# nCTEQ nuclear parton distributions

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Outline:

- Motivations & Introduction
- Framework
- Results
- Summary

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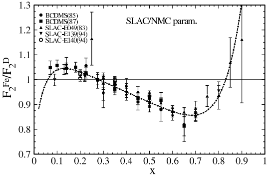
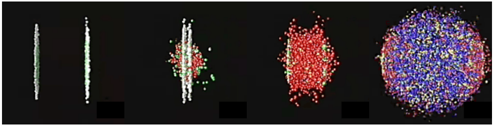
# Motivations: Why do we need nuclear PDFs?

- 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**

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

# 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. PDF of nucleus can be constructed as a sum of independent proton and neutron PDFs
3. Isospin symmetry $\begin{cases} u^{n/A}(x) = d^{p/A}(x) \\ d^{n/A}(x) = u^{p/A}(x) \end{cases}$
4. $x \in (0, 1)$ 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**

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

  - 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`]

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

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

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

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

- $A$-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 $(A, Z)$

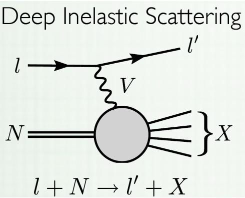
$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q)$$

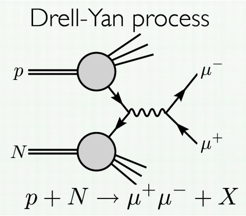
(bound neutron PDF $f_i^{n/A}$ by isospin symmetry)

# Data sets

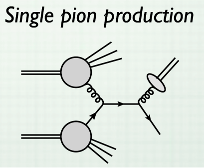
- NC DIS & DY

  **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)



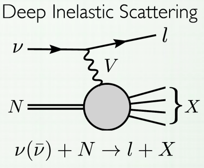

- Single pion production (new)




  **RHIC - PHENIX & STAR**

  N = Au

- Neutrino (to be included later)



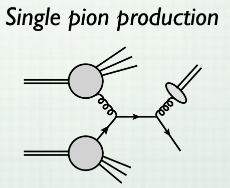

  **CHORUS CCFR & NuTeV**

  N = Pb N = Fe

# Data sets: Single pion production

**RHIC - PHENIX & STAR**

(N = Au)




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

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

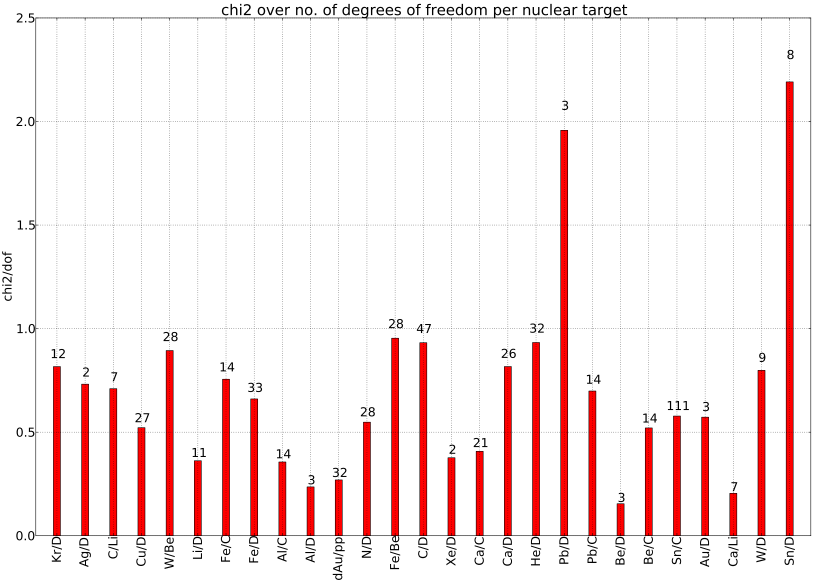
$$H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}$$

- 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



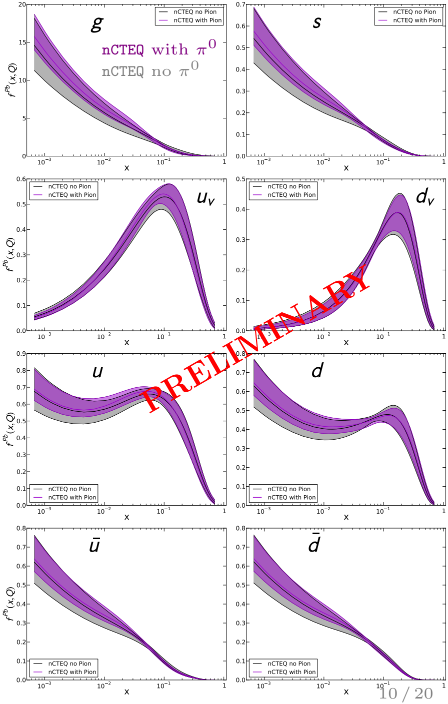
# nCTEQ results

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)



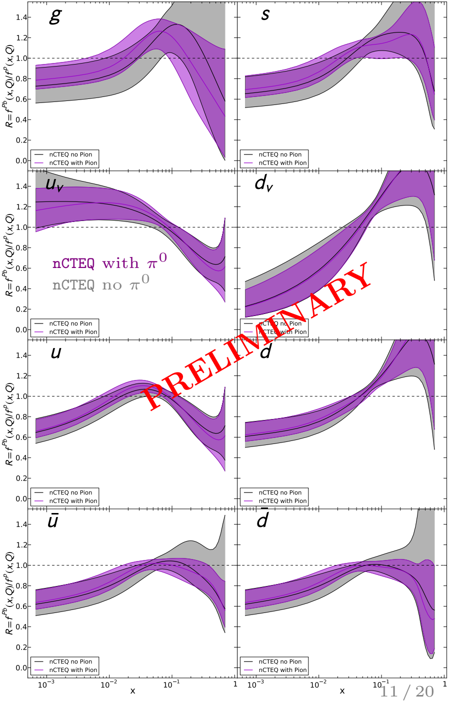
# nCTEQ results

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)

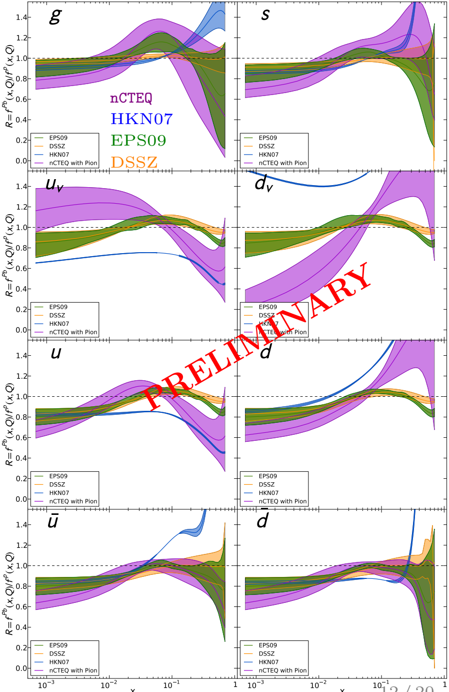


# nCTEQ results

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

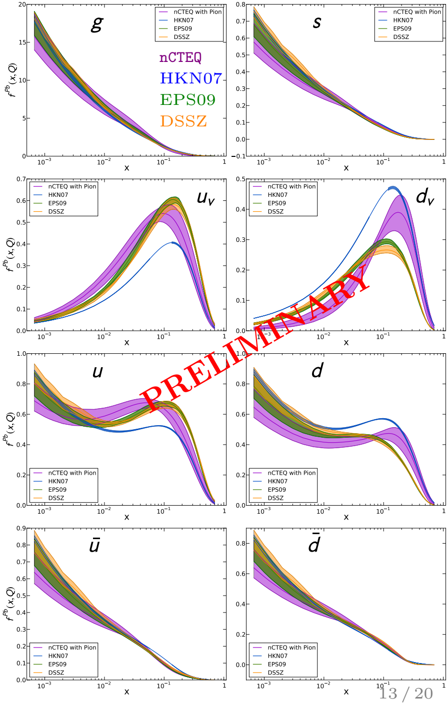


# nCTEQ results

Nuclear PDFs ($Q = 10$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**

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

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

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

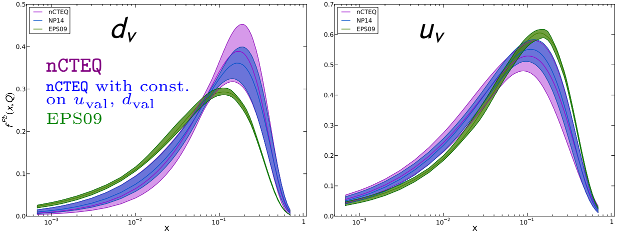
$$c_k^{d_v} = c_{k,0}^{d_v} + c_{k,1}^{d_v}\left(1 - A^{-c_{k,2}^{d_v}}\right)$$

**EPS09**

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

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

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




we set:

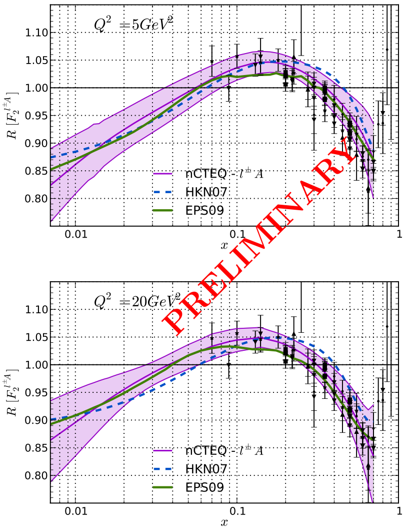
$$\begin{cases} c_1^{d_v} = c_1^{u_v} \\ c_2^{d_v} = c_2^{u_v} \end{cases}$$

# nCTEQ results: $F_2$ 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

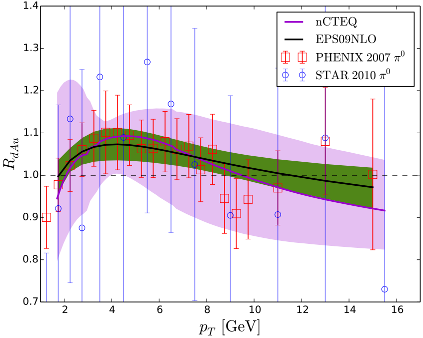


# nCTEQ results: $\pi^0$ production

Pion production, ratio

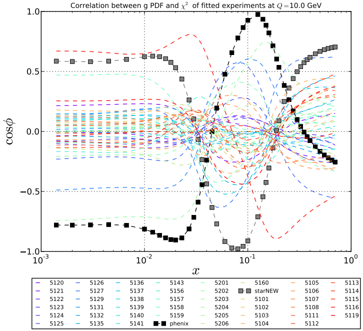
$$R^{\pi}_{\mathrm{dAu}} = \frac{\frac{1}{2A} d^2\sigma^{\mathrm{dAu}}_{\pi} / dp_T dy}{d^2\sigma^{\mathrm{pp}}_{\pi} / dp_T dy}$$

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



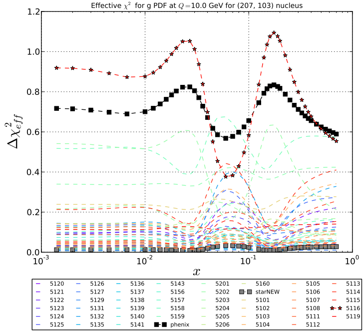
# nCTEQ results: gluon and $\pi^0$ production

Cosine of the correlation angle:



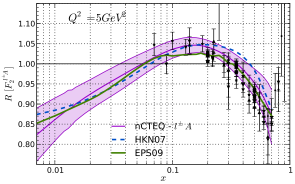

$$\cos\phi(X,Y) = \frac{\vec{\nabla}X\cdot\vec{\nabla}Y}{4\Delta X\Delta Y}$$

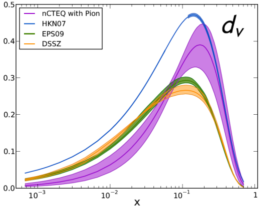
Effective $\chi^2$ change: $\Delta\chi^2_{eff}$



# Summary

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



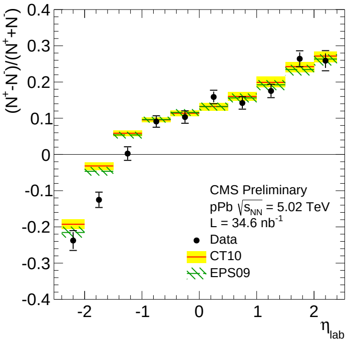

- To have reliable estimate of nuclear corrections we need more data (LHC *lead* run can help).
- Nuclear component important not only for heavy ion collisions, but also for the free-proton analysis.

# Summary

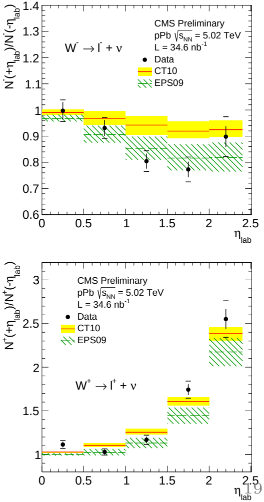
Plans for future:

- Official release of current analysis
- Among other things analyse LHC data, e.g. [CMS PAS HIN-13-007]

Charge asymmetry




Forward/backward asymmetry




- Sensitive to $\frac{u}{d}$ ratio should help to distinguish modification for $u$ and $d$

$x_{Pb} \sim (0.003, 0.2), \quad x_p \sim (0.001, 0.07)$

Nuclear CTEQ parton distribution functions - Hepforge - Google Chrome

ncteq.hepforge.org

nCTEQ is hosted by Hepforge, IPPP Durham

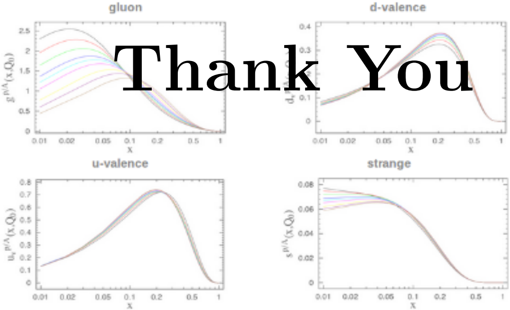
# nCTEQ

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].
The effects of the nuclear environement on the parton densities can be shown as modified parton densities

# Thank You




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 $F_2$ for a neutral current DIS as in the figure below on the left or ratios of of the same structure function $F_2$ but for a charged current DIS.

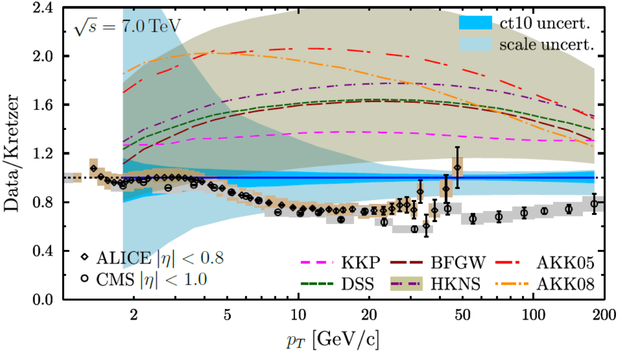
# BACKUP SLIDES

# Gluon fragmentation functions problem

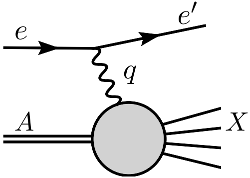
Charged hadrons production in CMS and ALICE

**[Nucl. Phys. B 883 (2014) 615, arXiv:1311.1415]; [arXiv:1408.4659]**

(to hard gluon to hadron FF)



# 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 $p_N$.

# Correlation cosine

$$\cos\phi(X,Y) = \frac{\vec{\nabla}X \cdot \vec{\nabla}Y}{4\Delta X \Delta Y}$$

$$\vec{\nabla}X \cdot \vec{\nabla}Y = \frac{1}{2}\sum_{i_{pdf}} \left(X^{(+)}_{i_{pdf}} - X^{(-)}_{i_{pdf}}\right)\left(Y^{(+)}_{i_{pdf}} - Y^{(-)}_{i_{pdf}}\right)$$

$$\Delta X = \sqrt{\sum_{i_{pdf}} \left(X^{(+)}_{i_{pdf}} - X^{(-)}_{i_{pdf}}\right)^2}$$

In the considered case:

$$\cos\phi\big(g(x,Q), \chi^2(i_{exp})\big)$$

$$= \sum_{i_{pdf}} \frac{\left(g^{(+)}_{i_{pdf}}(x) - g^{(-)}_{i_{pdf}}(x)\right)\left(\chi^{2\,(+)}_{i_{pdf}}(i_{exp}) - \chi^{2\,(-)}_{i_{pdf}}(i_{exp})\right)}{\sqrt{\sum_{i'_{pdf}}\left(g^{(+)}_{i'_{pdf}}(x) - g^{(-)}_{i'_{pdf}}(x)\right)^2}\sqrt{\sum_{i''_{pdf}}\left(\chi^{2\,(+)}_{i''_{pdf}}(i_{exp}) - \chi^{2\,(-)}_{i''_{pdf}}(i_{exp})\right)^2}}$$

# Another measure of correlations: Effective $\chi^2$ change

$$\Delta\chi^2_{eff}(i_{exp}, X) = \sum_{i_{pdf}} \frac{1}{2}\left(\left|\chi^{2\,(+)}_{i_{pdf}}(i_{exp}) - \chi^{2\,(0)}_{i_{pdf}}(i_{exp})\right| + \left|\chi^{2\,(-)}_{i_{pdf}}(i_{exp}) - \chi^{2\,(0)}_{i_{pdf}}(i_{exp})\right|\right)$$

$$\times\left(\frac{X^{(+)}_{i_{pdf}} - X^{(-)}_{i_{pdf}}}{\sqrt{\sum_{i'_{pdf}}\left(X^{(+)}_{i'_{pdf}} - X^{(-)}_{i'_{pdf}}\right)^2}}\right)^2$$