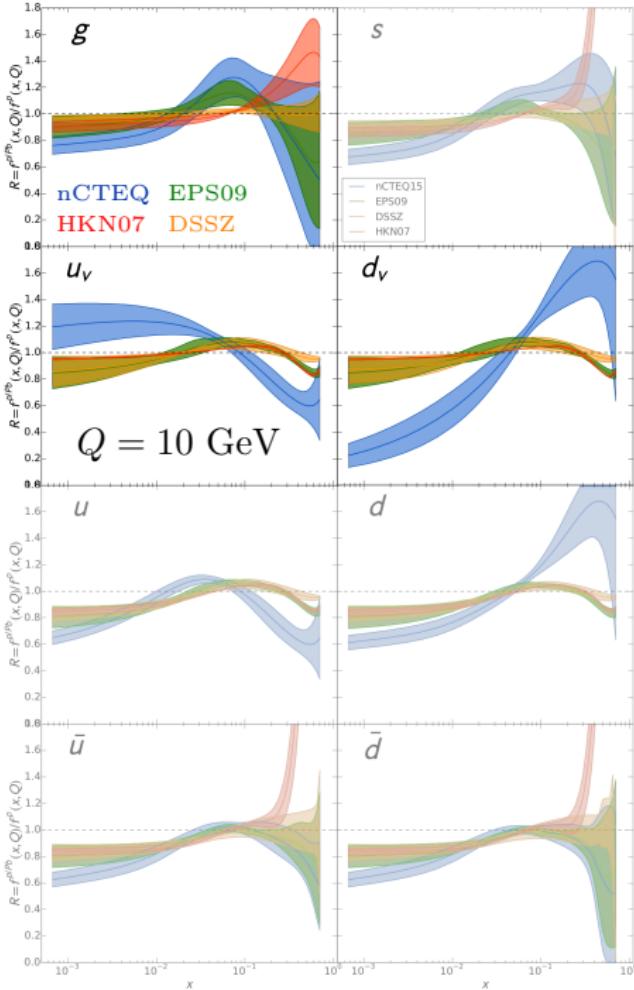


nCTEQ results

Nuclear correction factors
($Q = 10$ GeV)

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

- ▶ 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

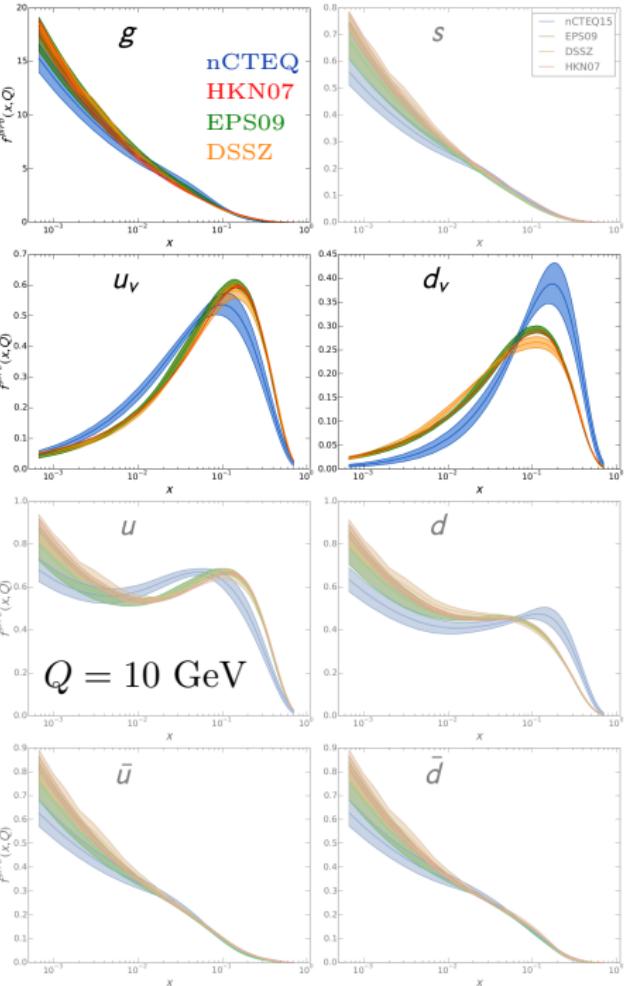


nCTEQ results

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

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

- ▶ nCTEQ features larger uncertainties than previous nPDFs
- ▶ better agreement between different groups (nPDFs don't depend on proton baseline)



nCTEQ vs. EPS09

nCTEQ

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

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

EPS09

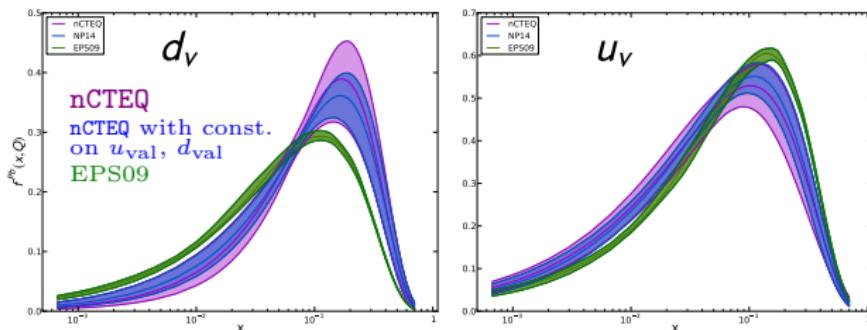
$$u_v^{p/A}(Q_0) = \textcolor{red}{R}_v(x, A, Z) u(x, Q_0)$$

$$d_v^{p/A}(Q_0) = \textcolor{red}{R}_v(x, A, Z) d(x, Q_0)$$

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

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

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



we set:

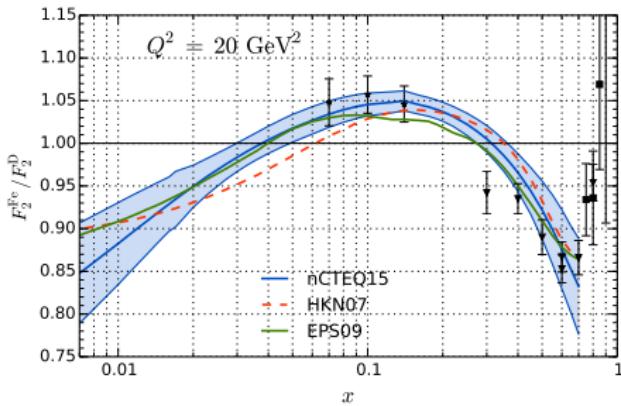
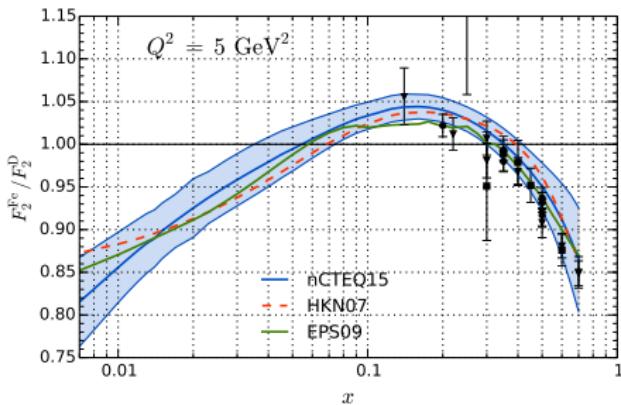
$$\begin{cases} c_1^{dv} = c_1^{uv} \\ c_2^{dv} = c_2^{uv} \end{cases}$$

nCTEQ results: F_2 ratios

Structure function ratio

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

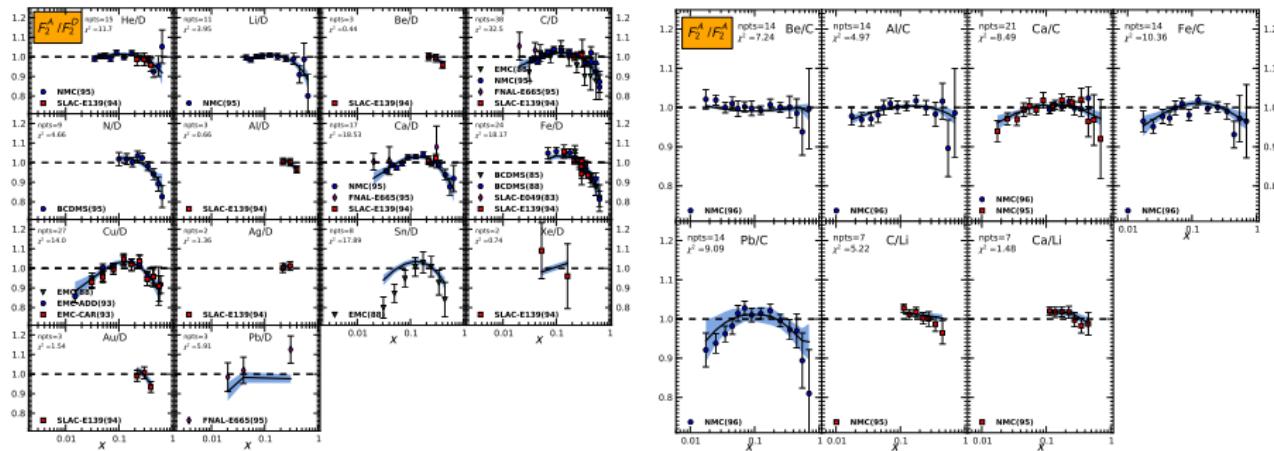
- ▶ good data description
- ▶ despite different u -valence & d -valence ratios are similar to EPS09



Description of fitted data: F_2 ratios

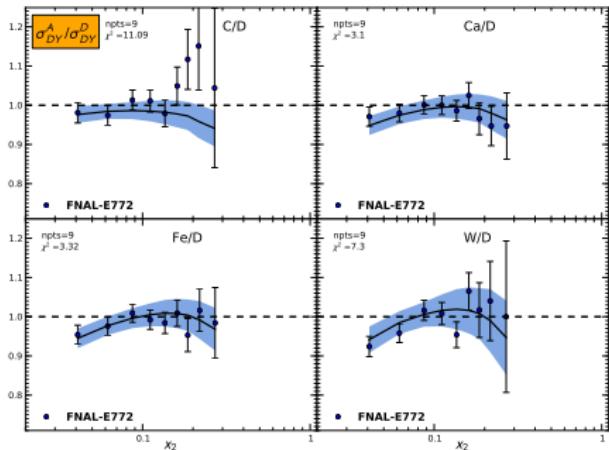
$$R = \frac{F_2^A(x,Q)}{F_2^D(x,Q)}$$

$$R = \frac{F_2^A(x,Q)}{F_2^{A'}(x,Q)}$$

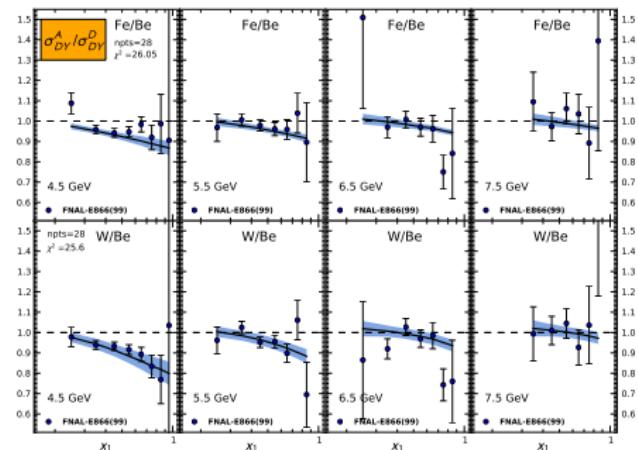


Description of fitted data: σ_{DY} ratios

$$R = \frac{\sigma_{DY}^A(x,Q)}{\sigma_{DY}^D(x,Q)}$$



$$R = \frac{\sigma_{DY}^A(x,Q)}{\sigma_{DY}^{A'}(x,Q)}$$

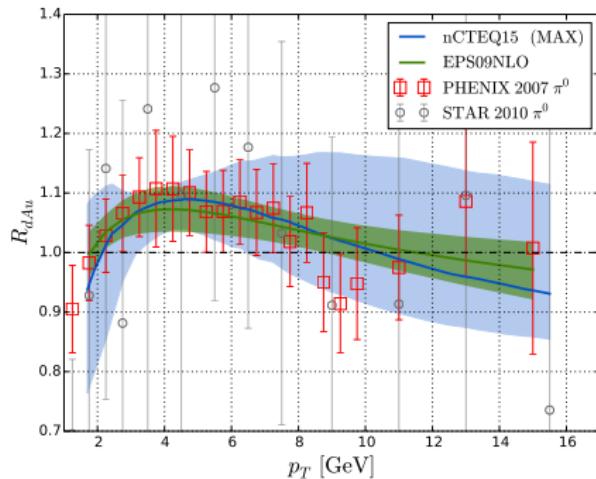


nCTEQ results: π^0 production

Pion production, ratio

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

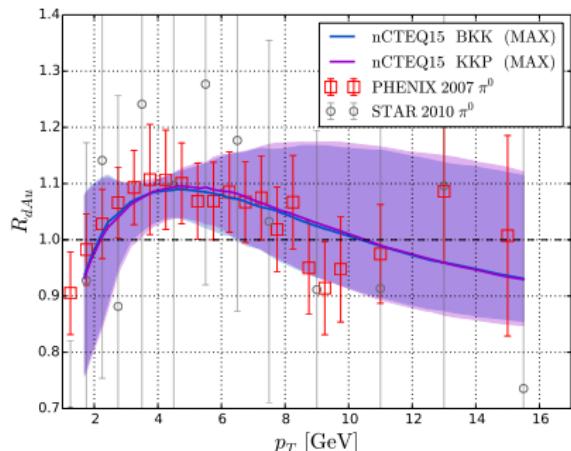
- ▶ good data description, however big experimental uncertainties do not allow for strong constraints on PDFs
- ▶ despite different u -valence & d -valence ratios are similar to EPS09



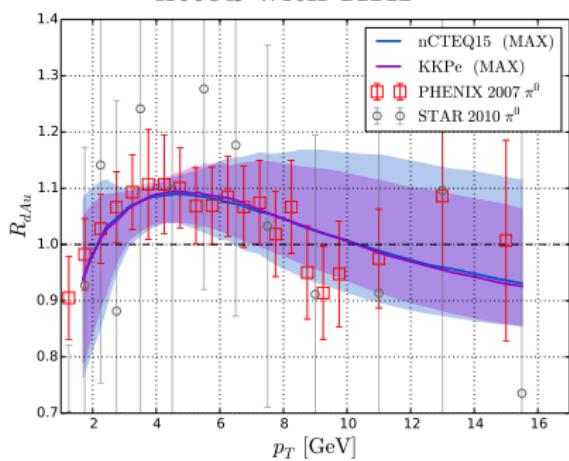
Fragmentation function dependence

- ▶ default FFs: BKK J. Binnewies, Bernd A. Kniehl, G. Kramer [Z. Phys. C65 (1995) 471-480, arXiv:hep-ph/9407347]
- ▶ other FFs, e.g.: KKP [Nucl.Phys. B582 (2000), arXiv:hep-ph/0010289]
- ▶ $R_{dAu}^{\pi} = \frac{\frac{1}{2A} d^2 \sigma_{\pi}^{dAu} / dp_T dy}{d^2 \sigma_{\pi}^{pp} / dp_T dy}$

KKP only when computing R_{dAu}^{π}



fitted with KKP



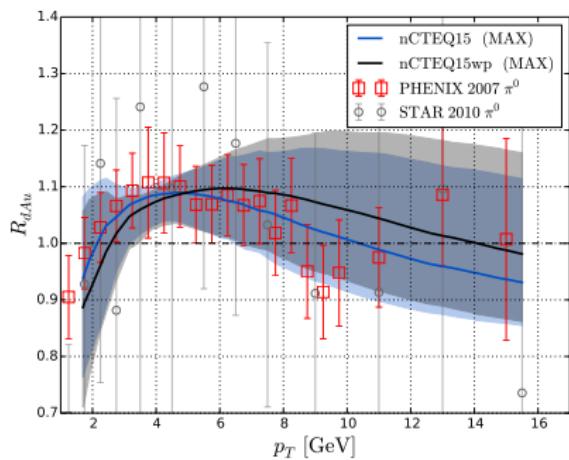
nCTEQ results

Ratio of pion yield

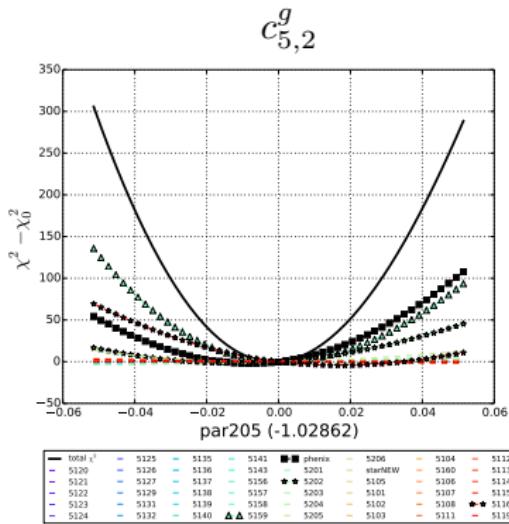
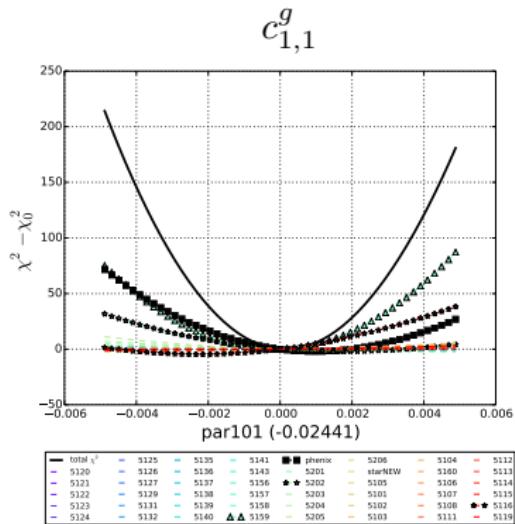
$$R_{\text{dAu}}^{\pi} = \frac{\frac{1}{2A} d^2\sigma_{\pi}^{\text{dAu}} / dp_T dy}{d^2\sigma_{\pi}^{\text{pp}} / dp_T dy}$$

Compare nCTEQ fits:

- ▶ nCTEQ15 with π^0 data
- ▶ nCTEQ15wp without π^0 data

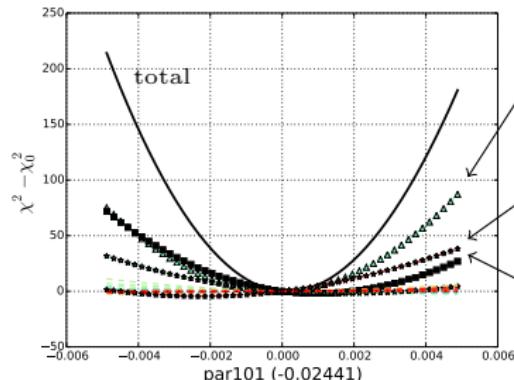


Constraints on gluon distribution

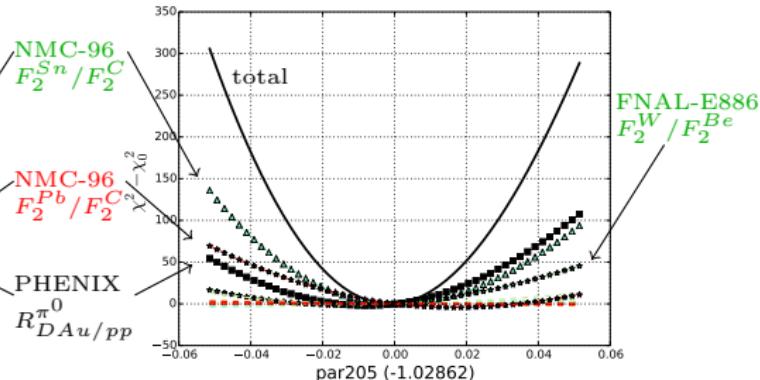


Constraints on gluon distribution

$$c_{1,1}^g$$



$$c_{5,2}^g$$



$\text{total } \chi^2$	5125	5135	5141	■■■ phenix	5206	5104	5112
5120	5126	5136	5145	5201	starNEW	5106	5113
5121	5127	5137	5146	5202	5107	5114	5115
5122	5128	5138	5147	5203	5108	5116	5117
5123	5131	5139	5158	5204	5102	5108	5118
5124	5132	5140	5159	5205	5103	5111	5119

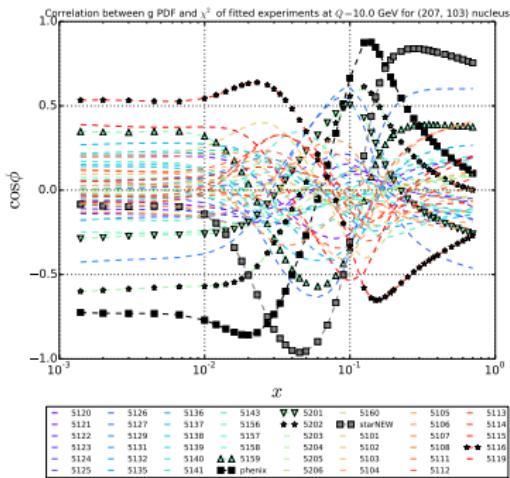
$\text{total } \chi^2$	5125	5135	5141	■■■ phenix	5206	5104	5112
5120	5127	5137	5146	5201	starNEW	5106	5113
5121	5128	5138	5147	5202	5107	5114	5115
5122	5129	5139	5157	5203	5108	5116	5117
5123	5131	5139	5158	5204	5102	5108	5118
5124	5132	5140	5159	5205	5103	5111	5119

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

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

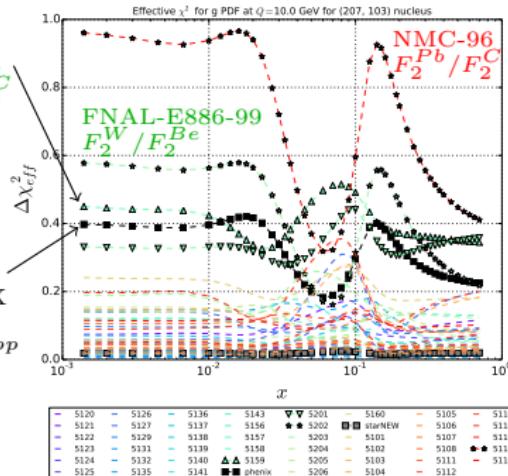
Constrains on gluon distribution

Cosine of the correlation angle



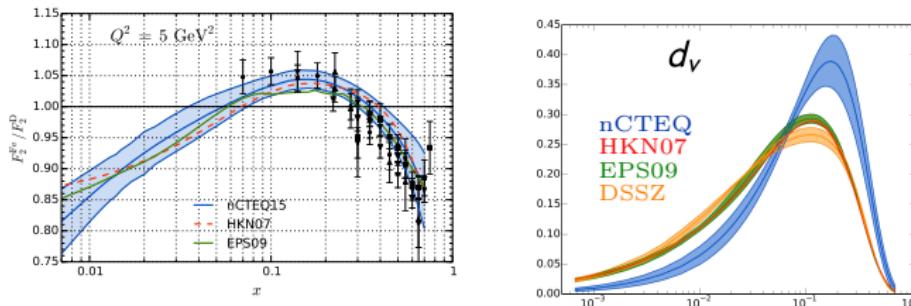
$$\cos \phi(g, \chi^2) = \frac{\vec{\nabla}g \cdot \vec{\nabla}\chi^2}{4\Delta g \Delta \chi^2}$$

Effective χ^2 change: $\Delta\chi^2_{eff}$



Summary

- ▶ We have updated the nCTEQ error PDFs.
- ▶ Regardless of big differences in valence distributions we obtain very good description of the fitted data.



- ▶ The big differences in valence PDFs show that uncertainties are strongly underestimated (assumptions replace uncertainties).
- ▶ To have reliable estimate of nuclear corrections we need more data (LHC *lead* run, JLAB).

D. B. Clark, *W/Z* productions in pPb and PbPb (Thursday)

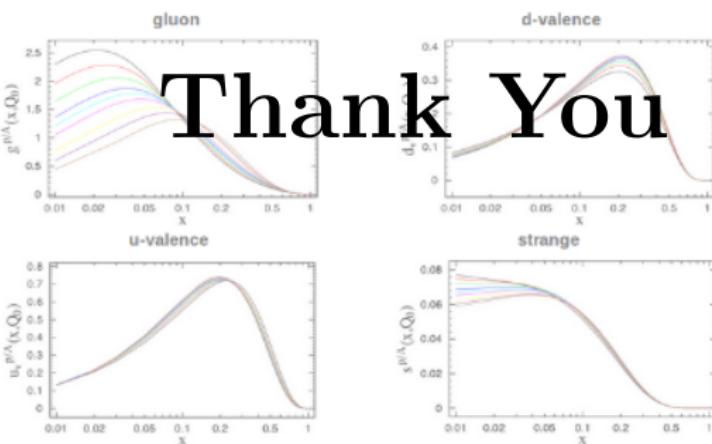
- ▶ Nuclear component important not only for heavy ion collisions, but also for the free-proton analysis.

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:0907.2357 \[hep-ph\]](#).
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.