Recent developments in the CTEQ-TEA global analysis

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LHC data sets included in CT17pre

245	1505.07024	LHCb Z (W) muon rapidity at 7 TeV(applgrid)
246	1503.00963	LHCb 8 TeV Z rapidity (applgrid);
249	1603.01803	CMS W lepton asymmetry at 8 TeV (applgrid)
250	1511.08039	LHCb Z (W) muon rapidity at 8 TeV(applgrid)
253	1512.02192	ATLAS 7 TeV Z p_T (applgrid)
542	1406.0324	CMS incl. jet at 7 TeV with R=0.7 (fastNLO)
544	1410.8857	ATLAS incl. jet at 7 TeV with R=0.6 (applgrid)
545	1609.05331	CMS incl. jet at 8 TeV with R=0.7 (fastNLO)
565	1511.04716	ATLAS 8 TeV tT p_T diff. distributions (fastNNLO)
567	1511.04716	ATLAS 8 TeV tT m_{tT} diff. distributions (fastNNLO)
573	1703.01630	CMS 8 TeV tT (p_T, y_t) double diff. distributions (fastNNLO)

- Using the new combined HERA c,b production data (arXiv:1804.01019)
- Many new data are included. The included old data continue having impact on global fits and tend to dilute the impact of new data.

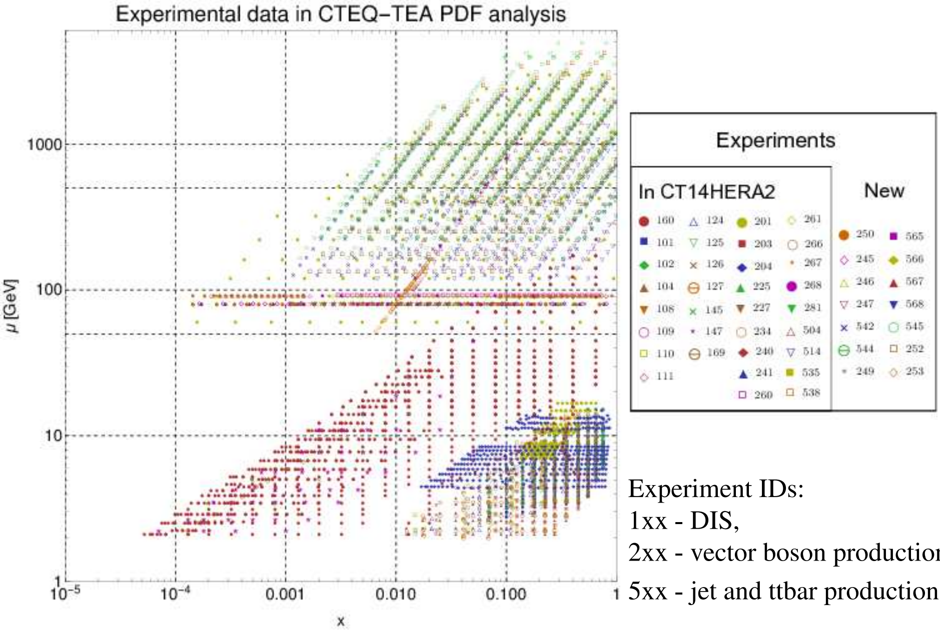
Top Quark Pair differential distributions

Modest effect observed if ttbar data are included together with the Tevatron and LHC jet production data. Its impact on gluon PDF is consistent with jet data, though jet data provide stronger constraint.

We currently include the following data

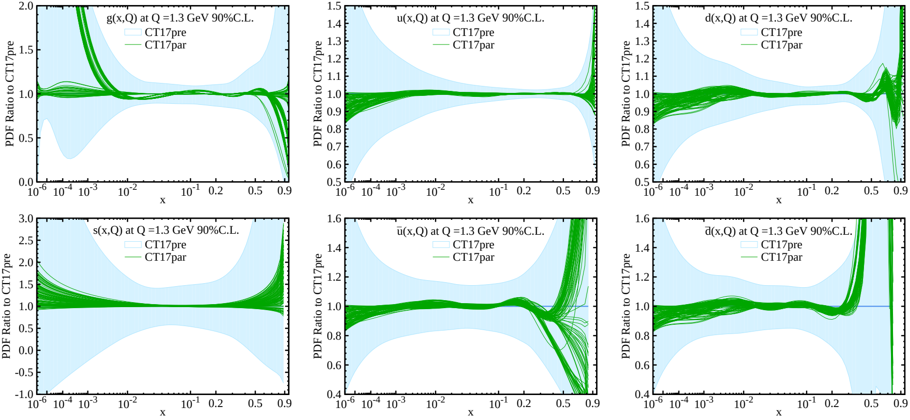
Data	Npts	χ^2/Npts(no fit)	χ^2/Npts
ATLAS 8 TeV abs. $d\sigma/dp_T$	8	0.34	0.33
ATLAS 8 TeV abs. $d\sigma/dm_{t\bar{t}}$	7	0.40	0.45
CMS 8 TeV Nor. $d^2\sigma/dp_T dy_t$	16	1.43	1.40

- Work in progress on performing fits with ATLAS 8TeV (M_{tt}, p_T) combined including the full correlation matrix. This will be used in place of the two separate data sets.
- Cross check with ePump : ATLAS 8TeV (M_{tt}, p_T) has modest impact.
- Work in progress on including independent total cross section measurements from both ATLAS and CMS.



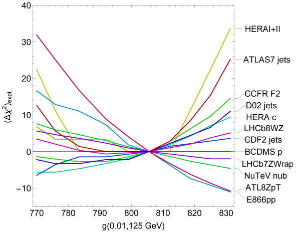
Experiment IDs:
1xx - DIS,
2xx - vector boson production,
5xx - jet and ttbar production

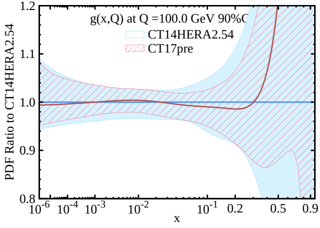
Various non-perturbative parametrization forms have been explored

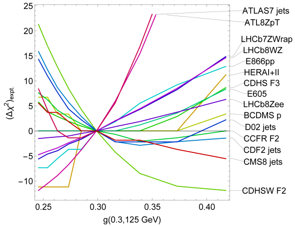


CT17par – sample result of using various non-perturbative parametrization forms.

Preview of CT17pre (g-PDF)

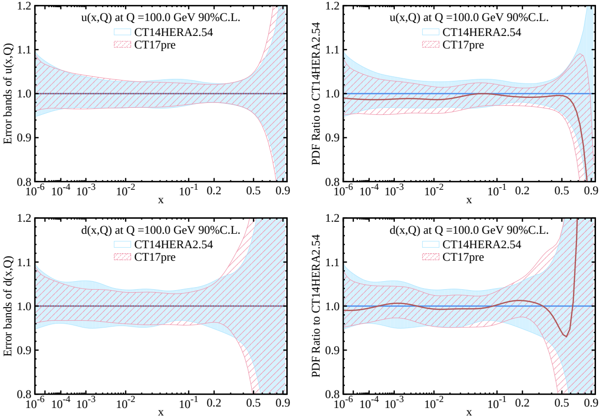






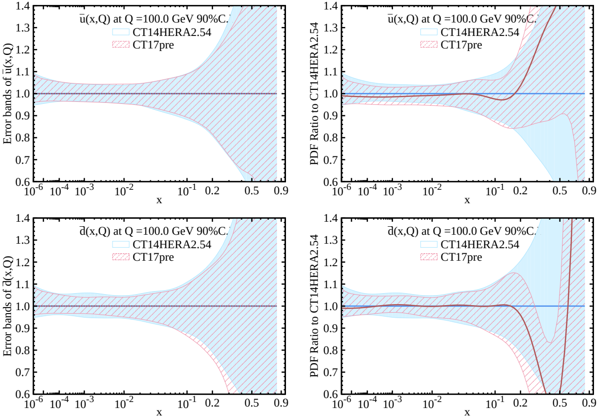
- Competing with the CDHSW F_2 and Tevatron jet data, which perfer larger gluon, the new included ATLAS7 jet and ATLAS8 Z p_T prefer a smaller gluon at x around 0.3.
- For gluon PDF at x around 0.01, new included ATLAS8 Z p_T data prefer a slightly larger gluon.
- The gluon PDF as $x \to 1$ is parametrization form dependent.

Preview of CT17pre
(u-PDF and d-PDF)



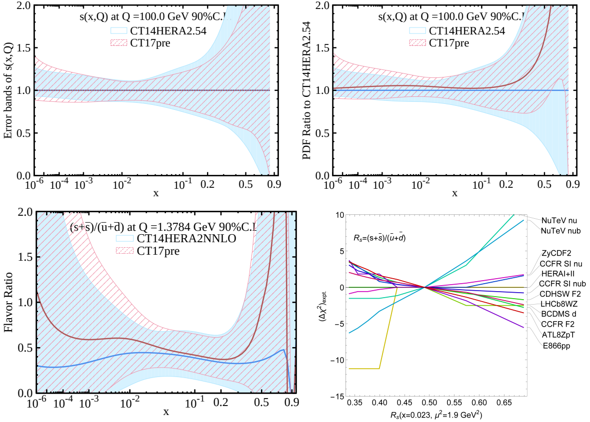
- Some changes on *u* and *d* at small x region and d around 0.2 mainly come from LHCb W and Z rapidity data, at 7 and 8 TeV.

Preview of CT17pre
($\bar{u}$-PDF and $\bar{d}$-PDF)



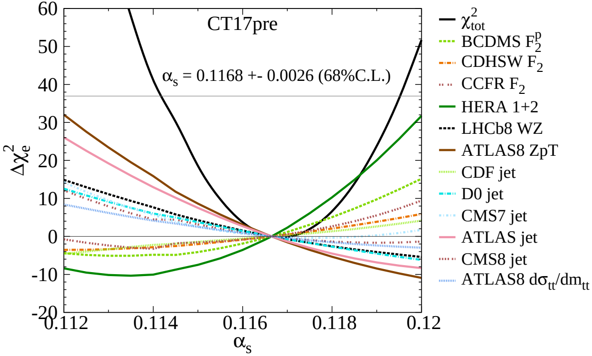
- Similarly, minor changes on $\bar{u}$ and $\bar{d}$ at small x region mainly come from LHCb W and Z rapidity data, at 7 and 8 TeV..
- The behavior of $\bar{u}$ and $\bar{d}$ as $x \to 1$ is parametrization form dependent.

R_s



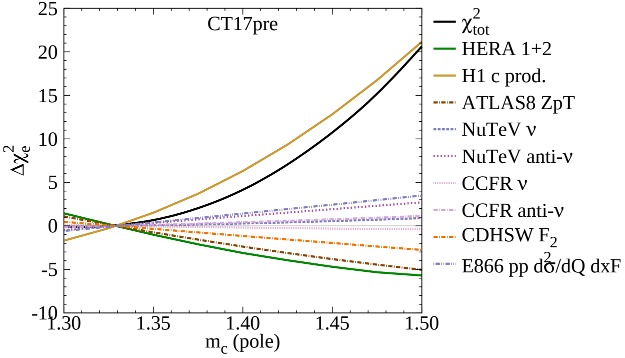
- LHCb W and Z (7,8 TeV) data prefer a larger s-PDF in the small-x region.
- NuTeV dimuon data strongly prefer a smaller Rs value, while the ATLAS8 Z p_T data prefer a slightly larger R_s value.
- R_s(CT17pre)$= \frac{s+\bar{s}}{\bar{u}+\bar{d}} = 0.53 \pm 0.16$ for $x = 0.023$ and $Q^2 = 1.9$ GeV^2.

$\alpha_s(M_z)$



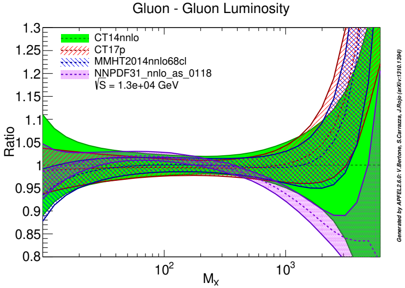
- The fixed target F_2 data and HERA DIS data prefer smaller α_s value.
- The ATLAS 8TeV Z p_T and ATLAS 7 TeV incl. jet data, bring the central value of $\alpha_s(M_z)$ from $0.115^{+0.006}_{-0.004}$ (CT14) to 0.1168 ± 0.0026 (CT17pre).

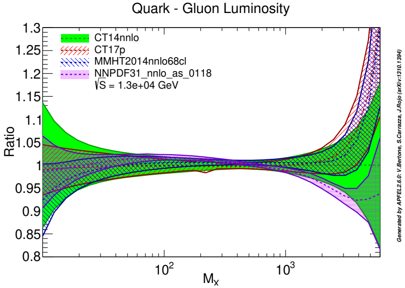
Charm mass m_c(pole)

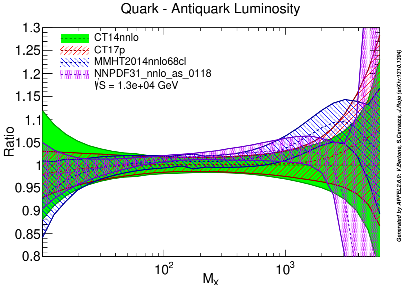


- The HERA charm production data strongly disfavor a large charm quark mass.
- The ATLAS 8 TeV Z p_T data prefer a larger m_c value.

Parton Luminosity

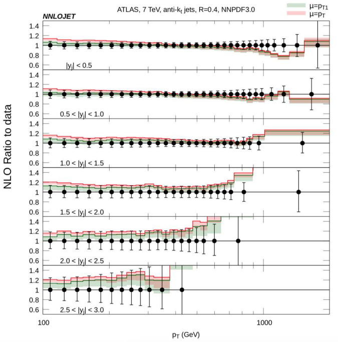


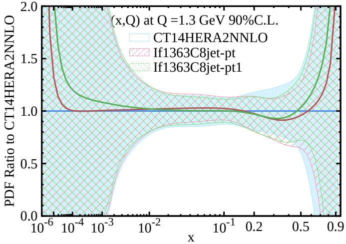


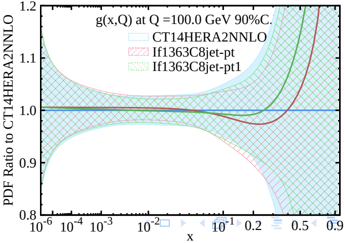


p_T v.s. p_{T1}

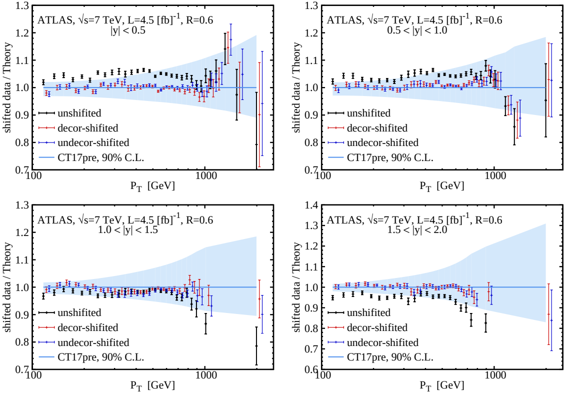
- Non-negligible difference between scale choice of p_T (inclusive jet p_T) and lead jet p_T (p_{T1}) for NNLO predictions
- Nominal choice by CTEQ-TEA is p_T
- In fact, fitted gluon is almost exactly the same in kinematic region where difference is important
- There is a resilience in the global fit due to other data present in this kinematic region (and evolution)







De-correlation for incl. jet



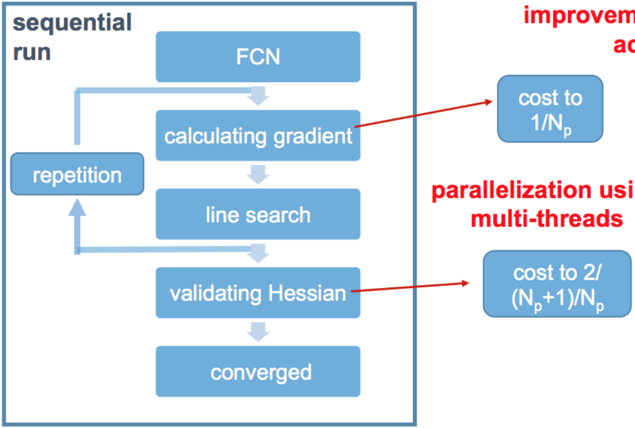
- The corr. error "jes16" and "jes62" of ATLAS 7 TeV incl. jet data are decorrelated according to Table 6 of 1706.03192. Its χ^2/N reduce from 2.34 to 1.68 for CT14HREA2NNLO.
- In the case of CMS 7 TeV incl. jet, the correlated error "JEC2" is decorrelated base on 1410.6765.
- Treatment of systematic error for CMS 8 TeV incl. jet is done as described in

Fitting code changes

upgrade to a parallelized version of the fitting code, through rearrangement of the minimization algorithm, rather than a redistribution of the data sets

MINUIT
variable matric method

after all a factor of 4~5 improvement on speed is achieved!



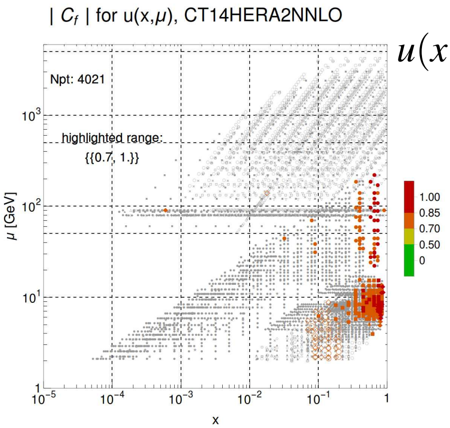
parallelization using multi-threads

PDFsense

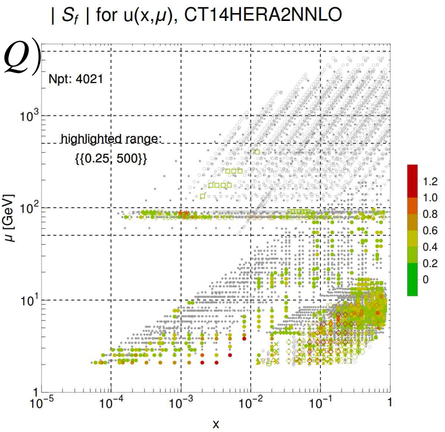
The sensitivity $S_f(x_i, \mu_i)$

$$S_f(x_i,\mu_i) = C_f(x_i,\mu_i)\frac{\Delta r_i}{\sqrt{\frac{\sum_i^N r_i^2}{N}}} = \frac{\vec{\nabla} f(x_i,\mu_i)\cdot\vec{\nabla} r_i}{\Delta f(x_i,\mu_i)\sqrt{\frac{\sum_i^N r_i^2}{N}}}$$

help us to visualize the potential impact on PDF in $x - Q$ plane.

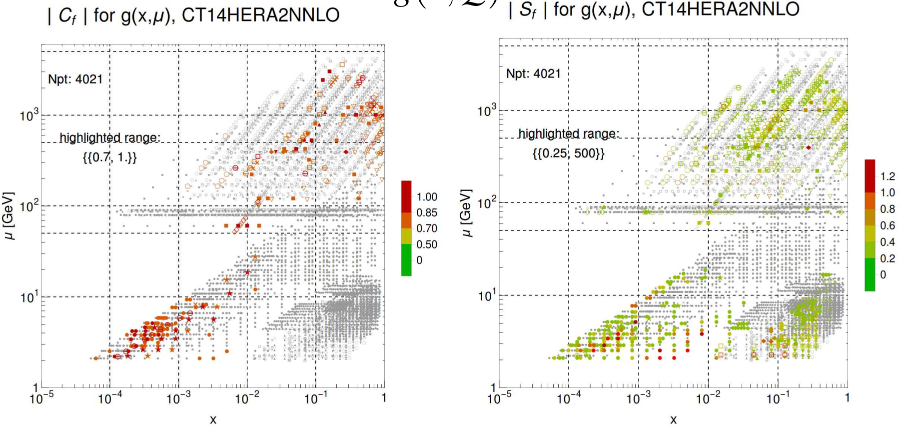


$u(x,Q)$



PDFsense

$$g(x, Q)$$



[Bo-Ting Wang et al., arXiv:1803.02777]

ePump - Error PDF Updating Method Package
Hessian Updating

- Updated Chi-square function :

$$\Delta\chi^2(Z) = \Delta\chi^2_{old}(Z) + (X_i^E - X_i(Z))C_{ij}^{-1}(X_j^E - X_j(Z))$$

Where $\Delta\chi^2_{old}(Z) = T^2 Z^2$.

- Minimize to find new best fit:

$$Z^2_{new} = (1+M)^{-1}A \text{ with } A^\alpha = \frac{1}{T^2}(X_i^E - X_i(0))C_{ij}^{-1}\Delta X_j^\alpha,\ M^{\alpha\beta} = \frac{1}{T^2}\Delta X_i^\alpha C_{ij}^{-1}\Delta X_j^\beta$$

- New best-fit PDF and new error PDF.

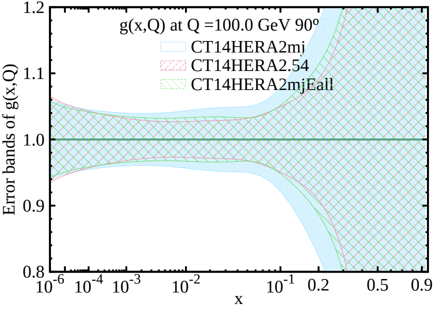
$$f^0_{new} = f^0 + \Delta f \cdot Z,\ f^{\pm(r)} = f^0_{new} \pm \frac{1}{\sqrt{1+\lambda^{(r)}}}\Delta f \cdot U^{(r)}$$

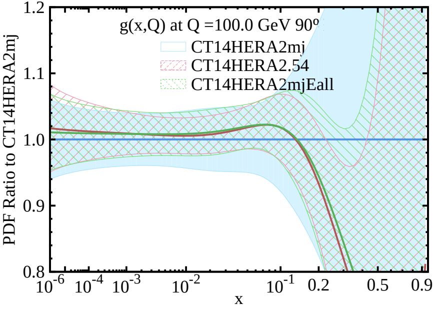
where $\lambda^{(r)}$ and $U^{(r)}$ are the eigenvalues and eigenvectors of matrix M.

[Carl Schmidt et al., arXiv:1806.07950]

Test 1: CT14HERA2 minus Jets

- Remove all CDF, D0, ATLAS 7TeV, CMS TeV jet data from CT14HERA2 and refit → CT14HERA2mj.
- Add back the 4 data sets to CT14HERA2mj by ePump and compare with CT14HERA2.

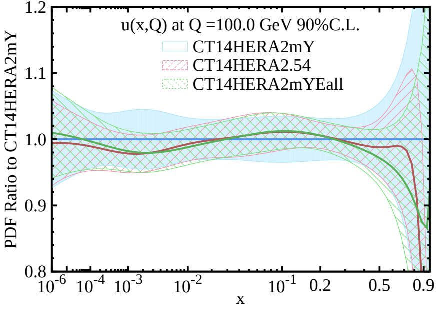




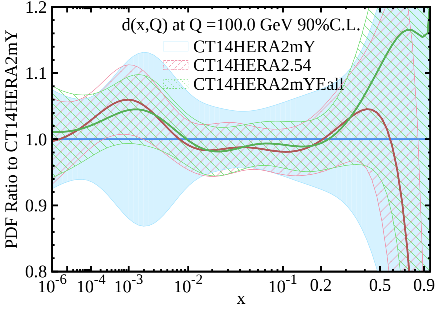
gluon - PDF

Test 2: CT14HERA2 minus Drell-Yan

- Remove 19 Drell-Yan data sets (fixed target exp., Tevatron and LHC) from CT14HERA2 and refit → CT14HERA2mY.
- Add back the 19 data sets to CT14HERA2mY by ePump and compare with CT14HERA2.



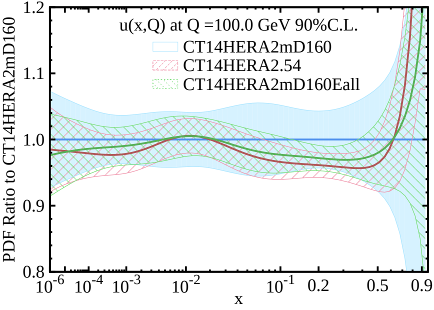
u-PDF



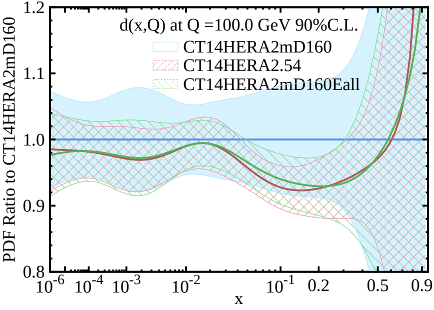
d-PDF

Test 3: CT14HERA2 minus DIS

- Remove 14 DIS data sets (excluding HERA1+2) from CT14HERA2 and refit → CT14HERA2mD160.
- Add back the 14 data sets to CT14HEA2mD160 by ePump and compare with CT14HERA2.



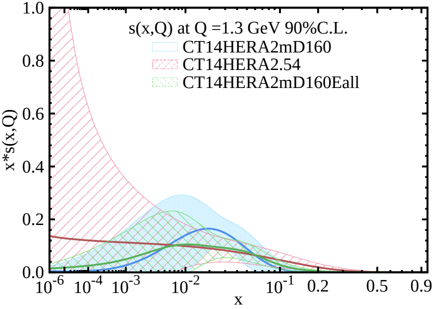
u-PDF



d-PDF

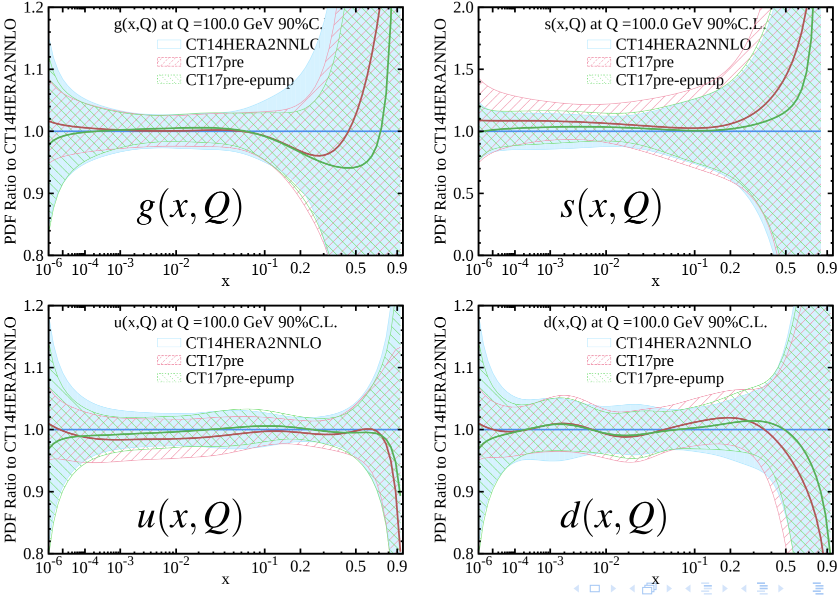
Test 3: CT14HERA2 minus DIS (2)

- Almost all of constraints on s-PDF are from NuTeV and CCFR neutrino dimuon data.



ePump work well in the x region constrained by data.

Adding New Data with ePump



Summary

- We observe some impact on PDFs from ATLAS and CMS incl. jet data, LHCb WZ production and ATLAS 8 TeV Z p_T data.
- Extensive studies on including more data and on non-perturbative parametrization form dependence are still ongoing.
- The **Sensitivity** $S_f(x_i, \mu_i)$ provides an easy way to visualize the potential impact to PDF in $x - Q$ plane (arxiv:1803.02777).
  The **PDFsense**, which can work out the sensitivity, is publicly available at http://metapdf.hepforge.org/PDFSense/
- **UpdatePDFs** function in **ePump** package is a fast and efficient method to estimate the effect of new data on the a current set of best-fit and Hessian error PDFs (arxiv:1806.07950).
  Extensively cross-checked against CT14 global fits
  ePump code is publicly available at http://hep.pa.msu.edu/epump/