PDF4LHC2021 Benchmarking

Thomas Cridge

University College London

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On behalf of PDF4LHC Collaboration

DIS 2021 Workshop

Outline

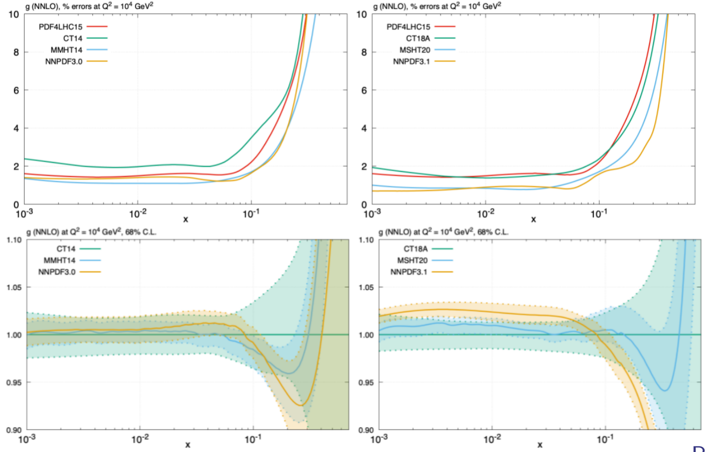
Work undertaken through many useful discussions, many thanks to all members involved.

Introduction - PDF Landscape

- PDF4LHC15 was a 1 year benchmarking exercise of the CT14, MMHT14, NNPDF3.0 PDFs which resulted in a combination set.
- It has now been more than 5 years since the PDF4LHC15 benchmarking exercise.
- Increasing amounts of data coming out of the LHC, greater precision, more channels, more differential $\Rightarrow$ many changes in PDFs.
- In addition there have been theoretical improvements $\Rightarrow$ full NNLO predictions, and methodological improvements (parameterisations, algorithms, etc).
- PDFs now known more accurately and precisely than ever before, but some differences remain $\Rightarrow$ benchmarking needed.
- We consider 3 global PDF fits most recent sets, which include much of the recent datasets: MSHT20, CT18, NNPDF3.1.

Introduction - Changes in PDFs

Gluon



Plots from L. Harland-Lang

- Reduction in PDF uncertainties seen across all 3 groups.
- Central value agreement not as good, some differences emerging.

Note: CT18A shown for ease of comparison, however CT18 is the default set.

PDF Benchmarking: Aim and Approach

- New PDFs CT18, MSHT2020, NNPDF3.1 ⇒ now is a good time to undertake a benchmarking exercise, examine and understand differences ahead of a new PDF4LHC future combination.
- End result of exercise will be a PDF4LHC21 set of PDFs.
- Desire to understand origin of differences:
  - Are they due to variations of experimental input, different theory settings, methodologies? Are these equally valid choices?
- Seek to remove as many differences in input/approach as possible:
  - Common input data - Small subset of datasets ⇒ reduced fits.
  - Common theory settings wherever possible.
  - Examine methodological differences in parallel as much as possible.
- Reduced fits offer *ease of comparison at expense of robustness*.
- To benchmark the reduced fits:
  - Compare PDFs directly to look for areas of difference.
  - Compare χ^2 to determine particular datasets showing differences.
  - Compare cross-sections and point-by-point theory predictions.

PDF Benchmarking: Datasets

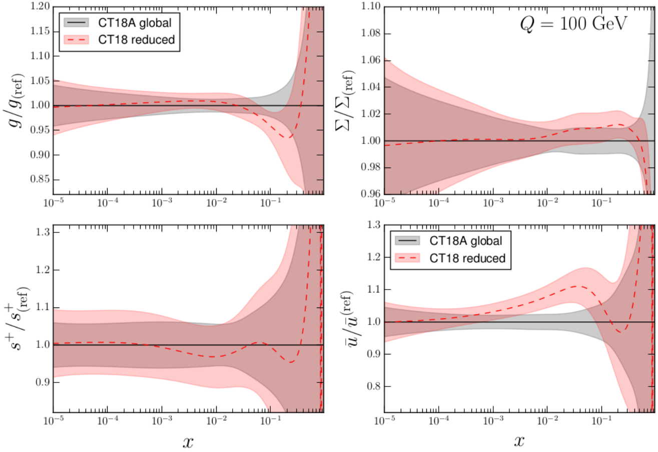
- Chosen subset of datasets fit by all 3 groups in (almost) the same way, list is surprisingly small! Small reduced fit set.
- Take most conservative cuts applied by any group for consistency.
- Ensure enough datasets and a sufficient variety of dataset types are fit to have some (but incomplete) constraints on all PDF flavours.
- Overall list:
  - NMC deuteron to proton ratio in DIS.
  - NuTeV dimuon cross-sections.
  - HERA I+II inclusive cross-sections from DIS.
  - E866 fixed target Drell-Yan ratio pd/pp data.
  - D0 Z rapidity distribution.
  - ATLAS W, Z 7 TeV rapidity distribution, only Z peak and central.
  - CMS 7 TeV W asymmetry.
  - CMS 8 TeV inclusive jet data.
  - LHCb 7, 8 TeV W, Z rapidity distributions.
  - BCDMS proton and deuteron DIS data.

PDF Benchmarking: Theory Settings

- Choose common theory settings for simplicity:
  - Same heavy quark masses ($m_c = 1.4$GeV, $m_b = 4.75$GeV) and $\alpha_S(M_Z^2) = 0.118$.
  - No strangeness asymmetry at input scale: $(s - \bar{s})(Q_0) = 0$.
  - Perturbative charm.
  - Positive definite quark distributions (lack of constraint may allow negative fluctuations).
  - No deuteron or nuclear corrections.
  - Fixed branching ratio for charm hadrons to muons.
  - NNLO corrections for dimuon data.
- Note: These are not the chosen settings for any one group, but rather are a compromise to the least common denominator in each case, *we would not recommend them for a full global fit*.

Reduced Fits: CT18 changes - central values

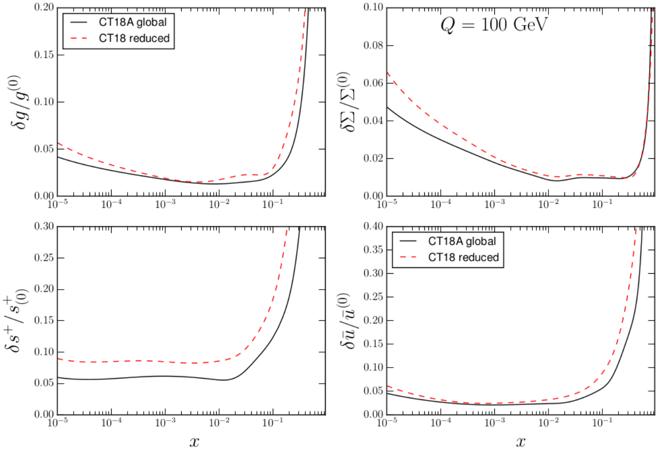
- Current Status:



- Good compatibility with some increase in $\bar{u}$, and change in high x gluon shape. Some changes in flavour decomposition.

Reduced Fits: CT18 changes - uncertainties

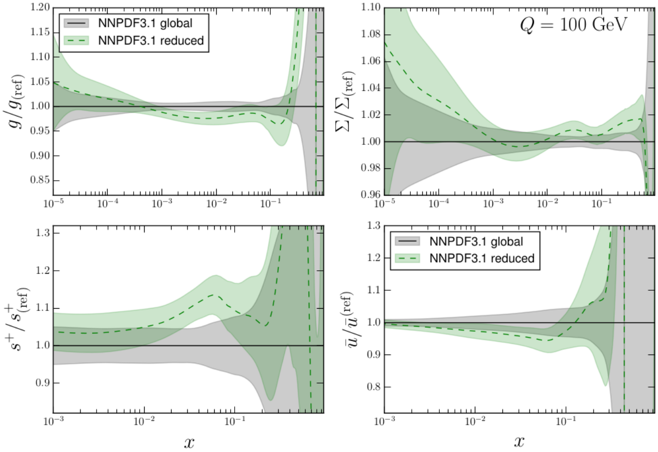
- Current Status:



- Some increase in *nominal* PDF uncertainties, particularly at low x.

Reduced Fits: NNPDF3.1 changes - central values

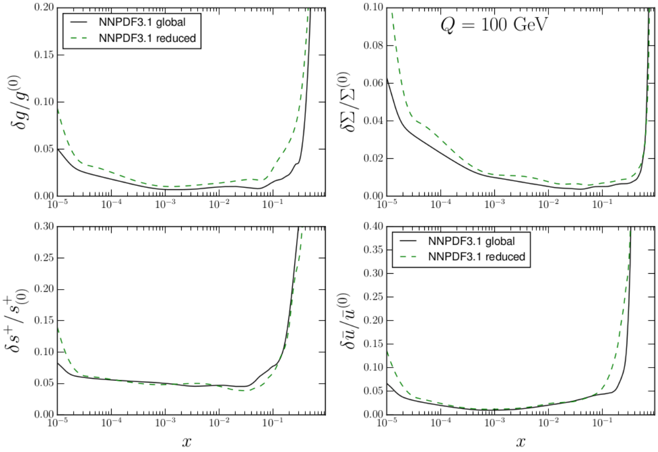
- Current Status:



- Good compatibility, changes in strangeness (see later) and change in large x gluon (removal of top data, addition of CMS 8 TeV jet).

Reduced Fits: NNPDF3.1 changes - uncertainties

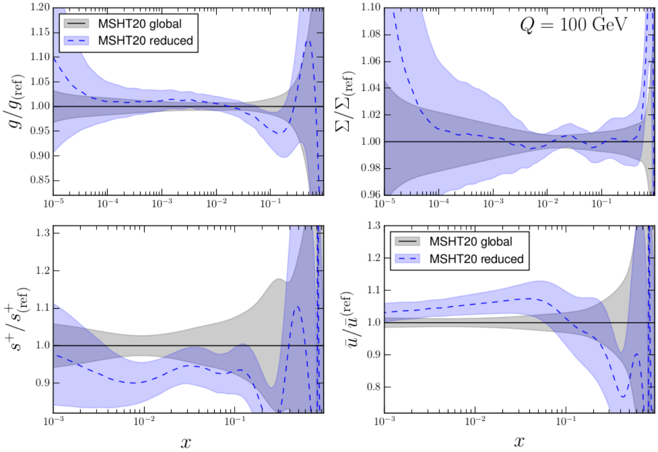
- Current Status:



- Generally slightly increased uncertainties, particularly for the gluon.

Reduced Fits: MSHT20 changes - central values

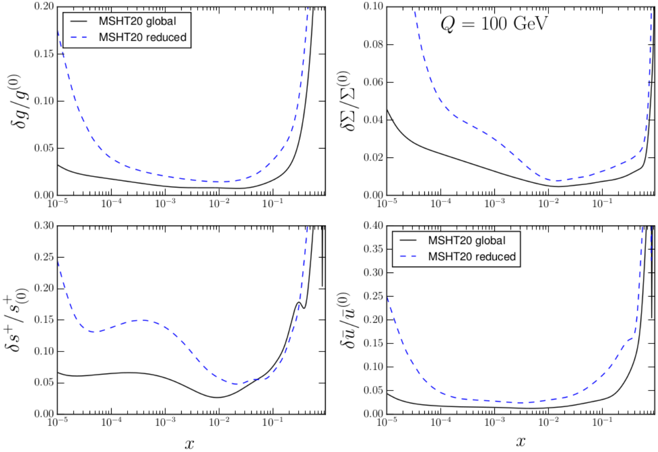
- Current Status:



- Good compatibility, changes in strangeness (removal of 8 TeV ATLAS W, Z data), flavour decomposition and large x gluon.

Reduced Fits: MSHT20 changes - uncertainties

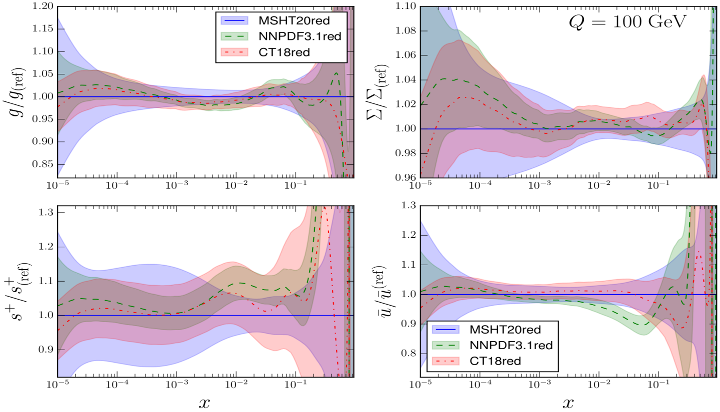
- Current Status:



- General marked increase in uncertainties of reduced fit, particularly outside of regions where there are data.

Reduced Fits PDF Comparison - central values

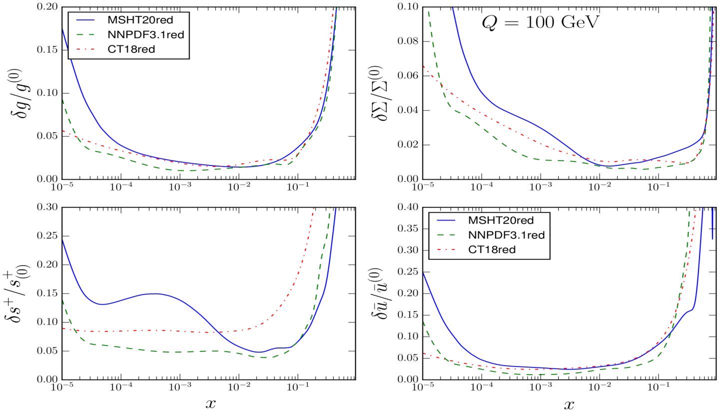
- Current Status:



- Good general agreement within uncertainties, perhaps with the exception of high x flavour decomposition of NNPDF.
- Nonetheless, strangeness and flavour decomposition improved through benchmarking (NuTeV - later). *Note this is without the $t\bar{t}$ added.

Reduced Fits PDF Comparison - uncertainties

- Current Status:



- Similar size uncertainties in data regions, MSHT generally larger errors where constraints lacking in reduced fit.
- Parallel study into differences in uncertainty bands ongoing.

*Note this is without the $t\bar{t}$ added.

PDF4LHC15 in Predictions Datasets χ^2 Comparison

- First make predictions with PDF4LHC15 PDFs, identifies any differences in theory/data between groups with fixed PDFs.
- Current status:

Table from T. Hobbs

ID	Expt.	N_{pt}	χ^2/N_{pt} (CT)	χ^2/N_{pt} (MSHT)	χ^2/N_{pt} (NNPDF)
101	BCDMS F_2^p	329/163††/325†	1.35	1.2	1.51
102	BCDMS F_2^d	246/151††/244†	0.97	1.27	1.24
104	NMC F_2^d/F_2^p	118/117†	0.92	0.93	0.94
124+125	NuTeV $\nu\mu\mu + \bar{\nu}\mu\mu$	38+33	0.75	0.73	0.84
160	HERAI+II	1120	1.27	1.24	1.74
203	E866 $\sigma_{pd}/(2\sigma_{pp})$	15	0.45	0.54	0.59
245+250	LHCb 7TeV& 8TeV W,Z	29+30	1.5	1.34	1.76
246	LHCb 8TeV $Z \to ee$	17	1.35	1.65	1.25
248	ATLAS 7TeV W,Z(2016)	34	6.71	7.46	6.51
260	D0 Z rapidity	28	0.61	0.58	0.61
267	CMS 7TeV eletron A_{ch}	11	0.45	0.5	0.73
269	ATLAS 7TeV W,Z(2011)	30	1.21	1.23	1.31
545	CMS 8TeV incl. jet	185/174††	1.53	1.89	1.78
Total	N_{pt}	—	2263	1991	2256
Total	χ^2/N_{pt}	—	1.31	1.36	1.62

- Similar overall quality of fit for MSHT and CT in χ^2/N, NNPDF significantly larger χ^2/N.
- Differences in some datasets:
  - Difference in NNPDF HERA χ^2 - flavour scheme, disappears in fit.

Reduced Fits Datasets χ^2 Comparison

- Current status:

ID	Expt.	N_{pt}	χ^2/N_{pt} (CT)	χ^2/N_{pt} (MSHT)	χ^2/N_{pt} (NNPDF)
101	BCDMS F_2^p	$329/163^{\dagger\dagger}/325^{\dagger}$	1.06	1.00	1.21
102	BCDMS F_2^d	$246/151^{\dagger\dagger}/244^{\dagger}$	1.06	0.88	1.10
104	NMC F_2^d/F_2^p	$118/117^{\dagger}$	0.93	0.93	0.90
124+125	NuTeV $\nu\mu\mu + \bar{\nu}\mu\mu$	38+33	0.79	0.83	1.22
160	HERAI+II	1120	1.23	1.20	1.22
203	E866 $\sigma_{pd}/(2\sigma_{pp})$	15	1.24	0.80	0.43
245+250	LHCb 7TeV& 8TeV W,Z	29+30	1.15	1.17	1.44
246	LHCb 8TeV $Z \to ee$	17	1.35	1.43	1.57
248	ATLAS 7TeV W,Z(2016)	34	1.96	1.79	2.33
260	D0 Z rapidity	28	0.56	0.58	0.62
267	CMS 7TeV eletron A_{ch}	11	1.47	1.52	0.76
269	ATLAS 7TeV W,Z(2011)	30	1.03	0.93	1.01
545	CMS 8TeV incl. jet	$185/174^{\dagger\dagger}$	1.03	1.39	1.30
Total	N_{pt}	—	2263	1991	2256
Total	χ^2/N_{pt}	—	1.14	1.15	1.20

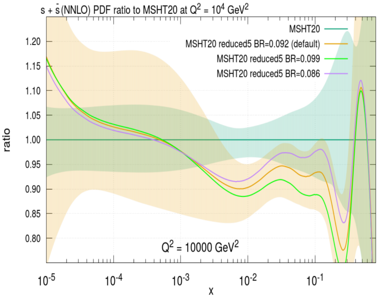
- Similar overall quality of fit in χ^2/N.
- Differences remaining in some datasets:
  - NuTeV agreement improved but difference remains, seen in $s + \bar{s}$.
  - Some potential differences in ATLAS 7 TeV W, Z and LHCb?
  - Some differences in NNPDF fit quality to small datasets.

Table from T. Hobbs

Flavour Decomposition - Strangeness and NuTeV

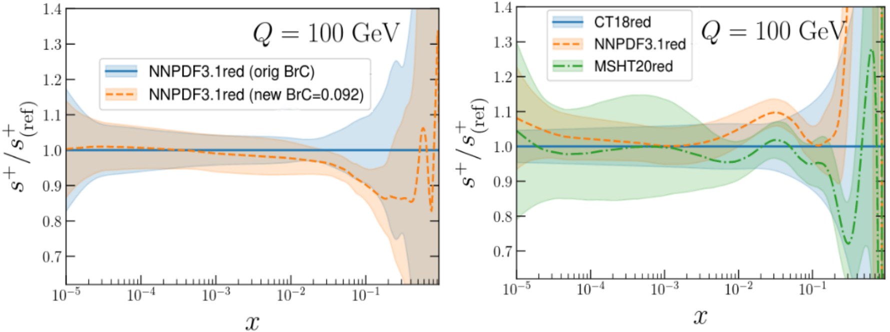
- One of the main differences between the first reduced sets was in the flavour decomposition and strangeness.
- NuTeV dimuon data key driver of this, complicated dataset:
  - Requires knowledge of charm $\rightarrow$ hadrons branching ratio (BR).
  - Non-isoscalar nature of target.
  - Prefers non-zero strangeness asymmetry.
  - Acceptance corrections required.
- BR($c \rightarrow \mu$) anti-correlated with total strangeness, 3 groups have different default values:
  - NNPDF 0.086 ± 0.05
  - MSHT 0.092 ± 0.1 variable.
  - CT 0.099, normalisation uncertainty.
- MSHT20 reduced fit χ^2/N:

Dataset /BR	0.086	0.092	0.099
NuTeV Dimuon	58.8/71	49.6/71	68.5/71
ATLAS 7 TeV W, Z	60.8/34	65.1/34	57.1/34



Flavour Decomposition - Strangeness and NuTeV

- Setting all variables the same in all 3 fits - same Dimuon BR fixed at 0.092, all treat non-isoscalarity, same acceptance corrections.
- NNPDF strangeness reduced as expected, CT strangeness increases.



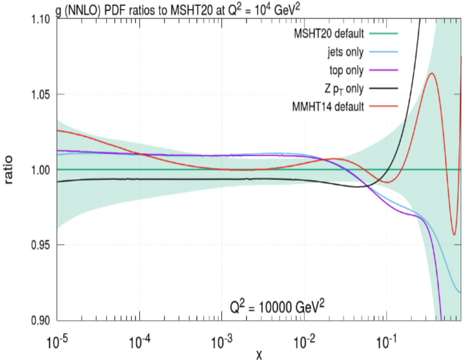
- Better strangeness agreement, certainly in data region, now largely within uncertainties between all 3 groups.
- Also aids reduction in flavour decomposition differences.

Plots from J. Rojo

High x gluon

- High x gluon of interest to both reduced and global fits.

- 3 main datasets play a role here - jet data, top data, Zp_T data, different pulls:
- Not straightforward to fit some of them:
  - Difficulties fitting all bins.
  - Possible tensions.
  - Issue of correlated systematics.



- MSHT, CT, NNPDF observe differences in the relative importance of these datasets and the quality of their individual fits
  - *does the same hold in reduced fits and can we understand this better in this context?*

ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets

- Comes differential in 4 variables with statistical and systematic correlations - $m_{tt}, y_t, y_{tt}, p_t^T$.
- MSHT*, CT+ difficulties fitting all 4 distributions simultaneously.
- MSHT, CT, ATLAS− cannot get good fit to y_t or y_{tt} individually.
- NNPDF however able to fit all 4 distributions well individually †.

Benchmarking:

- Start by adding this to the reduced fit, first check theory predictions for PDF4LHC15 read in (no fitting):
  - Data agree and theory agrees to better than 1%.
  - All groups χ^2 in agreement and follow same pattern:

Distribution/N	MSHT	CT	NNPDF
$p_t^T/8$	3.0	3.1	3.4
$y_t/5$	10.6	10.1	9.5
$y_{tt}/5$	17.6	15.3	16.2
$m_{tt}/7$	4.3	4.2	4.1

  - Differences in global fits likely not from $t\bar{t}$ theory implementations.

* S. Bailey & L.Harland-Lang 1909.10541.
† Czakon et al 1611.08609.
+ Kadir et al 2003.13740.
− ATL-PHYS-PUB-2018-017.

Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

- *What happens when this dataset is added to the reduced fits?*
- Two cases considered - "uncorrelated" (all systematic and statistical correlations between distributions turned off) and "correlated" (including all correlations, produces a very poor fit):

Distribution/N	$p_t^T/8$	$y_t/5$	$y_{tt}/5$	$m_{tt}/7$	Total
MSHT uncorrelated	3.9	8.4	12.5	6.4	31.2
NNPDF uncorrelated	7.2	3.9	5.1	2.5	18.7
CT uncorrelated	3.4	12.9	17.3	6.1	39.7
MSHT correlated	-	-	-	-	130.6
NNPDF correlated	-	-	-	-	122.7
MSHT decorrelated	-	-	-	-	35.3

- MSHT observe usual pattern as in global fits, p_t^T and m_{tt} can be fit but y_t, y_{tt} struggle, although better than in full fit. Awful fit if all correlations included, can fit with parton shower decorrelation.
- CT see usual global fit pattern also, poor fits to rapidities y_t, y_{tt}.
- NNPDF however able to fit rapidity distributions in uncorrelated case, yet correlated case similar to MSHT.

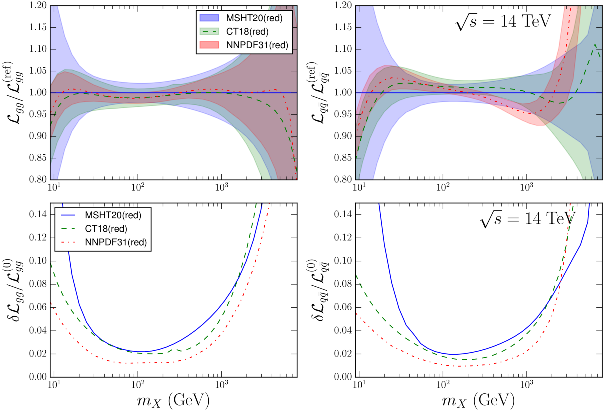
Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

Preliminary!

- Potential explanations lie in other datasets included - tensions?
- NNPDF-4.0, will have much more jet data, sees similar issues as MSHT, CT, ATLAS for this dataset.
- Useful to consider different jet datasets as well as CMS 8 TeV jets.
- Potential further explanation is division of training and validation data in NNPDF - training fraction 50% but for small datasets such a division is unfeasible - all data in training.
- Potentially double-weights small datasets - e.g. ATLAS $t\bar{t}$.
- May also explain NNPDF better fit of E866 DYratio data and CMS W charge asymmetry data (15 and 11 points respectively):

Dataset	MSHT uncorrelated	NNPDF uncorrelated	MSHT uncorrelated double weight
Total	2314.1	2731.4	2313.3
χ^2/N	1.15	1.20	1.15
DYratio (15)	9.5	5.2	9.2
CMS W asym. (11)	14.2	8.2	10.2
p_t^T (8)	3.8	7.2	4.2
y_t (5)	8.4	4.3	5.8
y_{tt} (5)	12.5	5.7	7.4
m_{tt} (7)	6.4	2.4	6.5
$t\bar{t}$ total	31.2	19.6	23.9

Reduced Fits: Current Status Summary*



- Very good agreement in gluon-gluon, quark-quark and quark-gluon luminosities. (Latter two in backup slides).
- Differences in quark-antiquark luminosity, still some flavour decomposition differences, although within MSHT uncertainties.

*Note this is without the $t\bar{t}$ added.

Conclusions and Future Work

- Fitting reduced datasets checks consistency between different groups, provides an environment to analyse origin of differences.
- Good overall consistency is now observed in the reduced fits between the three groups involved, particularly in luminosities.
- Sources of differences in strangeness in reduced fits largely identified, currently analysing high x gluon region of interest.
- Some differences in flavour decomposition and uncertainties of reduced fits remain, mainly outside of data regions.
- Several possibilities for further investigations:
  - Continue analysis of high x gluon differences, consider different jet datasets - and their effects on both the ATLAS $t\bar{t}$ and the gluon.
  - Ongoing effort to consider different uncertainties.
  - Expand reduced fits towards global fits.
- Overall very good progress towards benchmarking the global fits and beyond that eventual combination $\Rightarrow$ PDF4LHC21.

Many thanks to all those involved in this work/discussions, special thanks to T. Hobbs, T.-J. Hou, L. Harland-Lang, P. Nadolsky, E. Nocera, J. Rojo, R. Thorne for providing tables/plots/fits.

Backup Slides

Introduction - New Datasets (MSHT20)

LHCb W, Z data at high rapidity

CMS W+c

Precision DY data

⇒ Flavour Decomposition

LHC Jet, Zp_T, $t\bar{t}$ data

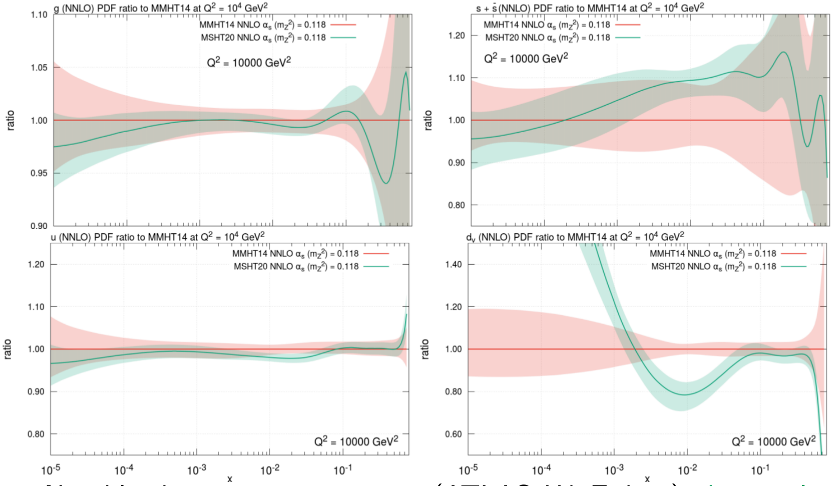
⇒ High x gluon

Data set	Points	NLO χ^2/N_{pts}	NNLO χ^2/N_{pts}
DØ W asymmetry	14	0.94 (2.53)	0.86 (14.7)
$\sigma_{t\bar{t}}$ [93]- [94]	17	1.34 (1.39)	0.85 (0.87)
LHCb 7+8 TeV $W + Z$ [95, 96]	67	1.71 (2.35)	1.48 (1.55)
LHCb 8 TeV $Z \to ee$ [97]	17	2.29 (2.89)	1.54 (1.78)
CMS 8 TeV W [98]	22	1.05 (1.79)	0.58 (1.30)
CMS 7 TeV $W + c$ [99]	10	0.82 (0.85)	0.86 (0.84)
ATLAS 7 TeV jets $R = 0.6$ [18]	140	1.62 (1.59)	1.59 (1.68)
ATLAS 7 TeV $W + Z$ [20]	61	5.00 (7.62)	1.91 (5.58)
CMS 7 TeV jets $R = 0.7$ [100]	158	1.27 (1.32)	1.11 (1.17)
ATLAS 8 TeV Z p_T [75]	104	2.26 (2.31)	1.81 (1.59)
CMS 8 TeV jets $R = 0.7$ [101]	174	1.64 (1.73)	1.50 (1.59)
ATLAS 8 TeV $t\bar{t} \to l + j$ sd [102]	25	1.56 (1.50)	1.02 (1.15)
ATLAS 8 TeV $t\bar{t} \to l^+l^-$ sd [103]	5	0.94 (0.82)	0.68 (1.11)
ATLAS 8 TeV high-mass DY [73]	48	1.79 (1.99)	1.18 (1.26)
ATLAS 8 TeV W^+W^-+ jets [104]	30	1.13 (1.13)	0.60 (0.57)
CMS 8 TeV $(d\sigma_{\bar{t}t}/dp_{T,t}dy_t)/\sigma_{t\bar{t}}$ [105]	15	2.19 (2.20)	1.50 (1.48)
ATLAS 8 TeV W^+W^- [106]	22	3.85 (13.9)	2.61 (5.25)
CMS 2.76 TeV jets [107]	81	1.53 (1.59)	1.27 (1.39)
CMS 8 TeV $\sigma_{\bar{t}t}/dy_t$ [108]	9	1.43 (1.02)	1.47 (2.14)
ATLAS 8 TeV double differential Z [74]	59	2.67 (3.26)	1.45 (5.16)
Total, LHC data in MSHT20	1328	1.79 (2.18)	1.33 (1.77)
Total, non-LHC data in MSHT20	3035	1.13 (1.18)	1.10 (1.18)
Total, all data	4363	1.33 (1.48)	1.17 (1.36)

- Lots of new information constraining PDFs.

MSHT20, 2012.04684

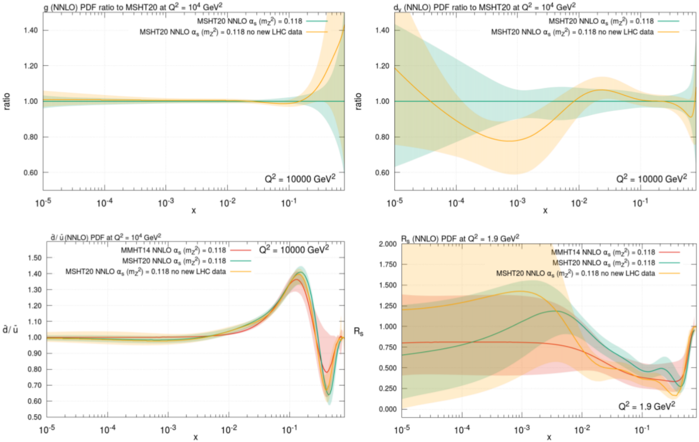
Introduction - Changes in PDFs: MSHT20



- Notable changes in strangeness (ATLAS W, Z data), down valence (new data and parameterisation), gluon (new jets, top, Zp_T data).

More details in R. Thorne's MSHT20 talk.

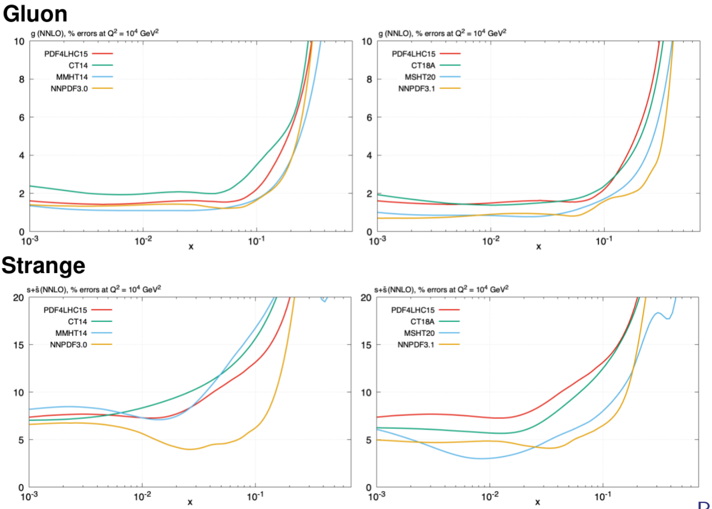
Effect of new LHC data in MSHT20



Main effect on details of flavour, i.e. d_V shape, increase in strange quark for $0.001 < x < 0.3$ and $\bar{d}, \bar{u}$ details, though also partially from parameterisation change. Decrease in high-x gluon.

*MSHT20 2012.04684. Slide from R. Thorne

Introduction - Changes in PDFs: Uncertainties

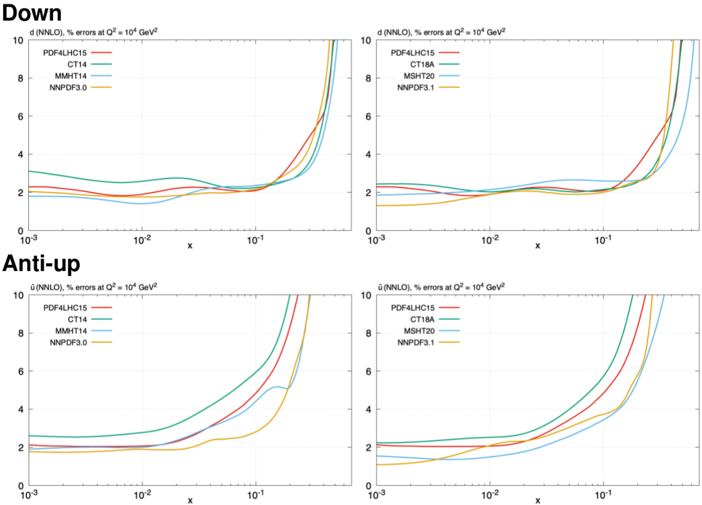


Plots from L. Harland-Lang

- Reduction in PDF uncertainties seen across all 3 groups.

Note: CT18A shown for ease of comparison, however CT18 is the default set.

Introduction - Changes in PDFs: Uncertainties



Plots from L. Harland-Lang

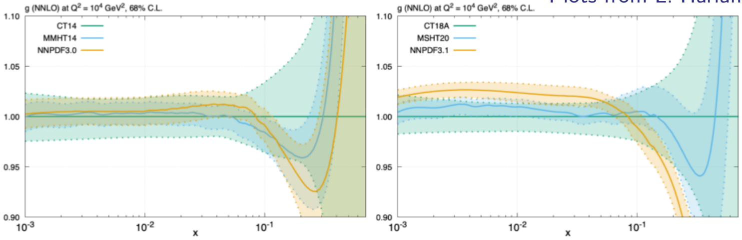
- Reduction in PDF uncertainties seen across all 3 groups.

Note: CT18A shown for ease of comparison, however CT18 is the default set.

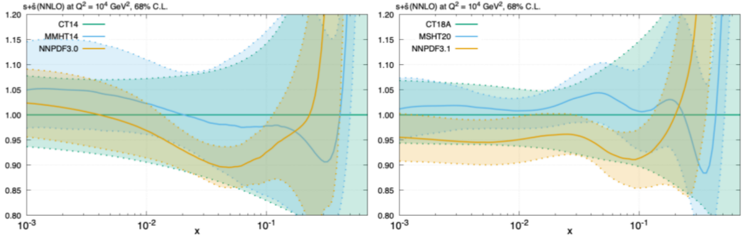
Introduction - Changes in PDFs: Central Values

Gluon

Plots from L. Harland-Lang



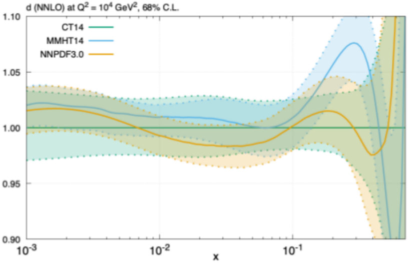
Strange

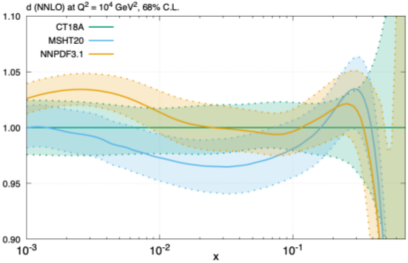


- Central value agreement not as good, some differences emerging.

Introduction - Changes in PDFs: Central Values

Down





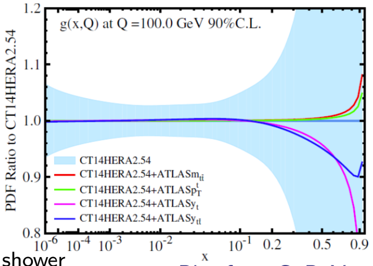
- Central value agreement not as good, some differences emerging.
- In summary:
  - Large amount of progress since the last PDF4LHC combination on experimental, theoretical and methodological fronts.
  - Some differences emerging between the 3 sets.

$\Rightarrow$ now is a good time to undertake a benchmarking exercise ahead of a new PDF4LHC future combination.

Plots from L. Harland-Lang

ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets

- MSHT*, find difficulties fitting all 4 distributions - $m_{tt}, y_t, y_{tt}, p_t^T$ - simultaneously. CT find same and fit only p_t^T and m_{tt} together.
- MSHT, CT+, ATLAS− cannot get good fit to y_t or y_{tt} individually.
- NNPDF however able to fit all 4 distributions well individually †.
- Different pulls observed for m_{tt}, p_t^T relative to y_t, y_{tt}:
- CT, MSHT decorrelate parton shower systematic to obtain reasonable fit to p_t^T and m_{tt} for former or all 4 for latter:



Plot from C.-P. Yuan

p_T	0.53
y_t	3.12
y_{tt}	3.51
M_{tt}	0.70
$p_T + M_{tt}$	5.73
Combined	7.00

Decorrelate parton shower (within and between) →

Distribution	p.s. correlated	p.s. decorrelated
Combined	7.00	1.80
$p_\perp^t + M_{tt}$	5.73	0.66

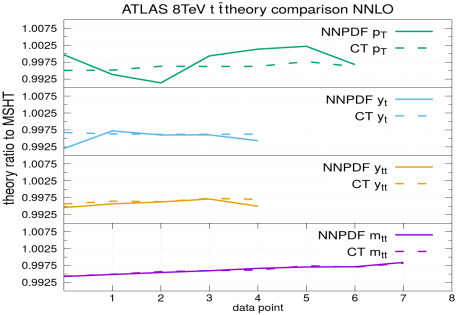
* S. Bailey & L.Harland-Lang 1909.10541.
† Czakon et al 1611.08609.
+ Kadir et al 2003.13740.
− ATL-PHYS-PUB-2018-017.

Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

- Start by adding this to the reduced fit, first check theory predictions for PDF4LHC15 read in (no fitting).
- Differences noted in data treatment due to shifting (MSHT) to centre of asymmetric errors, differences in theory due to inclusion (MSHT) or not (CT,NNPDF) of EW corrections.
- Upon removal of these differences, data agree and theory agrees to better than 1%.
- All groups χ^2 in agreement and follow same pattern:

Distribution/N	MSHT	CT	NNPDF
$p_t^T/8$	3.0	3.1	3.4
$y_t/5$	10.6	10.1	9.5
$y_{tt}/5$	17.6	15.3	16.2
$m_{tt}/7$	4.3	4.2	4.1

- Differences in global fits likely not from $t\bar{t}$ theory implementations.



ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets: MSHT20*

- MSHT observe the rapidity y_t and y_{tt} distributions have very poor fit quality even when fit alone.
- Moreover, fitting the p_t^T and m_{tt} together or all 4 datasets combined results also in a very poor fit:

p_T	0.53
y_t	3.12
y_{tt}	3.51
M_{tt}	0.70
$p_T + M_{tt}$	5.73
Combined	7.00

Decorrelate parton shower (within and between) →

Distribution	p.s. correlated	p.s. decorrelated
Combined	7.00	1.80
$p_\perp^t + M_{tt}$	5.73	0.66

- Tensions exists between shifts required for large systematics of the different distributions, particularly parton shower uncertainty (and ISR/FSR and hard scattering systematics).
- Two-point systematic evaluated using 2 Monte Carlo generators, assuming any correlation factor determined applies fully correlated way across all bins and distributions is a strong assumption.

* S. Bailey & L.Harland-Lang 1909.10541 and MSHT20 2012.04684.

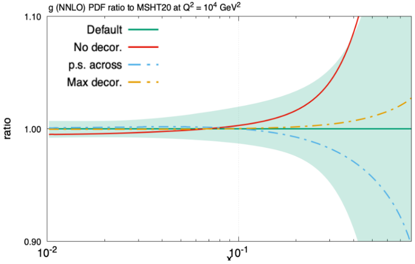
ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets: MSHT20*

- Assumption of full correlation of parton shower systematic can be relaxed, then a resonable fit is possible.
- CT decorrelate this systematic between distributions and fit the p_t^T and m_{tt} combination only by default †.
- MSHT do this decorrelation between all 4 distributions and also split it into 2 sources varying smoothly within each distribution:

$$\beta_i^{(1)} = \cos\left[\pi\left(\frac{y_{tt,i} - y_{tt,\min}}{y_{tt,\max} - y_{tt,\min}}\right)\right]\beta_i^{\rm tot}, \qquad \beta_i^{(2)} = \sin\left[\pi\left(\frac{y_{tt,i} - y_{tt,\min}}{y_{tt,\max} - y_{tt,\min}}\right)\right]\beta_i^{\rm tot}.$$

- Then a reasonable fit is possible, e.g. in MSHT20:

Baseline	No decor.	parton shower across	Max decor.
1.04	6.84	1.69	0.81

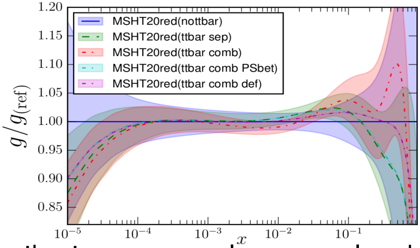


* S. Bailey & L.Harland-Lang 1909.10541 and MSHT20 2012.04684.

† T.-J. Hou et al, CT18 1912.10053.

ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets

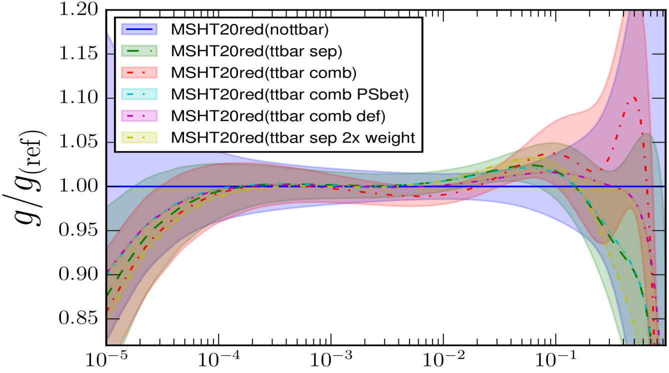
- What effect does the inclusion of this data in the reduced fit have on the gluon?



- Fitting all 4 distributions separately, uncorrelated ⇒ gluon moves down at high x, driven by the rapidity data.
- Applying correlations ⇒ gluon raised and shape altered at high x .
- Decorrelating parton shower between distributions ⇒ reverts the gluon to shape obtained when all 4 separately uncorrelated fitted.
- Additionally decorrelating within distributions ⇒ moves gluon closer to fit without $t\bar{t}$ data as its constraining power is reduced.
- Overall, gluon shape moves in direction of global fit gluon.

ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets gluon

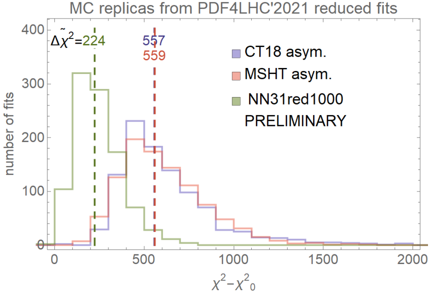
- What effect does the inclusion of this data in the reduced fit have on the gluon?

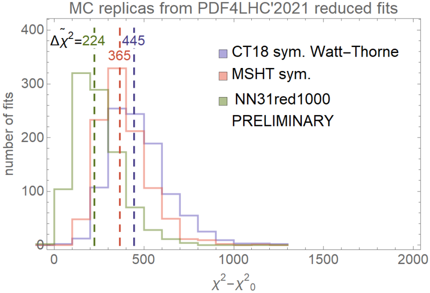


- Double weighting (yellow) pulls gluon further in direction of rapidity pull (lower at high x) as expected.

Reduced Fits χ^2 replica distributions

- As well as the overall PDFs, can analyse χ^2.
- Can use CT/MSHT reduced fit eigenvectors to generate replicas.

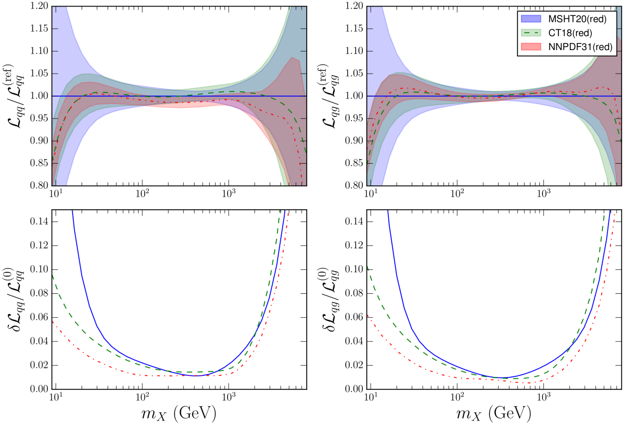




- Overall distributions of reduced fits replicas similar between CT and MSHT, particularly non-symmetrised versions.
- Symmetrised versions in better agreement with NNPDF but still different.
- Some limited qualitative agreement at least for symmetrised case.

Plots from P. Nadolsky

Reduced Fits: Current Status Summary*



- Very good agreement in the gluon-gluon, quark-quark and quark-gluon luminosities.
- Differences in quark-antiquark luminosity, still some flavour decomposition differences, although within MSHT uncertainties.

*Note this is without the $t\bar{t}$ added.

Deuteron and Nuclear Corrections in MSHT20

- Several older DIS datasets use deuteron or heavy nuclear targets.
- Deuteron data required to fully separate u, d at moderate-large x.
- Heavy nuclear data, via C.C. scattering, required for more constraints on flavour decomposition and strange (dimuon data).
- Deuteron correction is 4-parameter prefactor to usual average of p and n:

$$F^d(x,Q^2) = c(x)\left[F^p(x,Q^2)+F^n(x,Q^2)\right]/2,$$

$$\begin{aligned} c(x) &= (1+0.01N)\,[1+0.01c_1\ln^2(x_p/x)], & x<x_p, \\ c(x) &= (1+0.01N)\,[1+0.01c_2\ln^2(x/x_p)+0.01c_3\ln^{20}(x/x_p)], & x>x_p, \end{aligned}$$

- Nuclear correction is prefactor*: *de Florian et al arXiv:1112.6324.

$$f^A(x,Q^2) = R_f(x,Q^2,A)\; f(x,Q^2).$$

- This is multiplied by a 3-parameter modification function to allow penalty-free change in shape and/or normalisation.
- Both deuteron and nuclear corrections prefer modifications of 1%.

More details on all of this in MMHT14 1412.3989, MSHT20 2012.04684.

Future Work

- Several possibilities for further investigations:
  - Continue analysis of high x gluon differences, consider different jet datasets - and their effects on both the ATLAS $t\bar{t}$ and the gluon.
    $\Rightarrow$ Of interest to both reduced fit benchmarking and global fits.
  - Further work perhaps to identify source of flavour decomposition differences?
  - Ongoing effort to consider different uncertainties - CT implementing MSHT dynamic tolerance to analyse reduced fit uncertainty differences. Could repeat for NNPDF by generating Hessian set.
  - Expand reduced fits towards global fits to see how any remaining differences alter.
- Once this is done we can consider a combination of the global fit PDFs $\Rightarrow$ PDF4LHC21.

Conclusions

- Fitting reduced datasets is a good mechanism to check consistency between different groups, provides an environment where any differences in treatment are more relevant to the overall PDFs.
- Allows analysis of origin of differences ⇒ are they due to different, equally valid choices in theoretical, methodological or data approaches.
- Good overall consistency found between the three groups involved, particularly in luminosities.
- Sources of differences in strangeness in reduced fits largely identified, currently analysing high x gluon region of interest.
- Some differences in flavour decomposition and uncertainties remain, mainly outside of data regions.
- Overall very good progress towards benchmarking the global fits and beyond that eventual combination.

Many thanks to all those involved in this work/discussions, special thanks to T. Hobbs, T.-J. Hou, L. Harland-Lang, P. Nadolsky, E. Nocera, J. Rojo, R. Thorne for providing tables/plots/fits.