Nuclear PDFs

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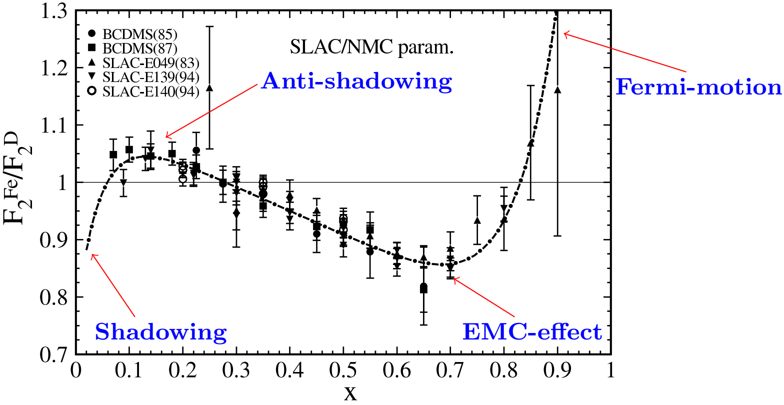
xFitter Meeting
19 - 22 March 2017,
St Hilda's College, Oxford, UK

Motivation

- Cross-sections in nuclear collisions are modified



- We translate this modifications into universal quantities: nuclear PDFs (nPDFs)

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]
  - **DSSZ**: de Florian, Sassot, Stratmann, Zurita
    [PRD 85, 074028 (2012), arXiv:1112.6324]
  - **EPS**: Eskola, Paukkunen, Salgado
    [JHEP 04 (2009) 065, arXiv:0902.4154]
  - NEW **EPPS16**: Eskola, Paakkinen, Paukkunen, Salgado
    [arXiv:1612.05741]

- **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 nPDF framework [PRD 93, 085037 (2016), arXiv:1509.00792]

- **Parametrization**
  - bound proton PDFs

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}$$

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

  - PDF of nucleus (A - mass, Z - charge)

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

- **Experimental data**
  - DIS (NMC, BCDMS, Hermes, SLAC, E665, EMC)
  - Drell-Yan (E772, E886)
  - Pion production (PHENIX, STAR)

  } 740 data pts.

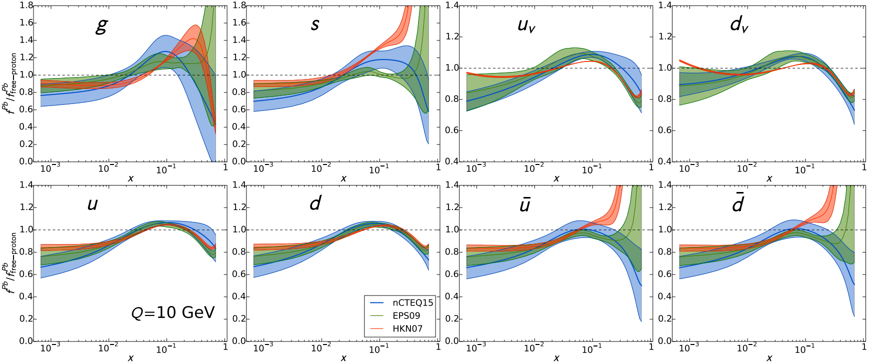
nCTEQ15 fit

Fit details

- $\chi^2/dof = 0.81$
- QCD@NLO
- Hessian error PDFs
- 740 data points

$$R^{Pb} = \frac{f^{Pb}}{f^{Pb}_{\text{free-proton}}}$$

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

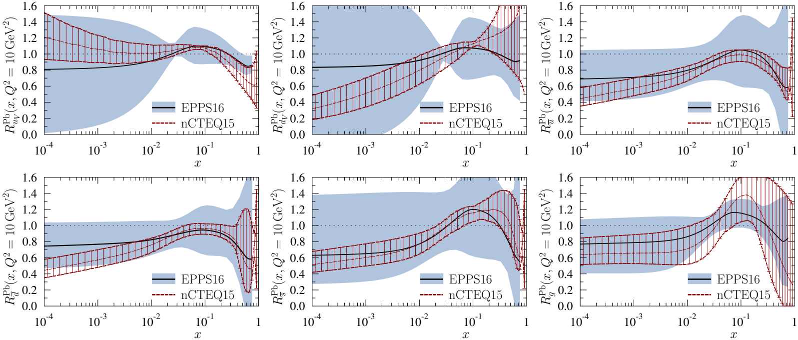


EPPS16 [arXiv:1612.05741]

First analysis with pPb LHC data:

- $W^{\pm}$ from CMS
- Z from CMS and ATLAS
- dijet from CMS

$$R^{p/Pb} = \frac{f^{p/Pb}(x,Q)}{f^{p}(x,Q)}$$



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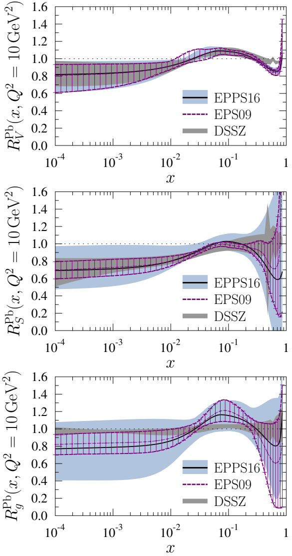

Differences with the free-proton PDFs

- Theoretical status of Factorization
- Parametrization – more parameters to model A-dependence
- Different data sets – much less data:
  - Less data → less constraining power → **more assumptions** (fixing) about fitting parameters

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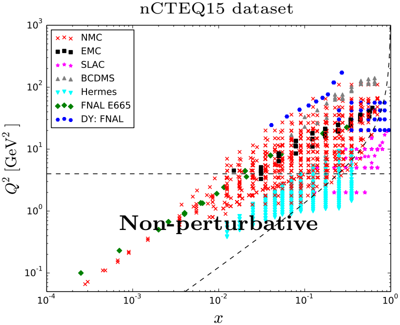

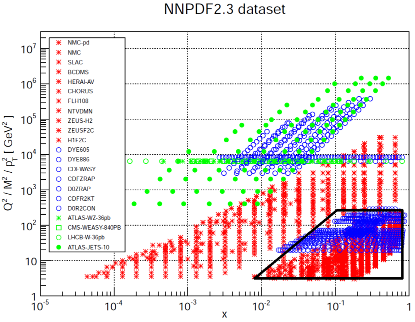

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Nuclear strange and LHC data

[arXiv:1610.02925]

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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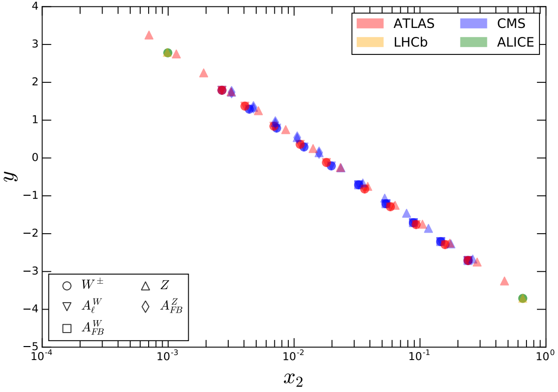

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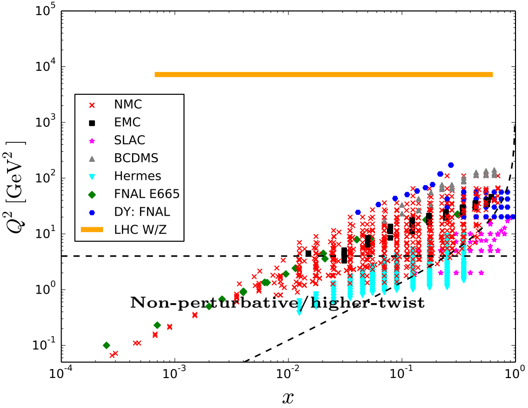
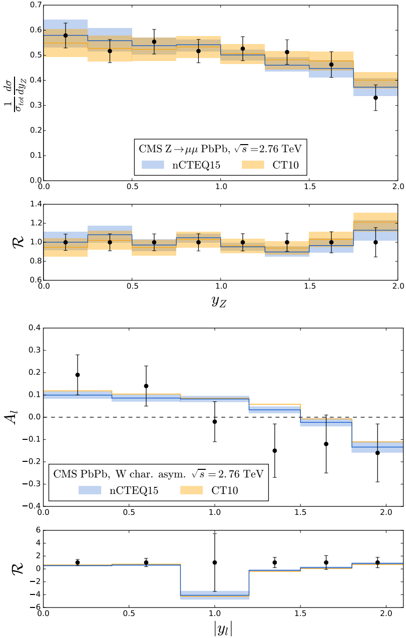


PbPb data

[JHEP 03 (2015) 022, 1410.4825; PRL 110 (2013) 022301, 1210.6486]
[PLB 715 (2012) 66, 1205.6334; EPJ C75 (2015) 23, 1408.4674]



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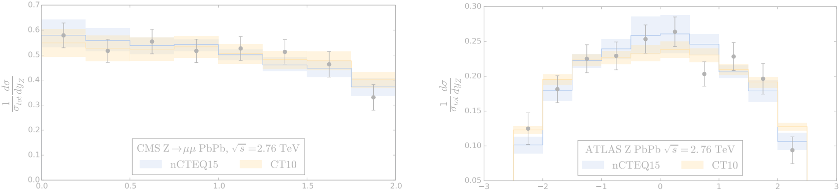
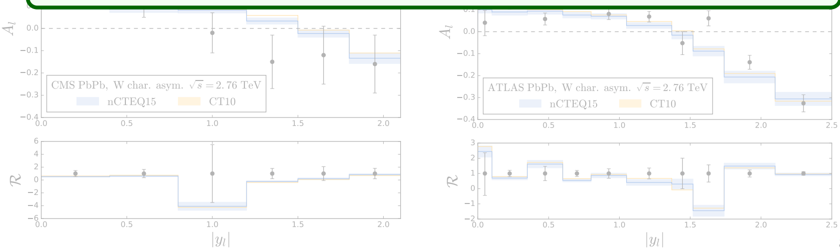


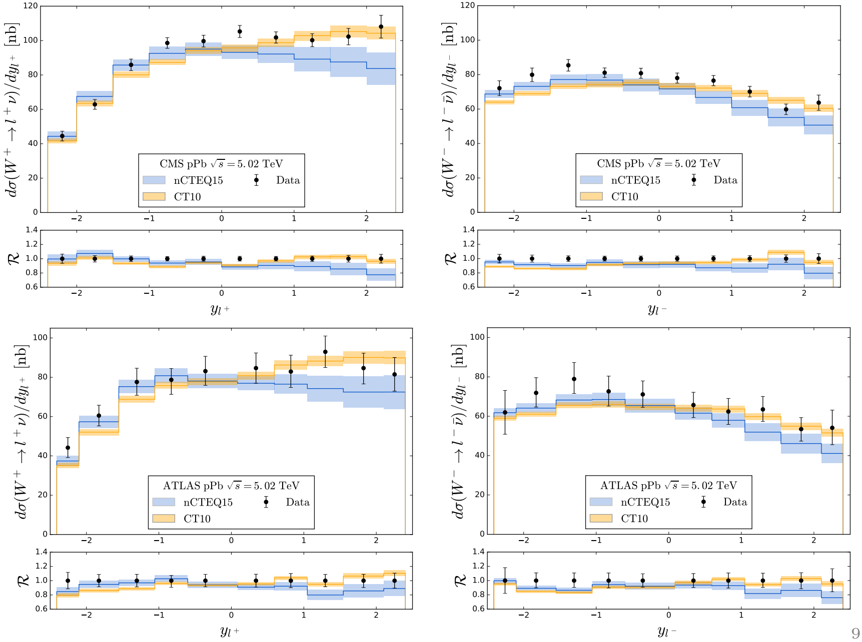
Comments

- Not very sensitive to nuclear corrections
- Uncertainties too large to bring constraints on nPDFs



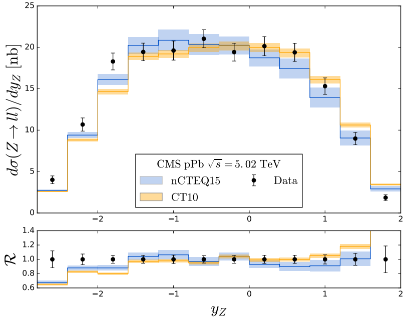
pPb data: CMS & ATLAS $W^{\pm}$

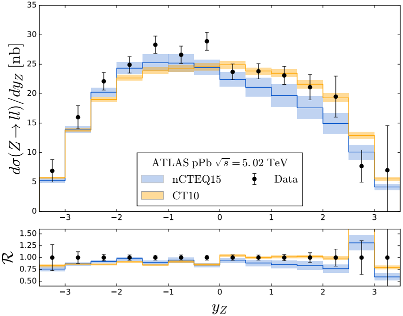
[PLB 750 (2015) 565, arXiv:1503.05825]
[ATLAS-CONF-2015-056]



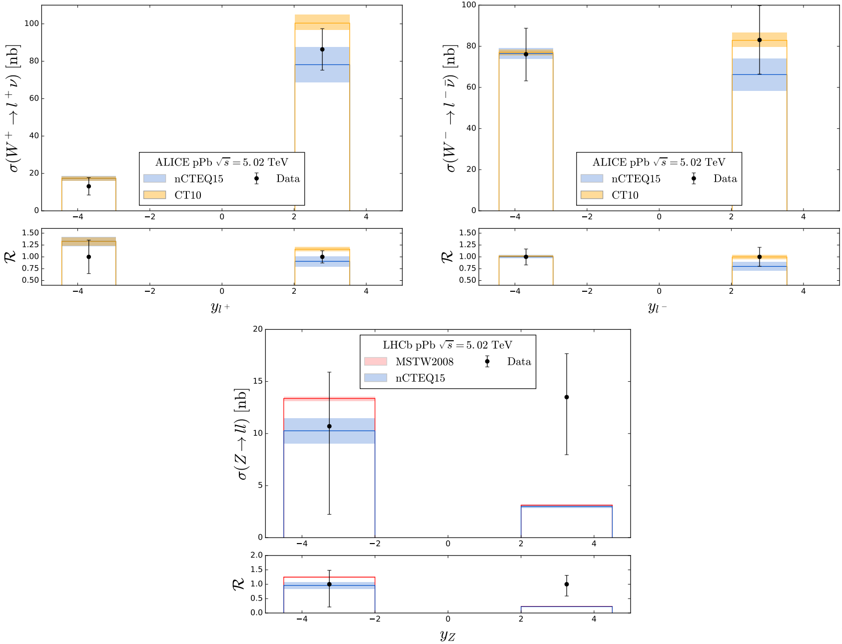
pPb data: CMS & ATLAS Z

[PLB 759 (2016) 36, arXiv:1512.06461]
[PRC 92 (2015) 044915, arXiv:1507.06232]





pPb data: LHCb & ALICE W/Z [arXiv:1511.06398] [JHEP 09 (2014) 030, arXiv:1406.2885]



pPb data

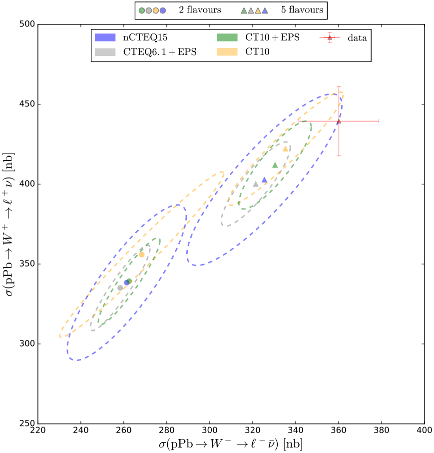
Comments

- Overall good description of the data
  - Very good for $y < 0$ where `nCTEQ15` has data.
  - Some leverage in the $y > 0$ (low x) region $\Rightarrow$ mainly extrapolation
- ALICE and LHCb $\Rightarrow$ interesting with more data
- Potential constraining power from the ATLAS and CMS W^+ rapidity distributions. In particular where we don't have data at the moment at $x \sim 3 \times 10^{-3}$ $\Rightarrow$ shadowing region

Strange quark

Correlation of W^+ vs. W^- cross section with CMS data

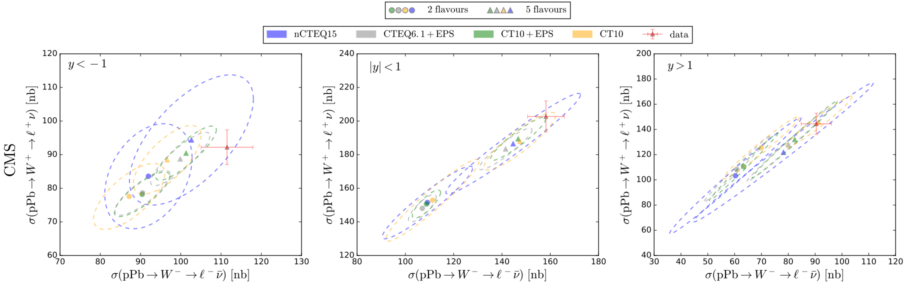
- Strange is fixed in `nCTEQ15`
- Compare 2- vs. 5-flavour scenario



- The impact of the strange is $\sim 30\%$
- Most of the difference between `CT10+EPS09` and `nCTEQ15` is the underlying strange contribution in `CT10` PDFs
- Nuclear corrections very close to each other
  - Consistently lower than proton-proton results $\Rightarrow$ **shadowing** sets up too early ?

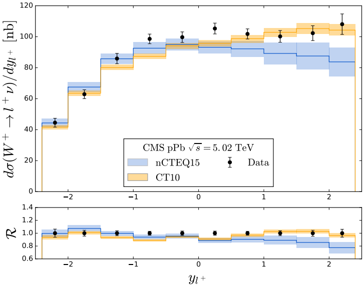
Strange quark

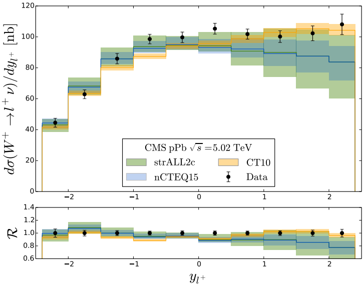
- As we move from $y < 0$ to $y > 0 \Rightarrow$ high-x to low-x
  - (i.e. from well constrained to less constrained region)



- At $y < 0$ nuclear corrections > 1 (anti-shadowing) $\Rightarrow$ pull results toward data
- As we move to higher y it seems we are little short $\Rightarrow$ **shadowing region**
- Hypothetic: small negative $s - \bar{s}$ asymmetry at high-x ?

What about strange form di-muon data?





Impact on the nCTEQ15 PDFs: reweighting analysis

Reweighting literature

- Intoruced by Giele and Keller [arXiv:hep-ph/9803393]
- Developed later by NNPDF [arXiv:1012.0836]
- Application and developments for Hessian PDF sets [arXiv:1310.1089, arXiv:1402.6623]

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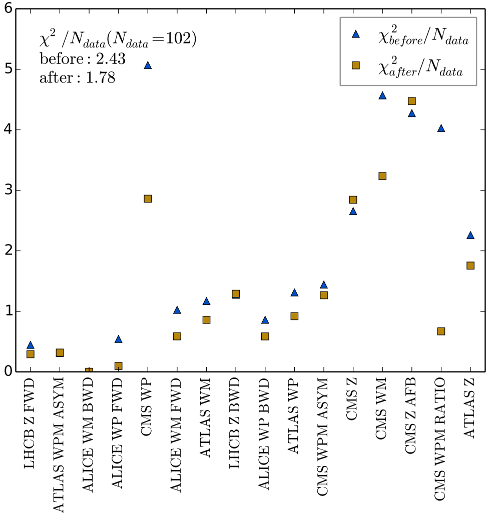
   To speed up calculations in case of pPb data we can exploit

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

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]

χ^2 values for all used data sets

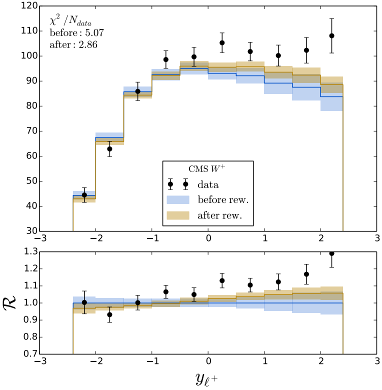


Reweighting with LHC data

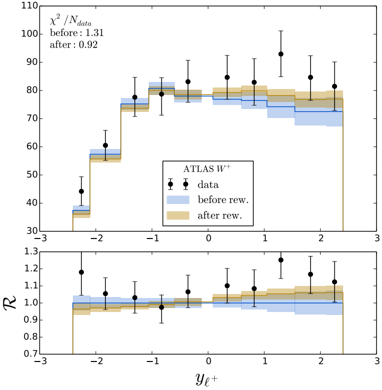
- CMS & ATLAS W^+ data

before reweighting
after reweighting

CMS W^+



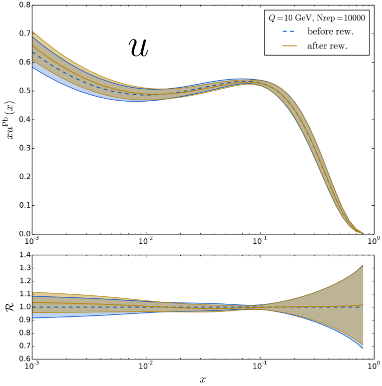
ATLAS W^+

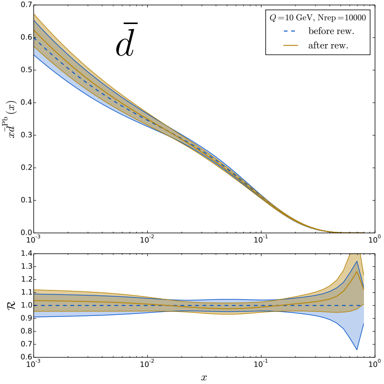


Reweighting with LHC data

- Example reweighted PDFs

  before reweighting
  after reweighting





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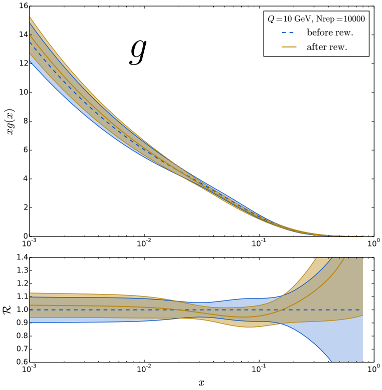
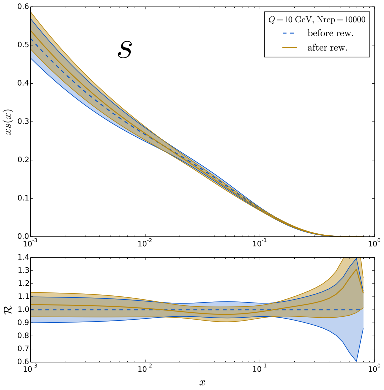
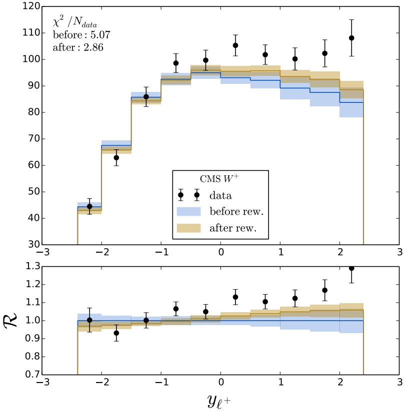




Caveats of the reweighting analysis



- Substantial region ($y \gtrsim 0 \to x \lesssim 10^{-2}$) where `nCTEQ15` PDFs are extrapolated
  - $y = 2 \to x \sim 10^{-3}$
  - earlier data $x \gtrsim 10^{-2}$
- limited flexibility of the PDF parametrization
  - can not simultanously accomodate modifications at positive and negative rapidites
- strange PDF tied to $\bar{u} + \bar{d}$ distribution

LHC jet data from EPPS16 [arXiv:1612.05741]

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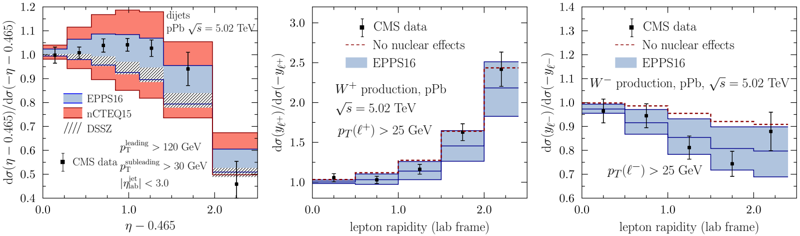

Summary

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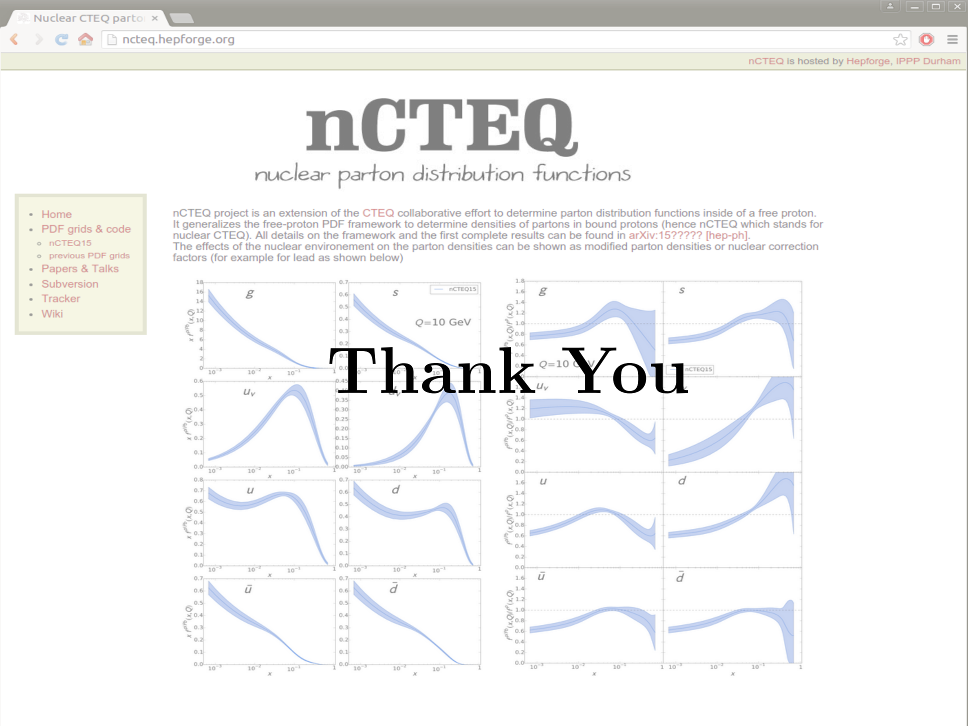
- LHC pPb data important for nPDFs:
  - gluon PDF
  - strange PDF
  - delayed shadowing? which could be compatible with what is indicated by the NuTeV neutrino DIS data
  - possible nuclear strange asymmetry
- Current LHC pPb data are still limited in precision, however, more data with higher statistics have been collected in Dec 2016.
- Full fit with these new data will be performed when the data will become available
  - 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

Summary

- More LHC data for different hard processes will allow for lead-only fit and also for further tests of uniersality of nPDFs.
- Data for *coloured* and *un-coloured* final states to test shadowing vs energy loss effects.

Thank You


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
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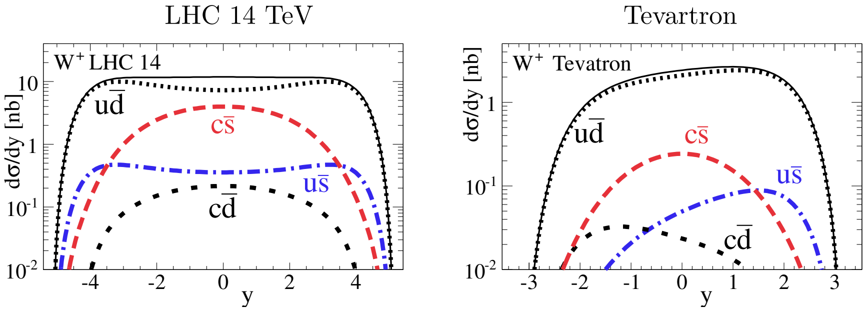
nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). All details on the framework 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)
nCTEQ15
Q=10 GeV

BACKUP SLIDES

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

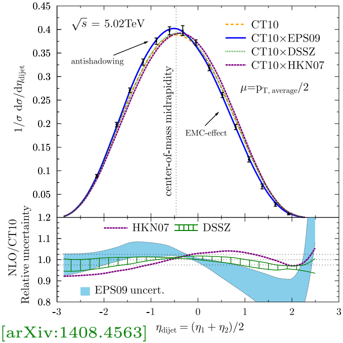
EPS study of LHC data impact

[EPJC (2016), 76:218, arXiv:1512.01528]

Used data:

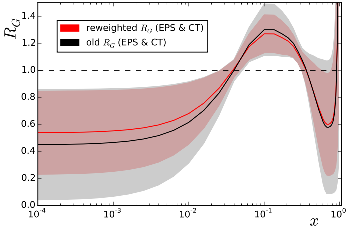
- W/Z boson production from pPb collisions
  - most importantly: CMS W production [arXiv:1503.05825]
- Jets & dijets
  - CMS dijets look promising [arXiv:1401.4433]
- Charged-particle production

Biggest impact comes from dijet data modifying gluon distribution



[arXiv:1408.4563]

[arXiv:1512.01528]



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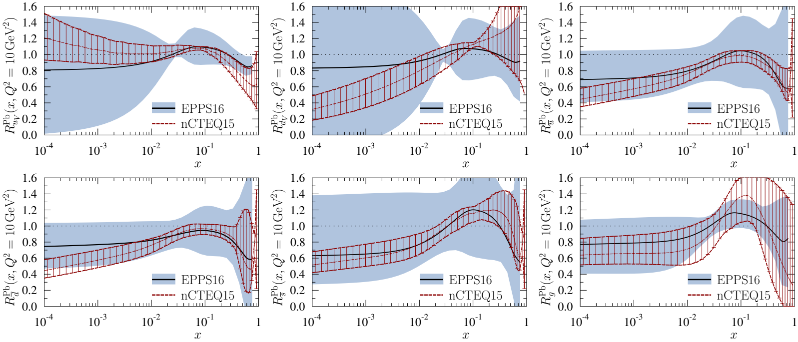

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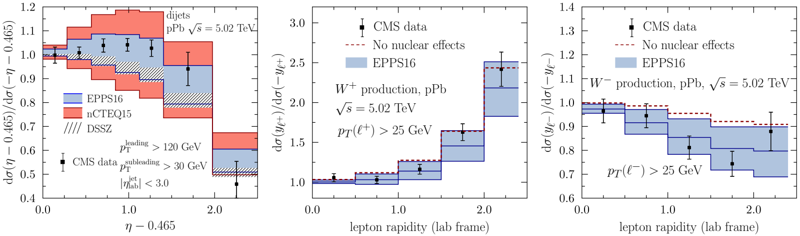
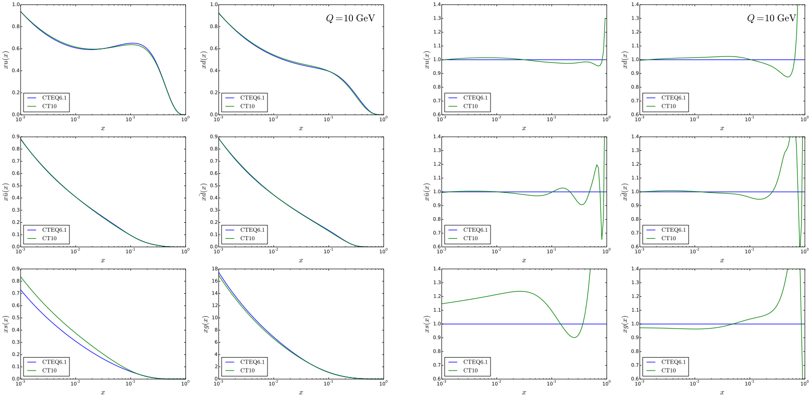


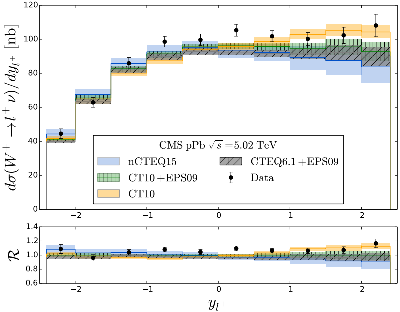
CT10 vs. CTEQ6.1 PDFs



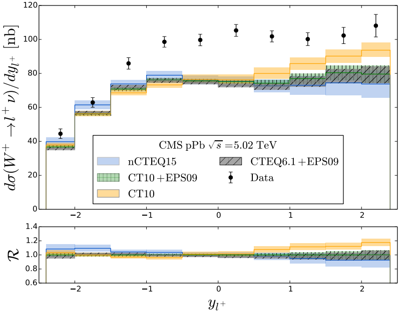
Importance of free-proton baseline

- CMS W^+ data [arXiv:1503.05825]

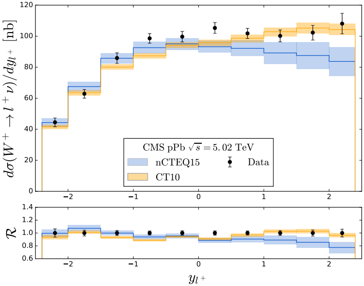
full result

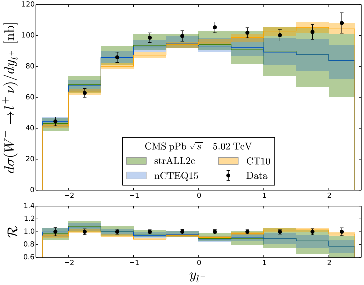


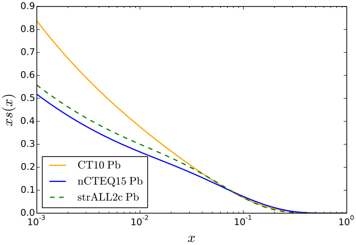
1 quark family (no s, c, b)

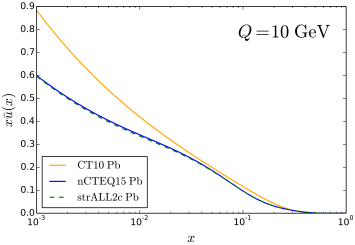


What about strange form di-muon data?

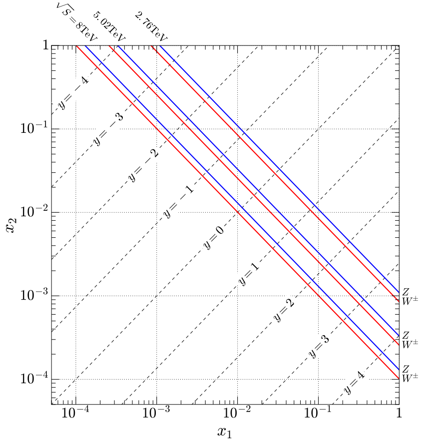


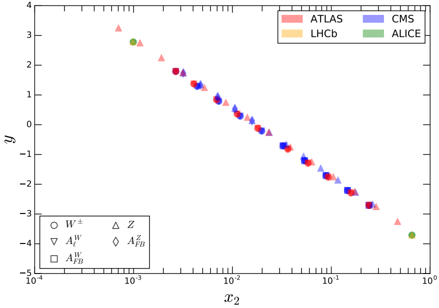






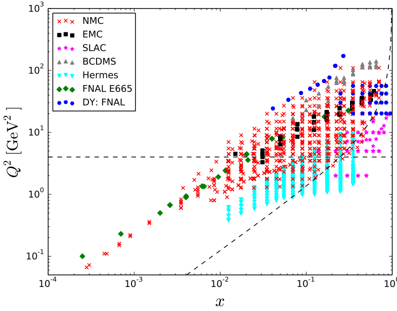
Kinematic reach of LHC $W^{\pm}/Z$ data



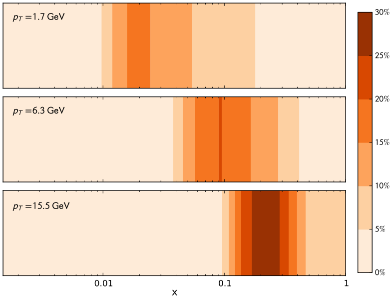


Kinematic reach of data

DIS and DY:



π^0 production:

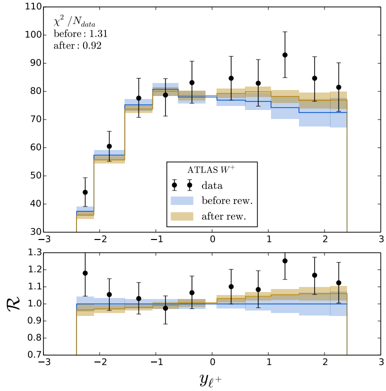


Reweighting with LHC data

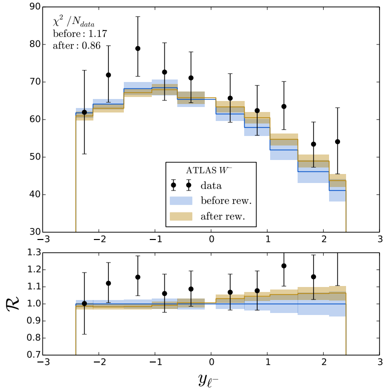
- ATLAS $W^{\pm}$ data [ATLAS-CONF-2015-056]

before reweighting
after reweighting

W^+



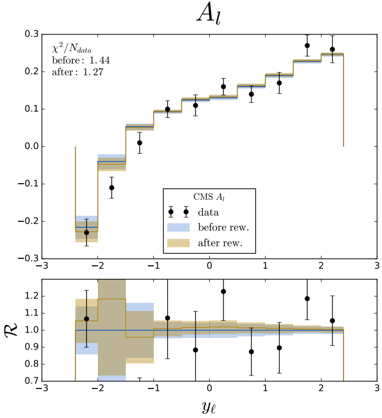
W^-

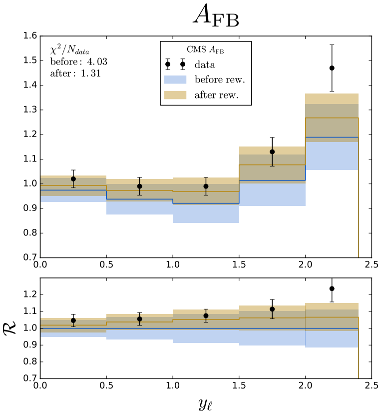


Reweighting with LHC data

- CMS charge lepton (A_l) and forward-backward (A_{FB}) asymmetries for $W^{\pm}$ [arXiv:1503.05825]

before reweighting
after reweighting

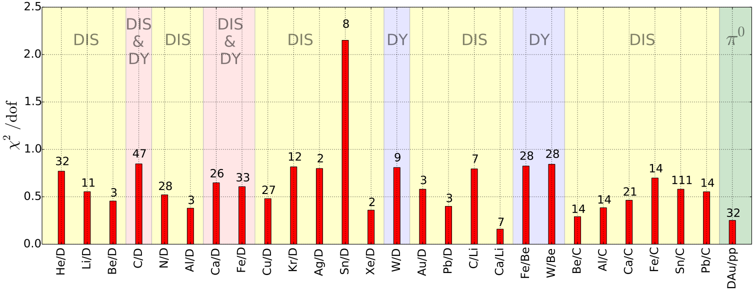




nCTEQ15 fit

Fit details

- $\chi^2/dof = 0.81$
- QCD@NLO
- Hessian error PDFs
- 740 data points



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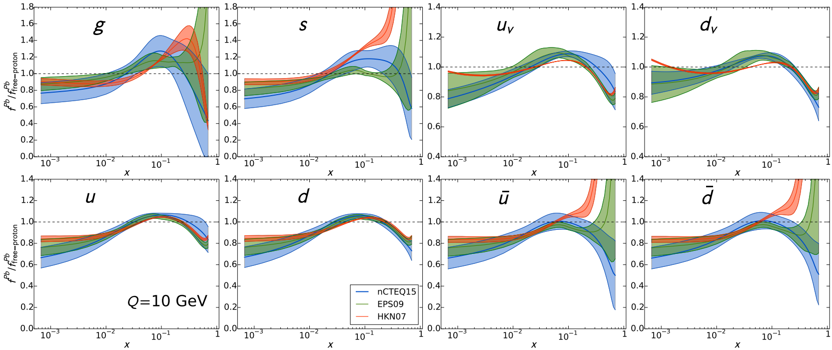
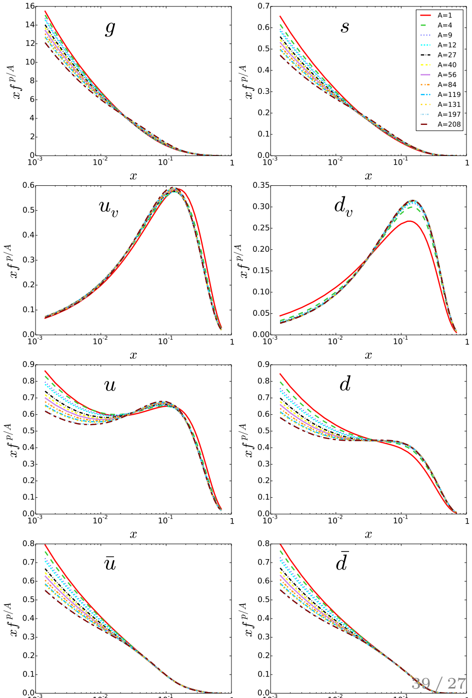


nCTEQ results

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

$$xf_i^A(x, Q)$$

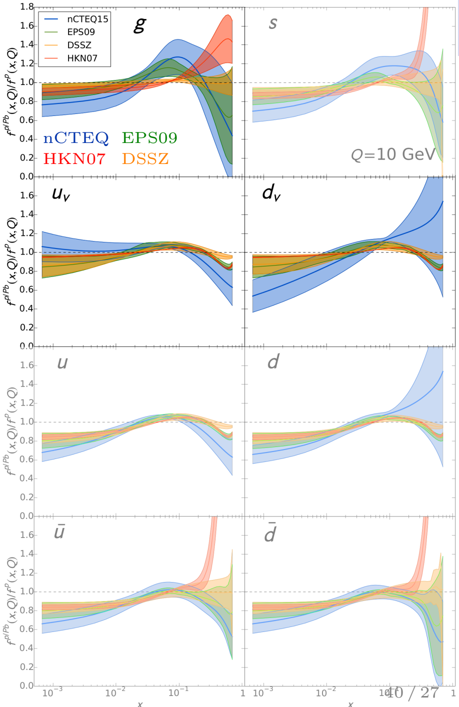


nCTEQ results

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

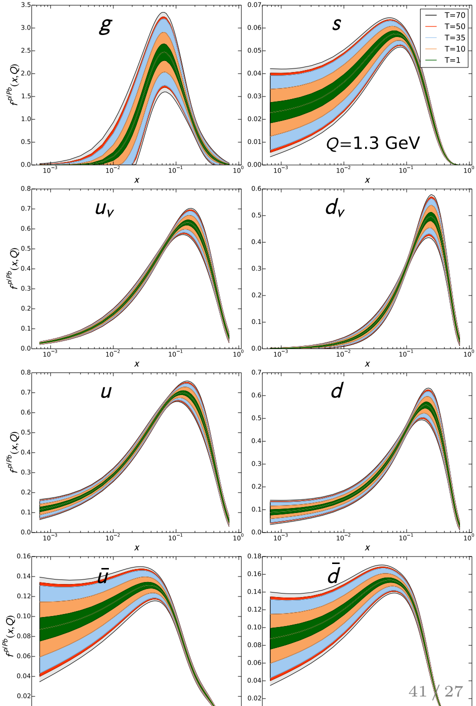
$$R_i(Pb) = \frac{f_i^{p/Pb}(x,Q)}{f_i^p(x,Q)}$$

- 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

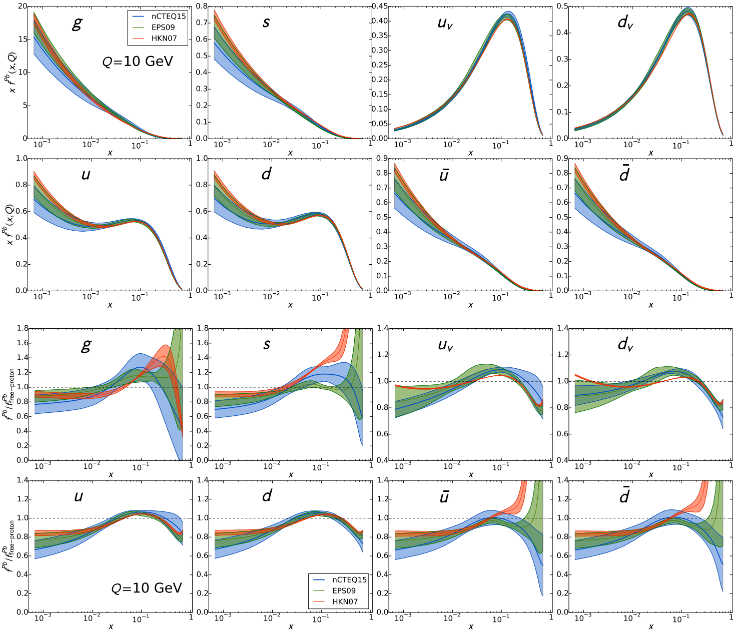


Tolerance criteria

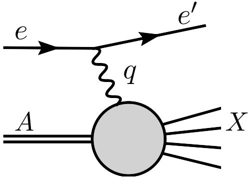
$$xf_i^{p/Pb}(x, Q = 1.3\text{GeV})$$



Nuclear lead PDFs ($f^A = \frac{Z}{A} f^{p/A} + \frac{A-Z}{A} f^{n/A}$)



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)

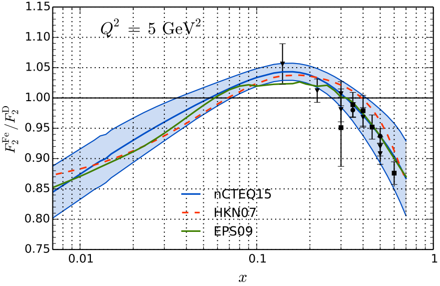
- Analogue variables for partons:
  - $p_N = \frac{p_A}{A}$ – *average* nucleon momentum
  - $x_N \equiv \frac{Q^2}{2\,p_N \cdot q} = A\,x_A$ – parton momentum fraction with respect to the avarage nucleon momentum p_N
  - $x_N \in (0, A)$ – parton can carry more than the average nucleon momentum p_N.

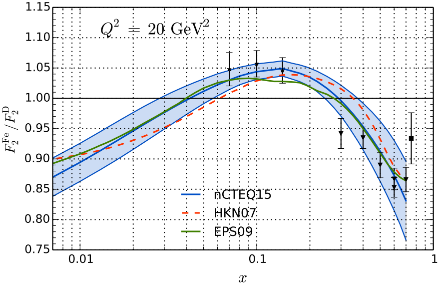
nCTEQ results: F_2 ratios

Structure function ratio

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

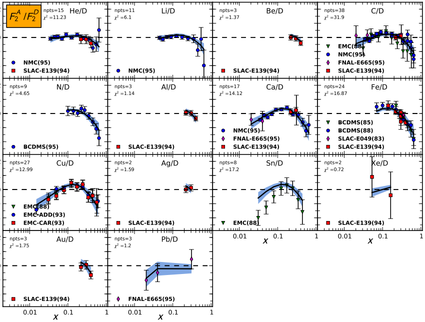
- good data description
- despite different u-valence & d-valence ratios are similar to EPS09



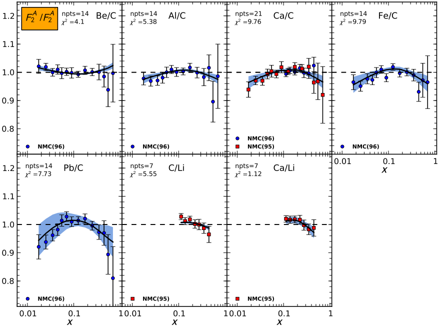


Description of fitted data: F_2 ratios

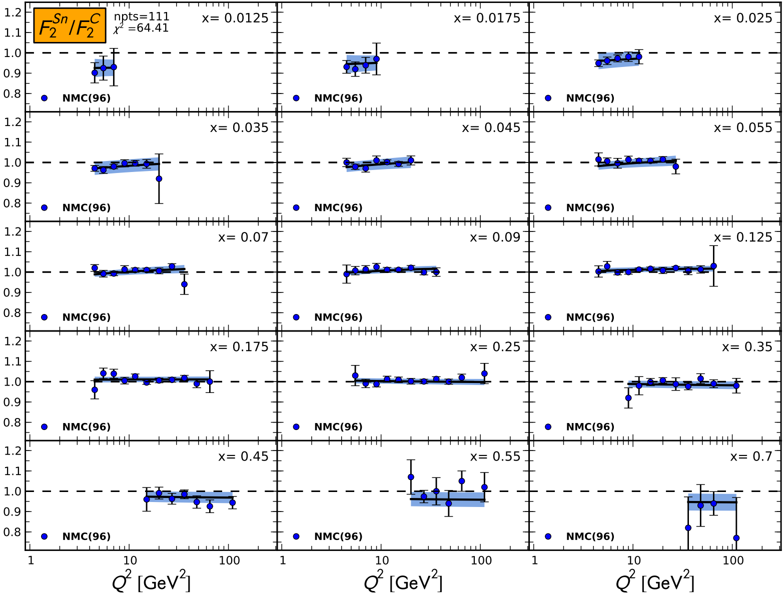
$$R = \frac{F_2^A(x,Q)}{F_2^D(x,Q)}$$



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

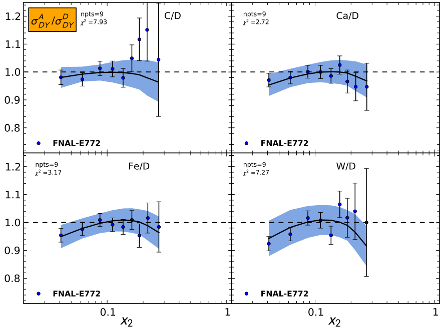


Description of fitted data: F_2 ratios for Sn/C

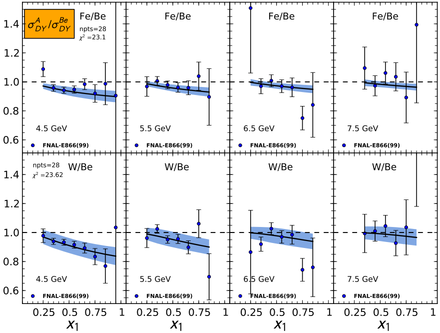


Description of fitted data: σ_{DY} ratios

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



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



EPS09:

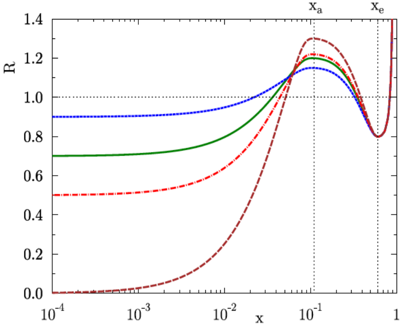
[N. Armesto, 2015 LHeC Workshop, Chavannes-de-Bogis, June 26th 2015]

- Very little freedom at small x.

  The fit function in EPS09:

$$R^{\mathrm{EPS09}}(x) = \begin{cases} a_0 + (a_1 + a_2 x)\left(e^{-x} - e^{-x_a}\right) & x \leq x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \leq x \leq x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \leq x \leq 1 \end{cases}$$

(power-law parametrization of A-dependence at x_a, x_e, and $x \to 0$)

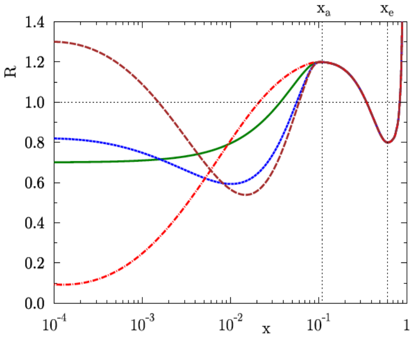


New ICs:

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

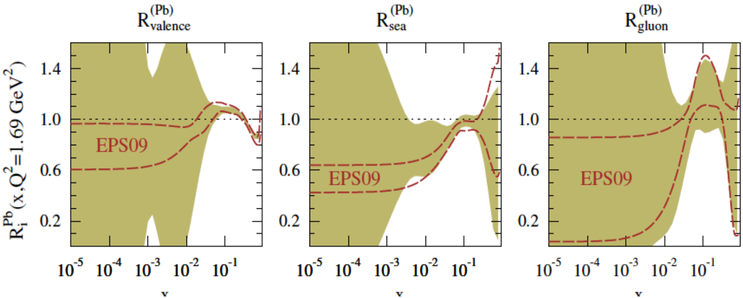
- Use a far more flexible form to reduce the bias at small x:

$$
\begin{aligned}
R(x \leq x_a) &= a_0 + a_1(x - x_a)^2 \\
&+ \sqrt{x}(x_a - x)\left[a_2 \log\left(\frac{x}{x_a}\right) + a_3 \log^2\left(\frac{x}{x_a}\right) + a_4 \log^3\left(\frac{x}{x_a}\right)\right]
\end{aligned}
$$



New fit framework:

The baseline fit using the new fit functions: no control over small x!



The lower bound restricted here by $F_L(Q^2 = 2\,\mathrm{GeV}^2, x > 10^{-5}) > 0$

Maybe against "physical intuition" (small-x theory predicts shadowing, $R_i < 1$), but consistent with the data.

E.g. in EPS09, small-x shadowing was essentially built in

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

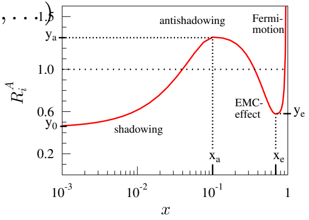
- LO & NLO PDFs with errors
- Error PDFs produced with *Hessian method*
- Parametrization (Q_0=1.3GeV)

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

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

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

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



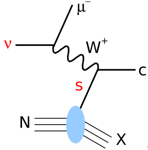
- CTEQ6.1M free proton baseline
- Neglects $x_N > 1$
- Data: DIS, DY, π^0 @ RHIC

Motivations: proton Strange PDF

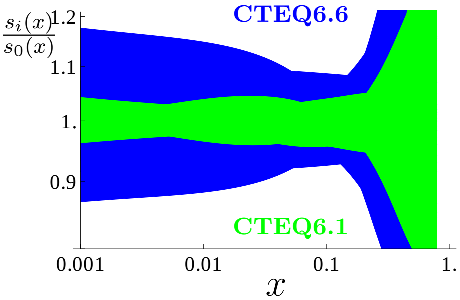
Before `CTEQ6.6` proton PDFs it was assumed
P. Nadolsky et al. PRD 78, 013004 (2008), `arXiv:0802.0007`

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

- 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.



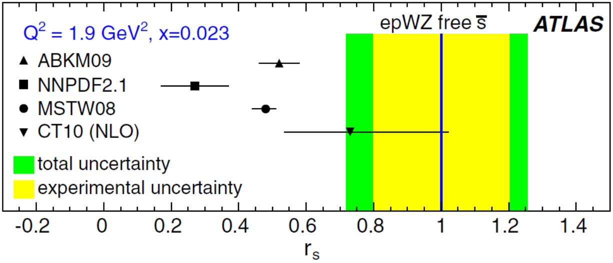
ATLAS strange measurement

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 $x = 0.023$:

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

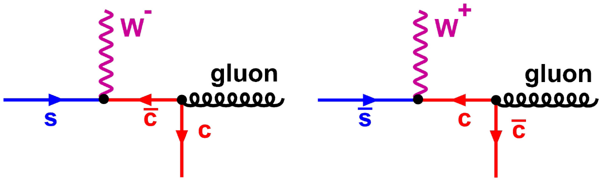


CMS Wc final states measurement

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