nPDFs and the LHC

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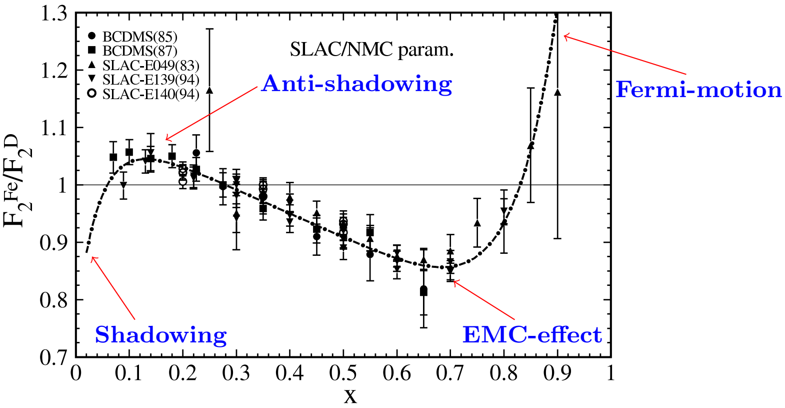
Outline

Motivation

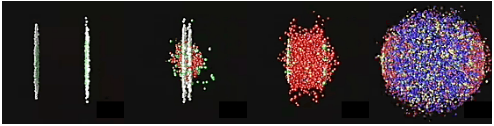
- Cross-sections in nuclear collisions are modified



- Can we translate this modifications into a universal quantities like nPDFs?

Motivations: Why do we need nuclear PDFs?

- Information on the structure of nucleus.
- Description of heavy ion collisions at the **LHC** and **RHIC**



- Description of electron DIS with nuclei: **EIC**, **LHeC**.
- 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. 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

Differences with the free-proton PDFs

- Theoretical status of Factorization
- Parametrization – more parameters to model A-dependence
- Different data sets – much less data:

  - Less data $\rightarrow$ less constraining power $\rightarrow$ **more assumptions** (fixing) about fitting parameters

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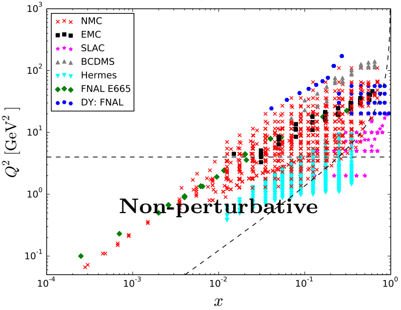
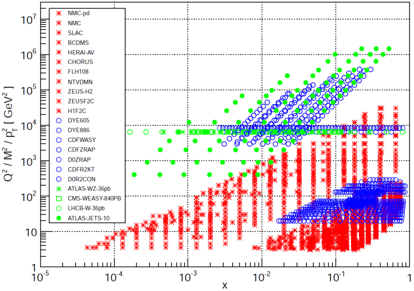
nCTEQ15 dataset



NNPDF2.3 dataset



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Available nuclear PDFs

- **Multiplicative nuclear correction factors**

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

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

- **Native nuclear PDFs**
  - `nCTEQ` [PRD 93, 085037 (2016), `arXiv:1509.00792`]

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

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

nCTEQ framework [PRD 93, 085037 (2016), arXiv:1509.00792]

- 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)

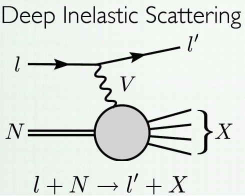
$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A-Z}{A} f_i^{n/A}(x, Q)$$

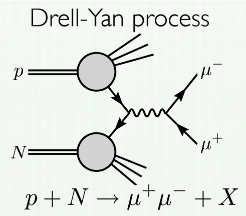
(bound neutron PDF $f_i^{n/A}$ by isospin symmetry)

Data sets

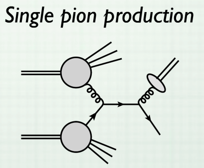
- NC DIS & DY

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)





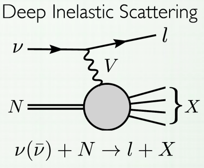
- Single pion production (new)



RHIC - PHENIX & STAR

N = Au

- Neutrino (to be included later)



CHORUS CCFR & NuTeV

N = Pb N = Fe

Fit details

Fit properties:

- fit @NLO
- $Q_0 = 1.3\text{GeV}$
- using ACOT heavy quark scheme
- kinematic cuts:
  $Q > 2\text{GeV}$, $W > 3.5\text{GeV}$
  $p_T > 1.7$ GeV
- 708 (DIS & DY) + 32 (single π^0)
  = 740 data points after cuts
- 16+2 free parameters
  - 7 gluon
  - 7 valence
  - 2 sea
  - 2 pion data normalizations
- $\chi^2 = 587$, giving $\chi^2/\text{dof} = 0.81$

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

Fit propert

- fit @N ... d
- $Q_0 =$ ... $a_i - a_i^0)(a_j - a_j^0)$
- using
- kinem
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  ... le → require numerical
  reducing derivatives
- $\chi^2 =$

Kinematic cuts

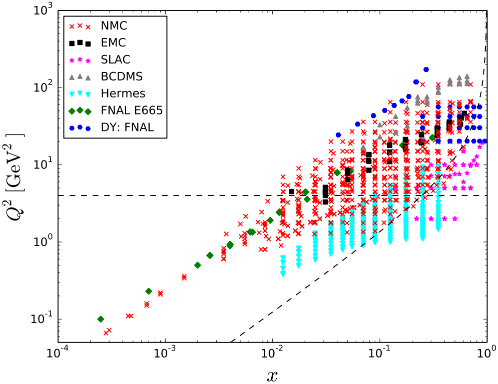
<u>nCTEQ:</u>

$$\begin{cases} Q > 2\ \text{GeV} \\ W > 3.5\ \text{GeV} \end{cases}$$

<u>EPS:</u> $Q > 1.3$ GeV

<u>HKN:</u> $Q > 1$ GeV

<u>DSSZ:</u> $Q > 1$ GeV



nCTEQ: 740 data points

EPS09: 929 data points

Fit details

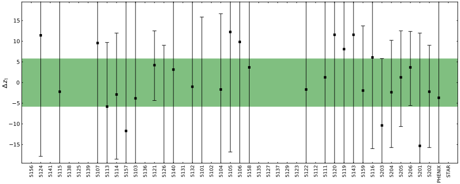
Fit properties:

- fit @NLO

Hessian method

- choice of tolerance: $T = 35$ [PRD65 (2001) 014012, arXiv:hep-ph/0101051]
- quadratic approximation

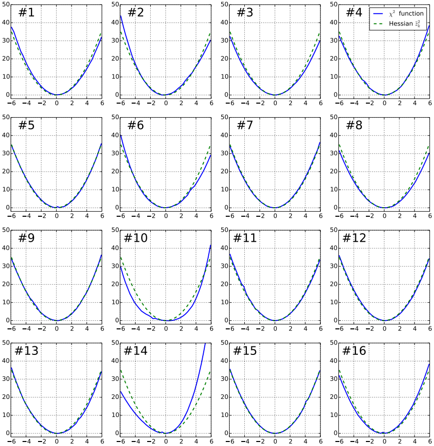
- 708 (DIS & DY) + 32 (single π^0) = 740 data points after cuts



normalizations

- $\chi^2 = 587$, giving $\chi^2/\text{dof} = 0.81$

Error analysis:



Fit details

Fit properties:

- fit @NLO

Fit quality

- $\chi^2/dof = 0.81$

sc

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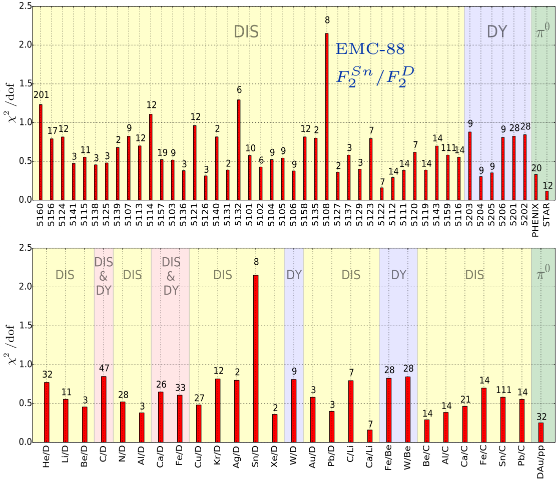


nCTEQ15 RESULTS

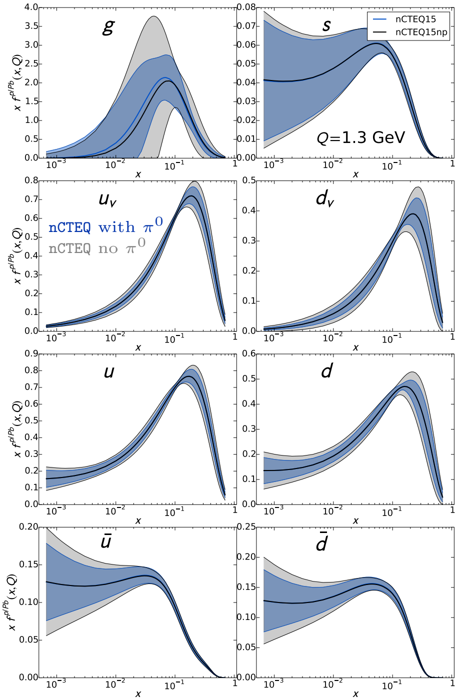
[PRD 93, 085037 (2016), arXiv:1509.00792]

Bound proton PDFs
($Q = 1.3$ GeV)

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

Compare `nCTEQ` fits:

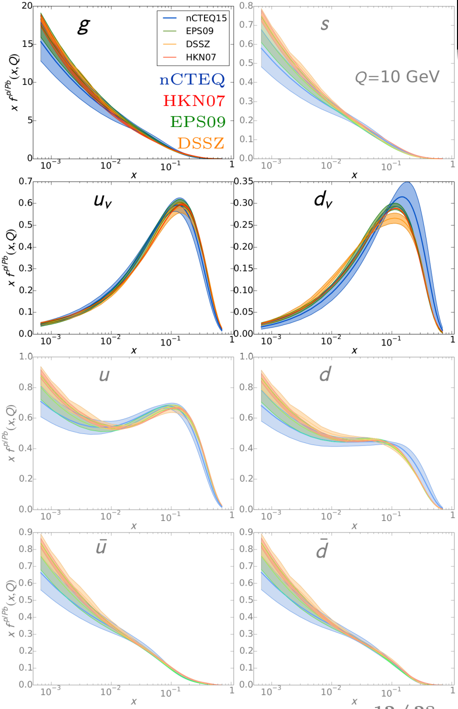
- `nCTEQ15` with π^0 data
- `nCTEQ15np` without π^0 data



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

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

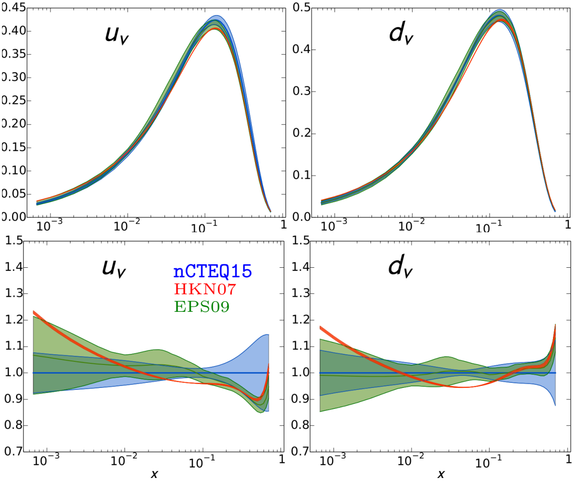
- nCTEQ features larger uncertainties than previous nPDFs
- better agreement between different groups (nPDFs don't depend on proton baseline)



Valence nuclear distributions

Full lead nucleus distribution:

$$f^{Pb} = \frac{82}{208} f^{p/Pb} + \frac{208-82}{208} f^{n/Pb}$$



nCTEQ15

$$u_v^{p/A} \neq d_v^{p/A}$$

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

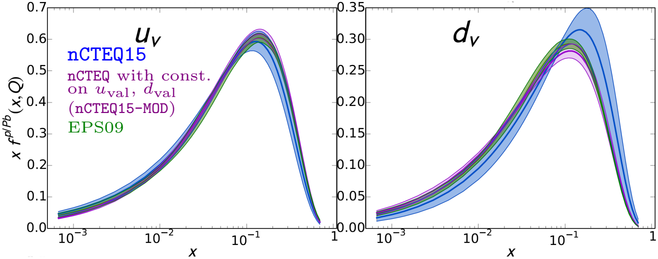
$$x d_v^{p/A}(Q_0) = x^{c_1^d}(1-x)^{c_2^d} e^{c_3^d x}(1+e^{c_4^d}x)^{c_5^d}$$

EPS09

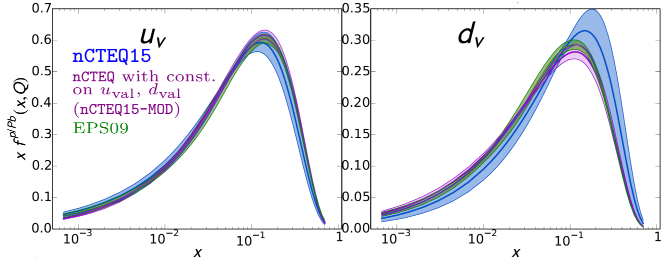
$$R_v^u(x,A,Z) = R_v^d(x,A,Z)$$

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

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



nCTEQ15-MOD: $u_v^{p/A} \simeq d_v^{p/A}$



- χ^2 of both fits is very similar (~ 590) $\rightarrow$ there is not enough data to properly constrint u and d distributions.
- Differences between u and d distributions are washed out in the nuclei

$$f^{Pb} = \frac{Z}{A} f^{p/Pb} + \frac{A-Z}{A} f^{n/Pb}$$

because of the proton/neutron combination.
- Additionally most of DIS data is isoscalar corrected $\rightarrow$ insensitive to u/d differences.
- Differences between the two fits represents an unaccounted systematic uncertainty of the nPDFs.

LHC data

Available pPb LHC data

- W/Z production
  - ATLAS [arXiv:1507.06232, ATLAS-CONF-2015-056]
  - CMS [arXiv:1512.06461, arXiv:1503.05825]
  - LHCb [arXiv:1406.2885]
  - ALICE [arXiv:1511.06398]
- Jets
  - ATLAS [arXiv:1412.4092]
  - CMS [arXiv:1401.4433, CMS-PAS-HIN-14-001]
- Charged particle production (FFs dependence)
  - CMS [CMS-PAS-HIN-12-017]
  - ALICE [arXiv:1405.2737, arXiv:1505.04717]
- Isolated photons (PbPb)
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Reweighting for Hessian PDFs [arXiv:1310.1089, arXiv:1402.6623]

1. Convert Hessian error PDFs into replicas

$$f_k = f_0 + \sum_{i}^{N} \frac{f_i^{(+)} - f_i^{(-)}}{2} R_{ki},$$

2. Calculate weights for each replica

$$w_k = \frac{e^{-\frac{1}{2}\chi_k^2/T}}{\frac{1}{N_{\rm rep}} \sum_i^{N_{\rm rep}} e^{-\frac{1}{2}\chi_k^2/T}}, \qquad \chi_k^2 = \sum_j^{N_{\rm data}} \frac{(D_j - T_j^k)^2}{\sigma_j^2}$$

3. Calculate observables with new (reweighted) PDFs

$$\langle \mathcal{O} \rangle_{\rm new} = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} w_k \mathcal{O}(f_k),$$

$$\delta \langle \mathcal{O} \rangle_{\rm new} = \sqrt{\frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} w_k \left(\mathcal{O}(f_k) - \langle \mathcal{O} \rangle\right)^2}.$$

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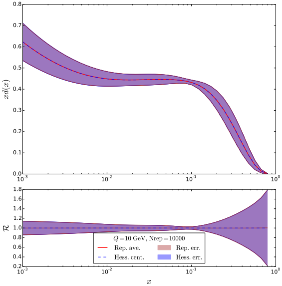

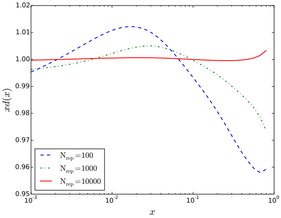

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To speed up calculations in case of pPb data we can exploit

$$\sigma_k = f^{\rm p} \otimes \hat{\sigma} \otimes \left[f_0^{\rm Pb} + \sum_i^N \frac{f_i^{{\rm Pb}(+)} - f_i^{{\rm Pb}(-)}}{2} R_{ki} \right].$$

Reweighting with LHC data

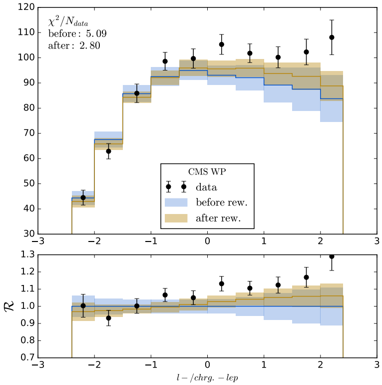
- We used only W/Z production data from pPb collisions
  - ATLAS [arXiv:1507.06232, ATLAS-CONF-2015-056]
  - CMS [arXiv:1512.06461, arXiv:1503.05825]
  - LHCb [arXiv:1406.2885]
  - ALICE [arXiv:1511.06398]
- The dominate role is played by the CMS W production data [arXiv:1503.05825]

Reweighting with LHC data

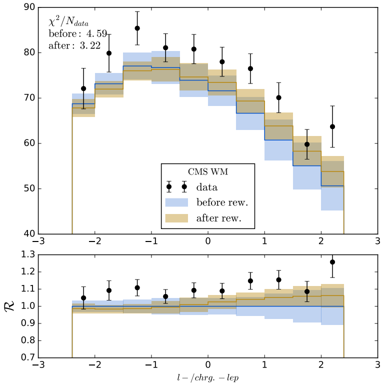
- CMS $W^{\pm}$ data [arXiv:1503.05825]

before reweighting
after reweighting

W^{+}



W^{-}

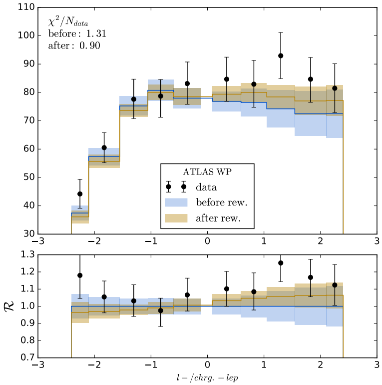


Reweighting with LHC data

- ATLAS $W^{\pm}$ data [ATLAS-CONF-2015-056]

  before reweighting
  after reweighting

W^{+}



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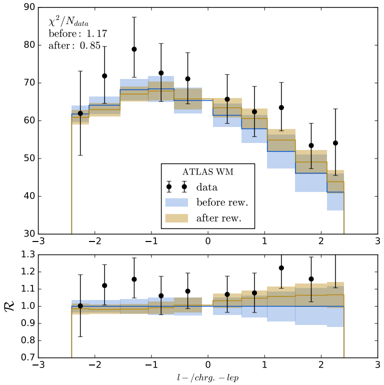
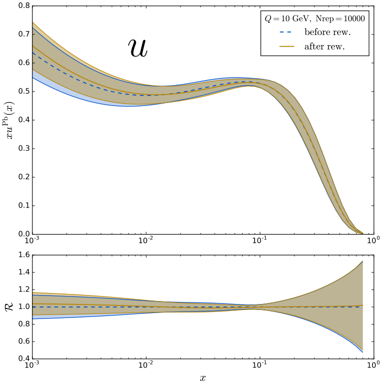
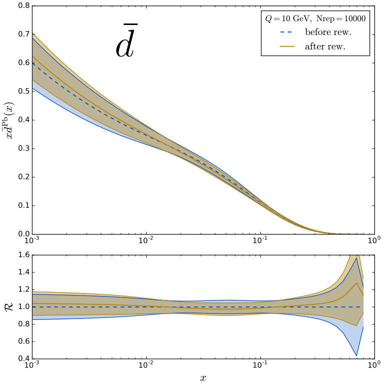


Reweighting with LHC data

- Example reweighted PDFs

before reweighting
after reweighting

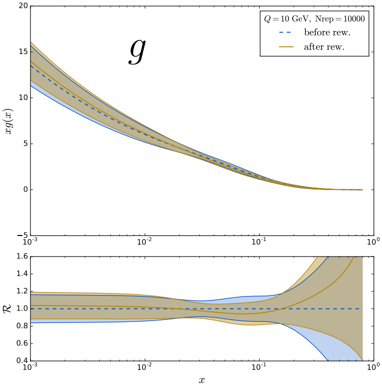


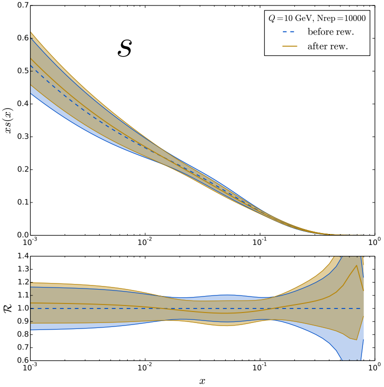


Reweighting with LHC data

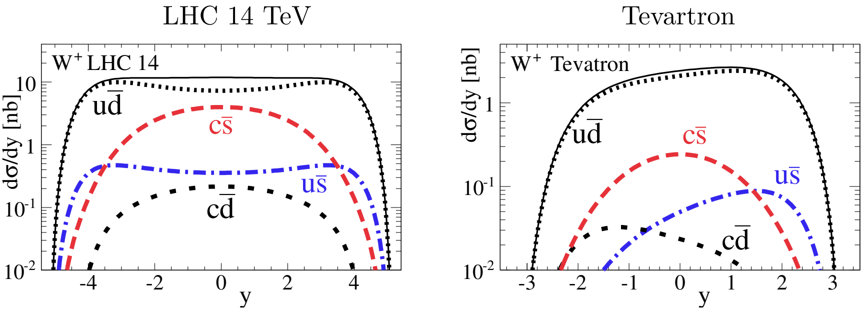
- Example reweighted PDFs

before reweighting
after reweighting





Strange and free-proton baseline

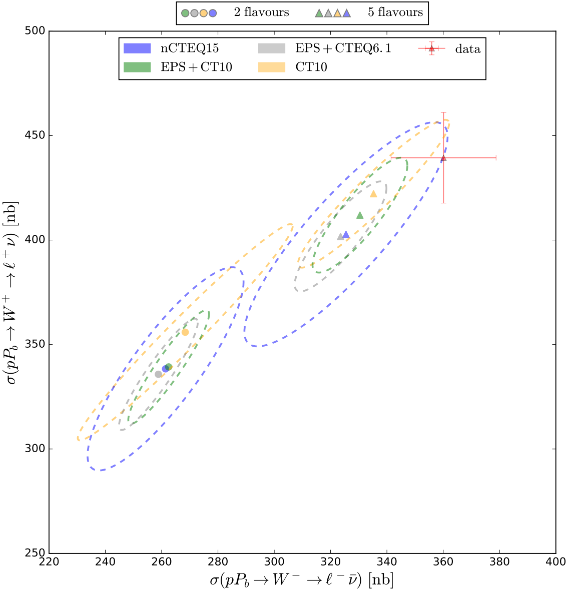


[PRD85 (2012) 094028, arXiv:1203.1290]

- Strange constributions at the LHC are much more important than in previous experiments.
- We should look more carefully at nuclear strange.
  - open strange degrees of freedom
  - use newer free-proton baseline with LHC data

Importance of free-proton baseline

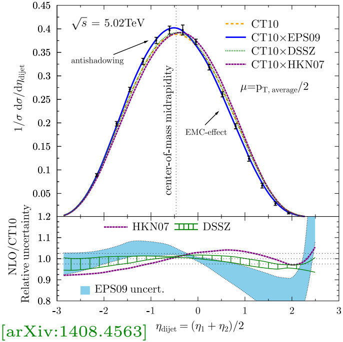
CMS $W^{\pm}$ data [arXiv:1503.05825]



Used data:

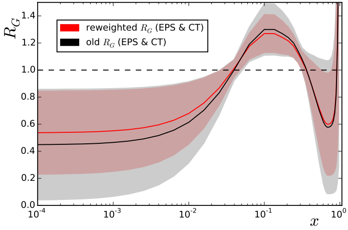
- W/Z boson production from pPb collisions
  - most importantly: CMS W production [arXiv:1503.05825]
- Jets & dijets
  - CMS dijets look promising [arXiv:1401.4433]
- Charged-particle production

Biggest impact comes from dijet data modifying gluon distribution



[arXiv:1408.4563]

[arXiv:1512.01528]

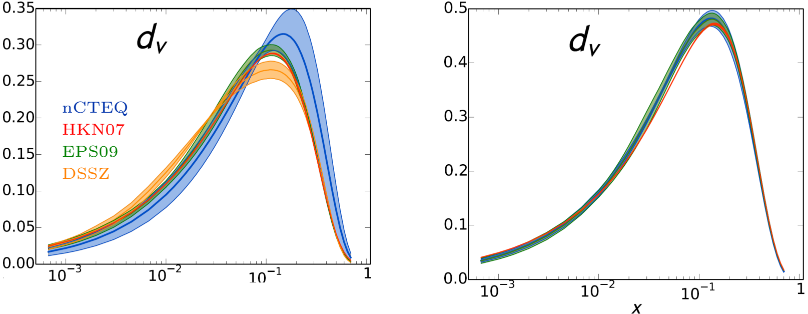


Summary

Summary

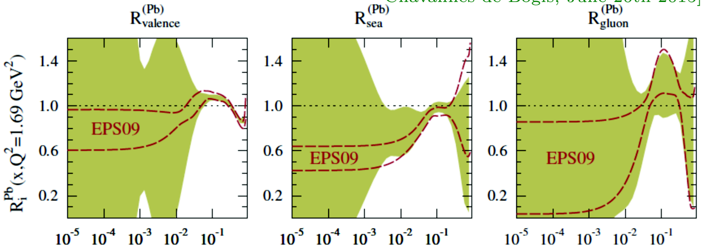
- I presented the available nPDF analysis;
  in particular the new **nCTEQ15** [arXiv:1509.00792]
  (PDFs available at: http://ncteq.hepforge.org
  and at LHAPDF website)

- There are substantial differences in bound proton PDFs which vanish for full nuclear PDFs
  - bound proton PDFs are only **effective** means of parametrization of full nPDFs



- Not all flavours are currently reliably determined in particular constraints on the nuclear gluon are very mild.
- nPDFs errors still substantialy underestimated especially at low-x (no data below $x \lesssim 0.01$)

[N. Armesto, 2015 LHeC Workshop Chavannes-de-Bogis, June 26th 2015]



Summary

- The LHC data is still not very precise which results in rather mild effects on nPDFs (in the reweighting studies).

- However, it is important to include the LHC data into the fits ($W^{\pm}$ and Z bosons, jets, dijets)
  - allows to remove assumptions (open new parameters, e.g. gluon, strange)
  - constraints on previously fixed distributions (hard to estimate impact via reweighting)
  - stabilizes fits
  - makes errors estimates more reliable

Nuclear CTEQ parto ×

ncteq.hepforge.org

nCTEQ is hosted by Hepforge, IPPP Durham

nCTEQ

nuclear parton distribution functions

- Home
- PDF grids & code
  - nCTEQ15
  - previous PDF grids
- 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). All details on the framework and the first complete results can be found in arXiv:15????? [hep-ph].
The effects of the nuclear environement on the parton densities can be shown as modified parton densities or nuclear correction factors (for example for lead as shown below)

Thank You