PDF4LHC2021

Benchmarking of CT18, MSHT20, NNPDF3.1 global PDF fits

Thomas Cridge

University College London

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On behalf of PDF4LHC21 Combination Group

PDF4LHC21 meeting

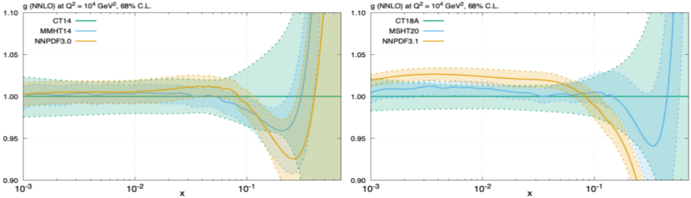
More information in article: TC arXiv:2108.09099 and to come in overall paper.

Introduction - PDF Landscape

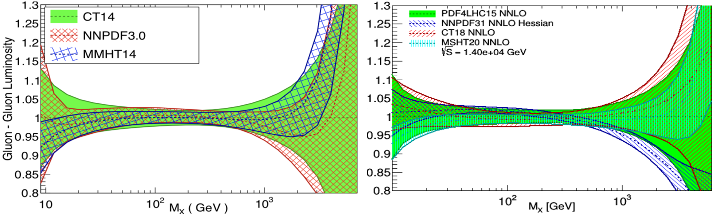
- PDFs of paramount importance for interpretation of LHC physics at Run III and beyond.
- Over the now > 6 years since PDF4LHC15, there have been many changes in the PDFs.
- Substantial new data, greater precision, new channels, more differential.
- Many theoretical improvements $\Rightarrow$ full NNLO predictions, methodological improvements (parameterisations, algorithms, etc).
- PDFs now known more accurately and precisely than ever before, but some differences emerging.
- Need to understand differences ahead of a new PDF4LHC21 combination $\Rightarrow$ benchmarking needed.
- We consider 3 global PDF fits, which include much of the recent datasets: MSHT20, CT18, NNPDF3.1.

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

Introduction - Changes in PDFs



Plots from L. Harland-Lang



Plots from J. Huston

- Reduction in PDF uncertainties seen across all 3 groups.
- Central value agreement not as good, some differences emerging.
- Consequences for combination, spread contributes to uncertainty.
- Motivates understanding differences ⇒ PDF4LHC21 benchmarking.

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

PDF Benchmarking: Aim and Approach

- 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.
- Once differences in reduced fits understood, add datasets of interest, focusing on areas of differences. Finish with full global fits.
- End result: PDF4LHC21 set of PDFs, both a Hessian set and Replica set representing the 3 published PDFs ⇒ Emanuele's talk.

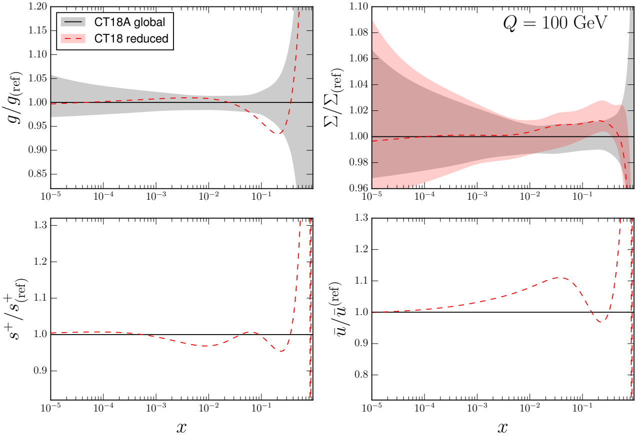
PDF Benchmarking: Datasets

- 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:
  - BCDMS proton and deuteron DIS data.
  - NMC deuteron to proton ratio in DIS.
  - E866 fixed target Drell-Yan ratio pd/pp data.
  - NuTeV dimuon cross-sections.
  - HERA I+II inclusive cross-sections from DIS.
  - 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.

PDF Benchmarking: Theory Settings

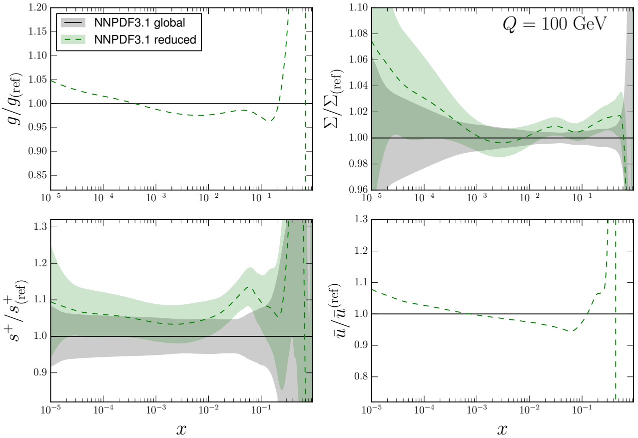
- Choose common theory settings for simplicity:
  - Same heavy quark masses ($m_c = 1.4\text{GeV}$, $m_b = 4.75\text{GeV}$) and strong coupling $\alpha_S(M_Z^2) = 0.118$.
  - No strangeness asymmetry at input scale: $(s - \bar{s})(Q_0) = 0$.
  - Perturbative charm.
  - Positive definite quark distributions (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 group, but rather are a compromise to the least common denominator. Relevant for benchmarking but *we would not recommend them for a global fit*.

Reduced Fits: CT18 reduced fit vs CT18A global fit



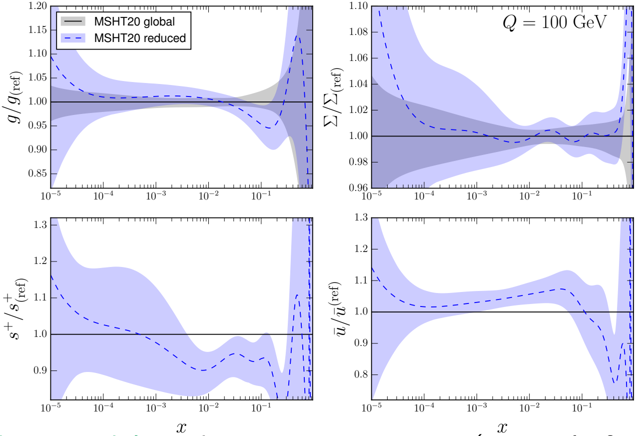
- Good compatibility with change in high x gluon shape and some increase in $\bar{u}$. Some changes in flavour decomposition.
- Some increase in *nominal* PDF uncertainties, particularly at low x.

Reduced Fits: NNPDF reduced fit vs NNPDF3.1 global



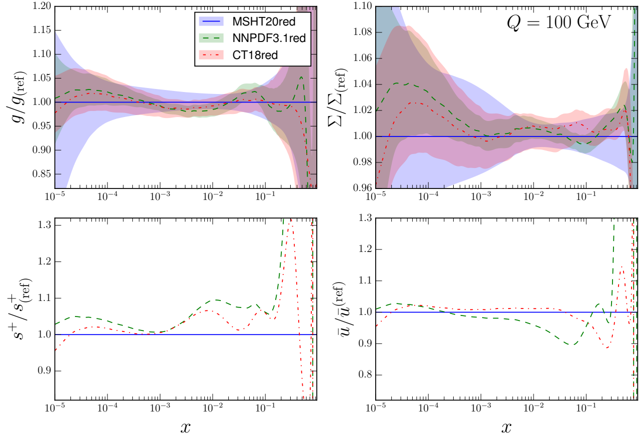
- Good compatibility, changes in strangeness (see later) and change in large x gluon (removal of top data, addition of CMS 8 TeV jet).
- Generally slightly increased uncertainties, particularly at low x.

Reduced Fits: MSHT reduced fit vs MSHT20 global fit



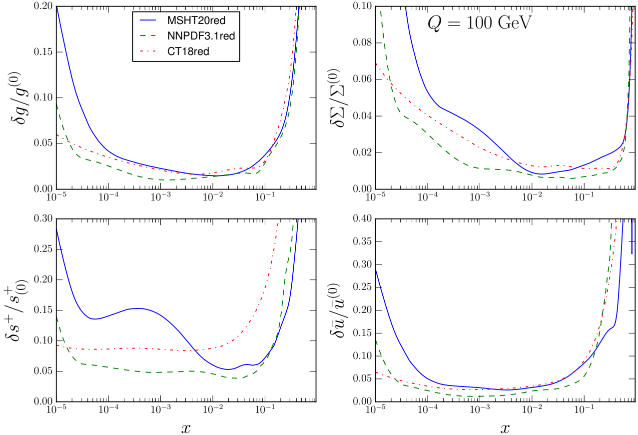
- Good compatibility, changes in strangeness (removal of 8 TeV ATLAS W, Z data), flavour decomposition and large x gluon.
- Marked increase in uncertainties of reduced fit, particularly outside of regions where there are data.

Reduced Fits PDF Comparison - central values



- Very good agreement within uncertainties, including gluon, 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



- 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.

Reduced Fits Datasets χ^2 Comparison

ID	Expt.	N_{pts}	χ^2/N_{pts} (CT)	χ^2/N_{pts} (MSHT)	χ^2/N_{pts} (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 electron 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_{pts}	—	2263	1991	2256
Total	χ^2/N_{pts}	—	1.14	1.15	1.20

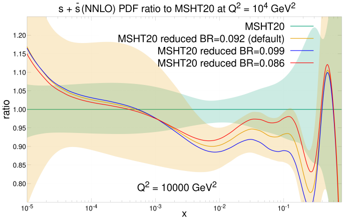
PDF4LHC21 reduced fit dataset χ^2/N_{pts} after fitting, ††MSHT †NNPDF.

- 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 differences in NNPDF fit quality to small datasets, e.g. CMS 7 TeV electron asymmetry.

Table from T. Hobbs

Flavour Decomposition - Strangeness and NuTeV

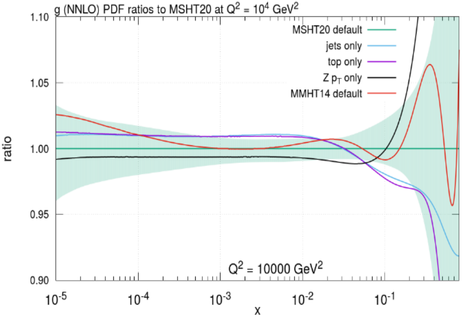
- One of the main differences between the first reduced sets was in the flavour decomposition and strangeness.
- NuTeV dimuon data key driver of this, complicated dataset:
  - Requires knowledge of charm hadron $\rightarrow$ muon branching ratio (BR).
  - Non-isoscalar nature of target.
  - Prefers non-zero strangeness asymmetry.
  - Acceptance corrections required.
- BR($c \rightarrow \mu$) anti-correlated with strangeness, 3 groups have different values:
  - NNPDF 0.087 ± 0.005
  - MSHT 0.092 ± 0.01 variable.
  - CT 0.099, normalisation uncertainty.



- Choose same BR fixed at 0.092 $\Rightarrow$ better strangeness agreement, largely within uncertainties between all 3 groups.
- Also aids reduction in flavour decomposition differences.

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.



- Global fit is a balance between these different pulls.
- 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 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.
- NNPDF3.0 however able to fit all 4 distributions well individually†.

Benchmarking:

- Adding to reduced fit, what happens?

Distribution/N	$p_t^T/8$	$y_t/5$	$y_{tt}/5$	$m_{tt}/7$	Total
MSHT PDF4LHC15 in	3.0	10.6	17.6	4.3	35.5
NNPDF PDF4LHC15 in	3.4	9.5	16.2	4.1	33.2
CT PDF4LHC15 in	3.1	10.1	15.3	4.2	32.7
MSHT fit uncorrelated	3.8	8.4	12.5	6.4	31.2
CT fit uncorrelated	3.4	12.9	17.3	6.1	39.7
NNPDF fit uncorrelated	7.2	3.9	5.1	2.5	18.7
MSHT fit correlated	-	-	-	-	130.6
NNPDF fit correlated	-	-	-	-	122.7
MSHT fit decorrelated	-	-	-	-	35.3

Before Fitting

All groups χ^2 in agreement, same pattern - poor χ^2 for rapidity data.

After Fitting (Uncorrelated)

MSHT and CT see poor fits to rapidities y_t, y_{tt} but NNPDF see good fits to rapidities, as in global fits.

After Fitting (Correlated)

MSHT and NNPDF both see very poor fit to all 4 distributions with correlations, as in global fits.

- Same behaviour as in global fits after fitting....

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

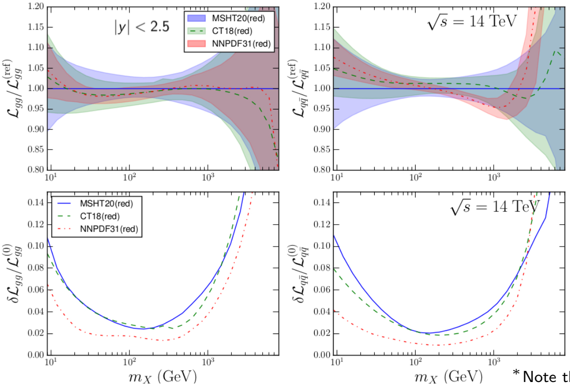
Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

- How can we explain these differences in global and reduced fits?
- Global fits have different fit environments - different weights and other datasets included, tensions may affect fit quality for this dataset:
  - NNPDF3.0 had little jet data - perhaps tensions cause issues in y_t, y_{tt}. NNPDF4.0 sees similar behaviour to other groups.
  - NNPDF reduced fit up-weights this dataset by putting all data in training (as small dataset) - perhaps up-weighting causes difference.
- Investigate weights and tensions in reduced fit environment:

Dataset (N)	MSHT reduced (default CMS8j)	NNPDF reduced (default CMS8j)	MSHT reduced (CMS7j)	MSHT reduced (AT7j)	MSHT reduced (no jets)	MSHT reduced (CMS8j, double weight $t\bar{t}$)
χ^2/N	1.15	1.20	1.11	1.17	1.12	1.15
p_t^T (8)	3.8	7.2	4.0	4.6	4.5	4.2
y_t (5)	8.4	4.3	6.4	5.5	5.2	5.8
y_{tt} (5)	12.5	5.7	7.2	5.2	6.6	7.4
m_{tt} (7)	6.4	2.4	6.4	6.4	7.4	6.5
$t\bar{t}$ total	31.2	19.6	24.0	21.6	23.8	23.9

- Weights and tensions with other datasets notably affect fit quality, removing these differences $\Rightarrow$ similar behaviour can be observed.

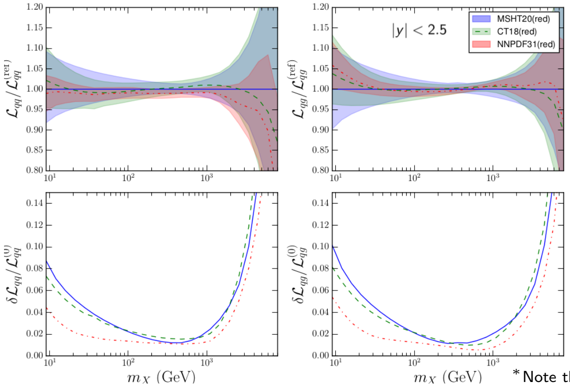
Reduced Fits: Luminosity comparison



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

- Very good agreement in the luminosities across gg, qq, qg, $q\bar{q}$.
- Gluon-gluon luminosity agreement across entire m_X range.
- Differences in uncertainties, particularly at low masses and in gg.
- Same data and theory settings → consistent PDFs. Reduced fits well understood, benchmarking successful!

Reduced Fits: Luminosity Comparison



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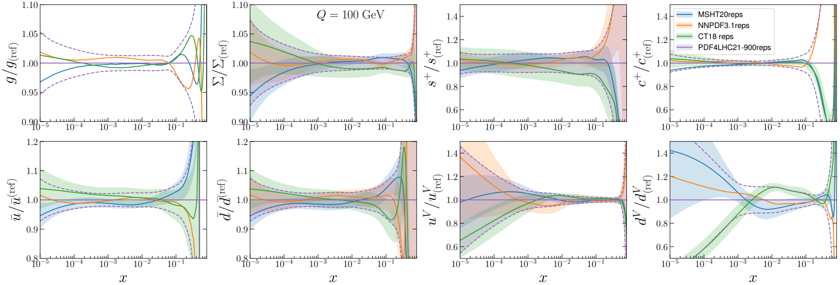
- Same data and theory settings → consistent PDFs. Reduced fits well understood, benchmarking successful!

Global Fits Comparison:

- Expand to global fits ⇒ differences then represent genuine and valid differences in choices, assumptions and methodology.

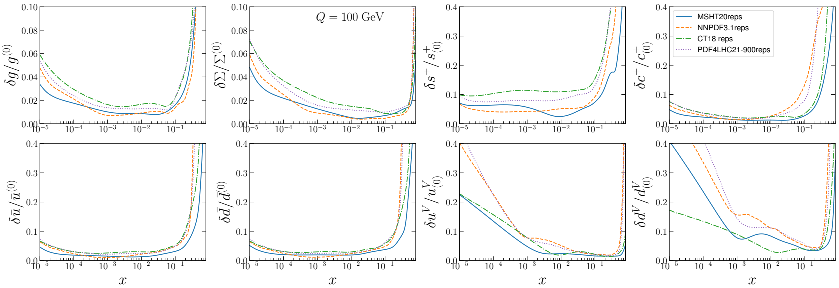


- Good consistency at level of global fits, gluon in good agreement across most of x range.
- See expected differences in high x gluon, in strangeness and charm. Some difference in d_V.
- Consistent within *indicative* PDF4LHC21 combination uncertainties.

*Global fits have slight modifications, more information on this in Emanuele's talk.

Global Fits Uncertainty Comparison:

- Compare uncertainties of global fits*.



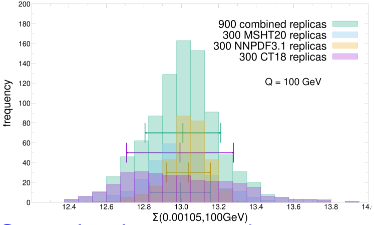
- Good general agreement with differences largely in extreme regions.
- Gluon uncertainty agrees in MSHT and NNPDF, larger in CT.
- Strangeness/Charm uncertainty higher in CT/NNPDF, as expected.
- Up and down antiquark uncertainty in excellent agreement.
- Agreement in up valence, some differences in down valence.
- Compare also with *indicative* combination uncertainties.

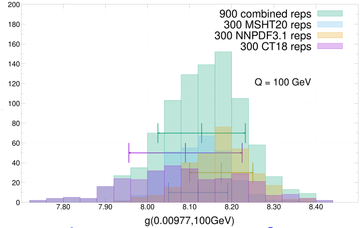
*Global fits have slight modifications, more information on this in Emanuele's talk.

Global Fits Specific Comparisons†:

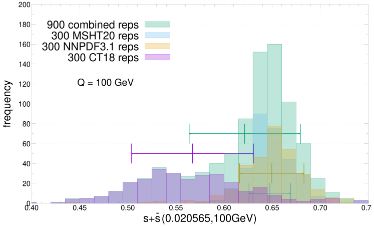
† More in Emanuele's talk on details of combination, here just *indicative*.

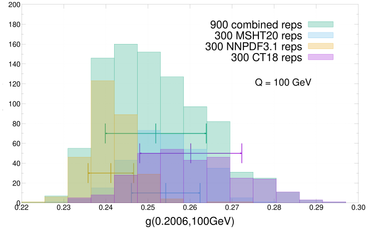
- Central value is average of those of the 3 global fits* input.
- Central values agree closely ⇒ uncertainty is average of 3 groups:





- Central values spread ⇒ uncertainty has component from spread.

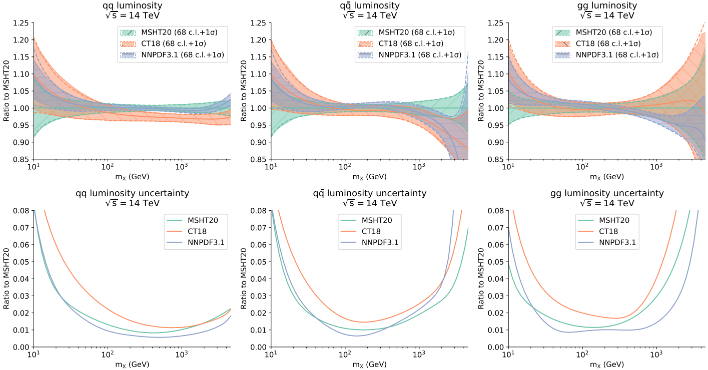




*Global fits have slight modifications, more information on this in Emanuele's talk.

Global Fits Luminosities Comparisons:

- Compare global fits* at the level of the parton-parton luminosities:



Plots from E. Nocera

- Very good agreement for all m_X for qq, $q\bar{q}$, gg luminosities.
- Exception is CT18 slightly lower for qq for $m_X \gtrsim 100 GeV$.
- Differences in uncertainties reflect differences in methodology and data used.

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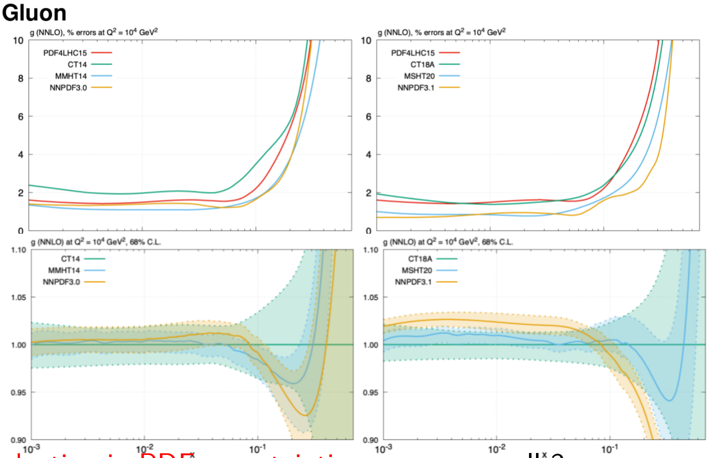
Conclusions

- New data, theoretical improvements, PDF methodological improvements have meant substantial changes since PDF4LHC15.
- We have performed a benchmarking exercise of the 3 global fit PDF groups sets: MSHT20, CT18, NNPDF3.1.
- Based on comparing "Reduced Fits" ⇒ very good consistency is now observed between the three groups, particularly in luminosities.
- Good consistency remains at level of global fits over significant majority of x and PDFs.
- Remaining differences observed are expected from dataset and other choices ⇒ uncertainty contribution from spread accurately reflects PDF differences ⇒ conservative uncertainty estimate.
- End result: Proceed with combination to obtain PDF4LHC21 combination set of PDFs with central PDFs as average of three groups and conservative uncertainty estimates ⇒ Emanuele's talk!

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 - Changes in PDFs



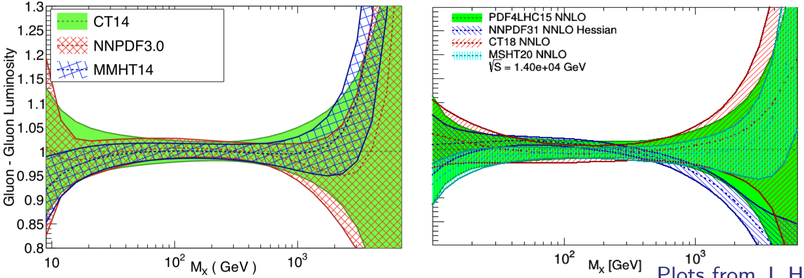
- Reduction in PDF uncertainties seen across all 3 groups.
- Central value agreement not as good, some differences emerging.

Plots from L. Harland-Lang

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

Introduction - Changes in PDFs

N.B. Different baseline for ratio in two plots and different colours.



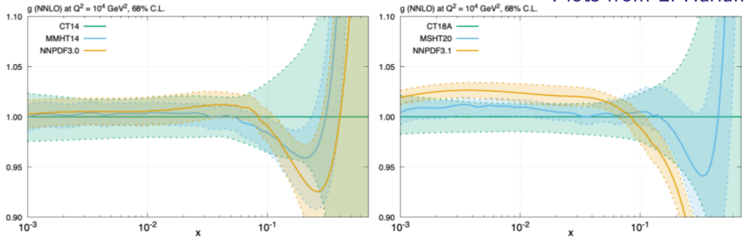
Plots from J. Huston

- Central value spread effects gluon-gluon luminosity.
- If these were to be combined à la PDF4LHC15, there will be some contribution to uncertainty from spread as well as the uncertainties.
- Motivates understanding these differences and their origin $\Rightarrow$ PDF4LHC21 benchmarking.
- New PDFs CT18, MSHT20, NNPDF3.1 $\Rightarrow$ now is a good time to undertake a benchmarking exercise, ahead of new $\Rightarrow$ PDF4LHC21 combination - feedback on what is ultimately provided is welcome!

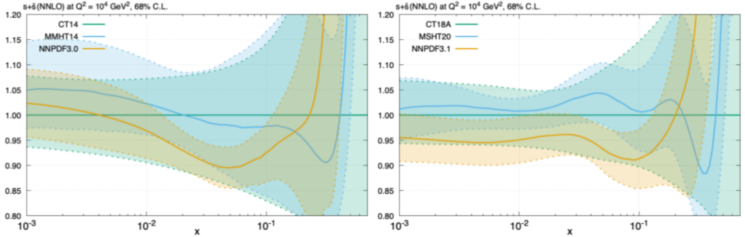
Introduction - Changes in PDFs: Central Values

Gluon

Plots from L. Harland-Lang



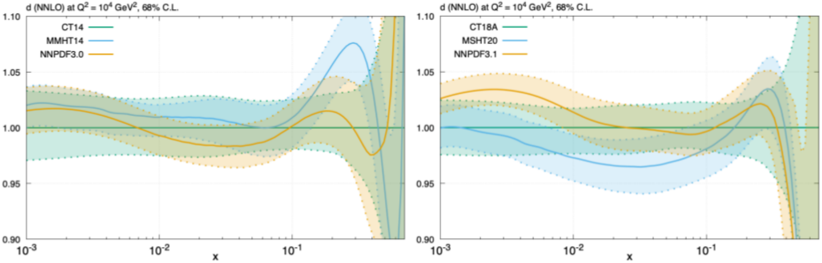
Strange



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

Introduction - Changes in PDFs: Central Values

Down



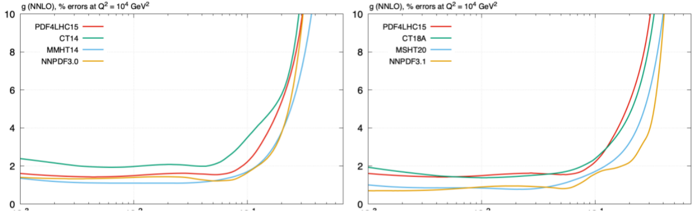
- Central value agreement not as good, some differences emerging.
- In summary:
  - Large amount of progress since the last PDF4LHC combination on experimental, theoretical and methodological fronts.
  - Some differences emerging between the 3 sets.

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

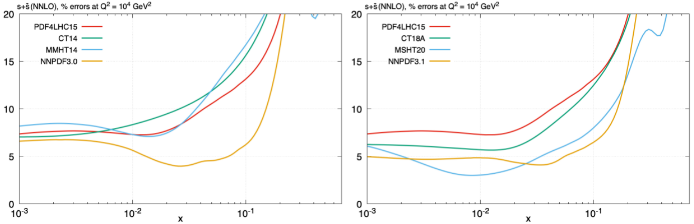
Plots from L. Harland-Lang

Introduction - Changes in PDFs: Uncertainties

Gluon



Strange



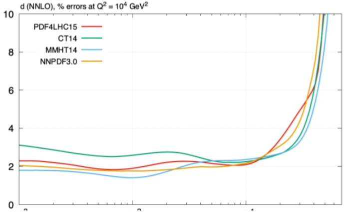
- Reduction in PDF uncertainties seen across all 3 groups.

Plots from L. Harland-Lang

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

Introduction - Changes in PDFs: Uncertainties

Down



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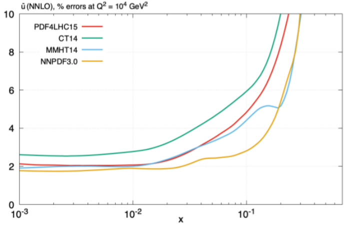

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Plots from L. Harland-Lang

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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

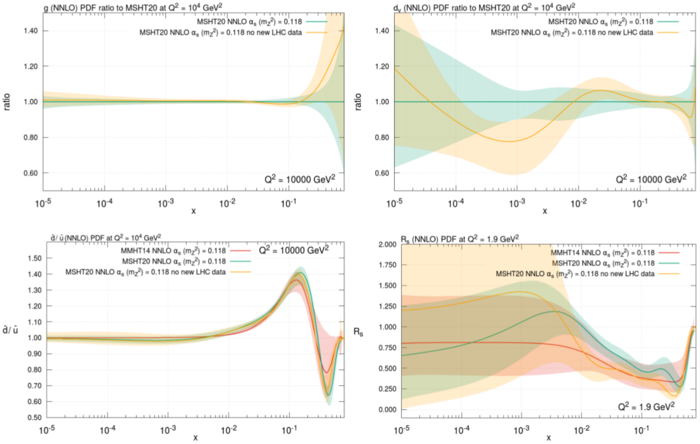
⇒ High x gluon

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 $(d\sigma_{t\bar{t}}/dp_{T,t}dy_t)/\sigma_{t\bar{t}}$ [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 $\sigma_{t\bar{t}}/dy_t$ [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

Effect of new LHC data in MSHT20

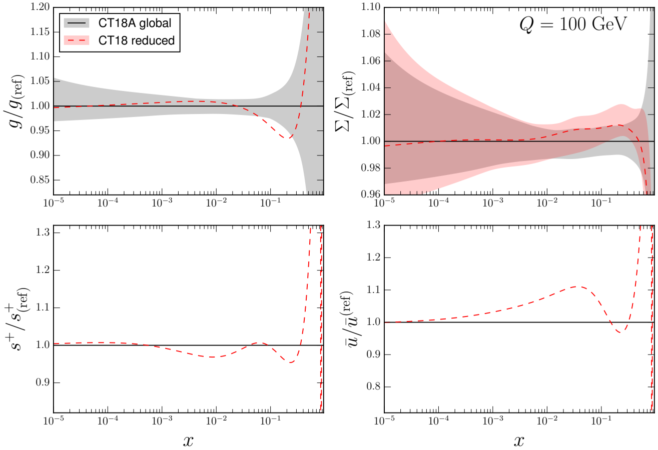


Main effect on details of flavour, i.e. d_V shape, increase in strange quark for $0.001 < x < 0.3$ and $\bar{d}, \bar{u}$ details, though also partially from parameterisation change. Decrease in high-x gluon.

*MSHT20 2012.04684. Slide from R. Thorne

Reduced Fits: CT18 changes - central values

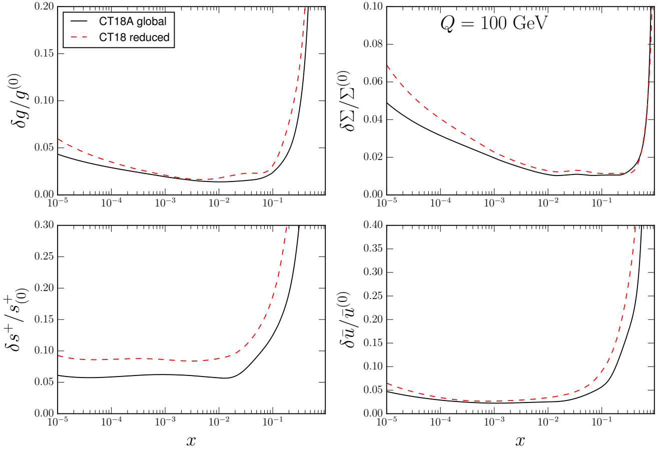
- Current Status:



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

Reduced Fits: CT18 changes - uncertainties

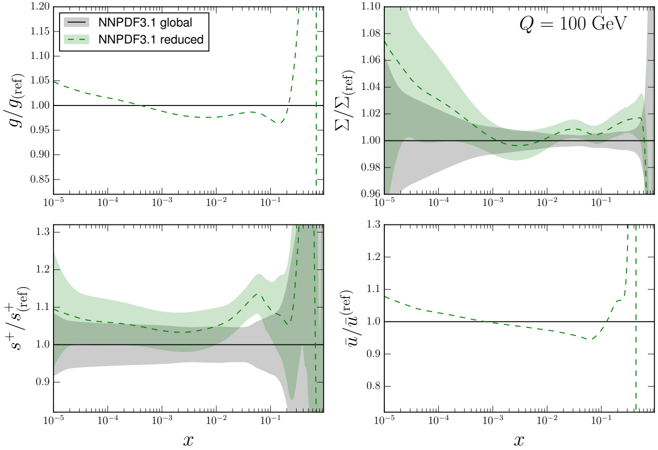
- Current Status:



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

Reduced Fits: NNPDF3.1 changes - central values

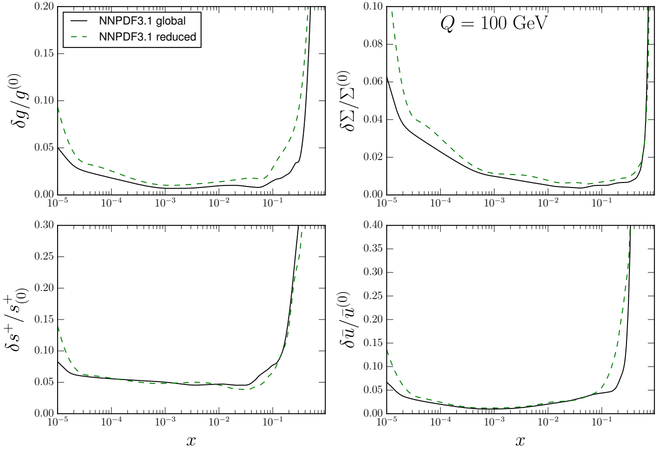
- Current Status:



- 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

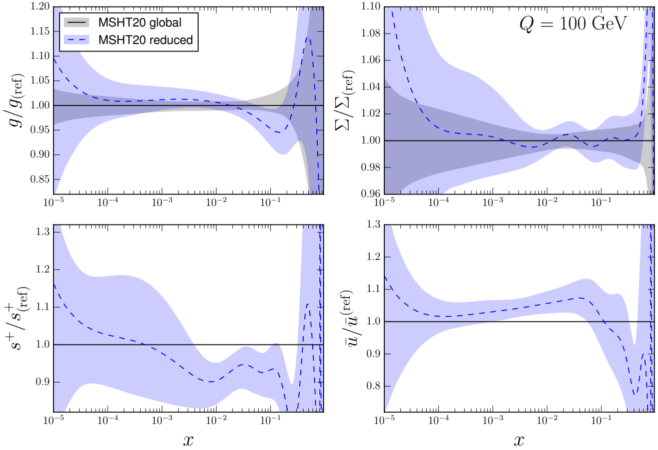
- Current Status:



- Generally slightly increased uncertainties, particularly for the gluon.

Reduced Fits: MSHT20 changes - central values

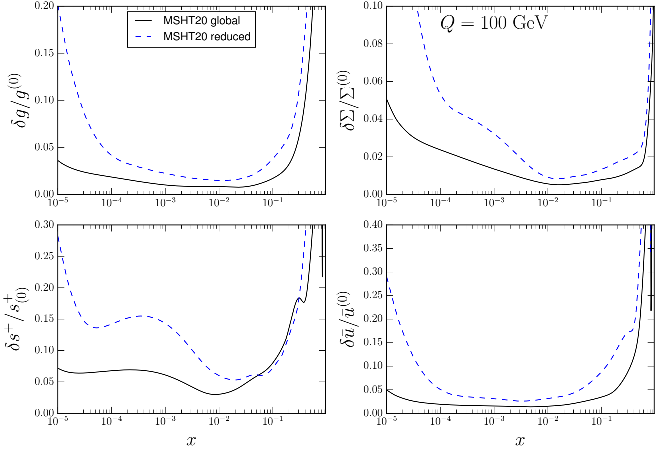
- Current Status:



- 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.

PDF4LHC15 in Predictions Datasets χ^2 Comparison

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

ID	Expt.	N_{pt}	χ^2/N_{pt} (CT)	χ^2/N_{pt} (MSHT)	χ^2/N_{pt} (NNPDF)
101	BCDMS F_2^p	$329/163^{\dagger\dagger}/325^{\dagger}$	1.35	1.2	1.51
102	BCDMS F_2^d	$246/151^{\dagger\dagger}/244^{\dagger}$	0.97	1.27	1.24
104	NMC F_2^d/F_2^p	$118/117^{\dagger}$	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 electron 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	$185/174^{\dagger\dagger}$	1.53	1.89	1.78
Total	N_{pt}	—	2263	1991	2256
Total	χ^2/N_{pt}	—	1.31	1.36	1.62

PDF4LHC21 reduced fit dataset χ^2/N_{pt} with PDF4LHC15 PDF inputs, i.e. before fitting, ††MSHT †NNPDF.

- 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.

Table from T. Hobbs

Reduced Fits Datasets χ^2 Comparison

ID	Expt.	N_{pts}	χ^2/N_{pts} (CT)	χ^2/N_{pts} (MSHT)	χ^2/N_{pts} (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 electron 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_{pts}	—	2263	1991	2256
Total	χ^2/N_{pts}	—	1.14	1.15	1.20

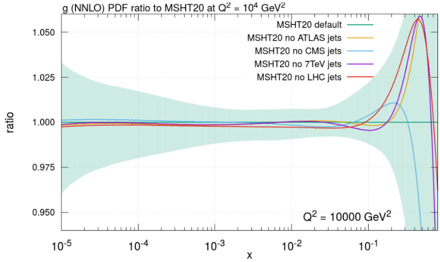
PDF4LHC21 reduced fit dataset χ^2/N_{pts} after fitting, ††MSHT †NNPDF.

- 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 differences in NNPDF fit quality to small datasets, e.g. CMS 7 TeV electron asymmetry.

Table from T. Hobbs

High x gluon - Jet tensions

- Not only tensions between different dataset types at high x, also tensions within dataset types, e.g. between different jet measurements.
- ATLAS 7 TeV jets pulls gluon down at high x, whereas CMS jets (mainly 8 TeV) pull gluon up.
- Global fit is a balance between these different pulls and those of Zp_T, $t\bar{t}$ datasets here.



† MSHT20, TC, S. Bailey, L. Harland-Lang, A. Martin, R. Thorne 2012.04684

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.
- NNPDF3.0 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):

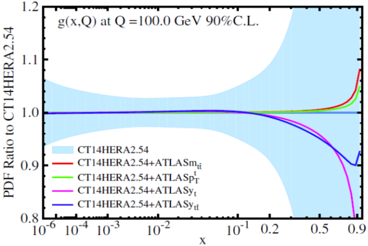
Distribution/N	$p_t^T/8$	$y_t/5$	$y_{tt}/5$	$m_{tt}/7$	Total
MSHT uncorrelated	3.8	8.4	12.5	6.4	31.2
NNPDF uncorrelated	7.2	3.9	5.1	2.5	18.7
CT uncorrelated	3.4	12.9	17.3	6.1	39.7
MSHT correlated	-	-	-	-	130.6
NNPDF correlated	-	-	-	-	122.7
MSHT decorrelated	-	-	-	-	35.3

- 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 explanation division of training and validation in NNPDF.
- Training fraction usually 50%, for small datasets this is unfeasible - all data in training.
- Potentially double-weights small datasets - e.g. ATLAS $t\bar{t}$.
- Affects balance of p_t^T, m_{tt} and y_t, y_{tt}, which have some tension.

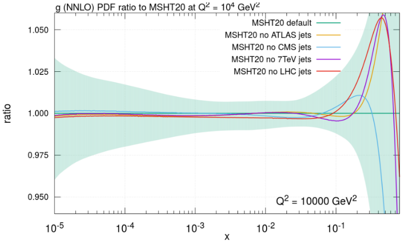


Dataset	MSHT uncorrelated	NNPDF uncorrelated	MSHT uncorrelated double weight
Total	2314.1	2731.4	2313.3
χ^2/N	1.15	1.20	1.15
DYratio (15)	9.5	5.2	9.2
CMS W asym. (11)	14.2	8.2	10.2
p_t^T (8)	3.8	7.2	4.2
y_t (5)	8.4	4.3	5.8
y_{tt} (5)	12.5	5.7	7.4
m_{tt} (7)	6.4	2.4	6.5
$t\bar{t}$ total	31.2	19.6	23.9

- May also explain NNPDF better fit of E866 DYratio data and CMS W charge asymmetry data (15 and 11 points respectively):

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

- Additional explanations are other datasets included - tensions?
- Tensions exist within and between different dataset types at high x.
- ATLAS 7 TeV jets favour lower gluon at high x, whereas CMS 8 TeV jets pull gluon up.
- ATLAS 8 TeV $t\bar{t}$ data pull gluon down.
- Global fit is a balance between these different pulls.



† MSHT20, TC, S. Bailey, L. Harland-Lang, A. Martin, R. Thorne, 2012.04684

- Tensions may be part of reason this dataset, and particularly the rapidities, is poorly fit. So far only included CMS 8 TeV jet dat.
- *Could this also be affecting the ATLAS 8 TeV $t\bar{t}$ lepton+jets in the reduced fits and the global fits?*

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

Preliminary!

- Additional explanations are other datasets included - tensions?
- NNPDF-3.0 had little jet data. NNPDF-4.0 will have much more, it sees similar issues as MSHT, CT, ATLAS for this dataset.
- Useful to consider different jet datasets as well as CMS 8 TeV jets*:

Dataset (N)	MSHT reduced (default CMS8j)	MSHT reduced + CMS7j	MSHT reduced + AT7j	MSHT reduced (CMS7j only)	MSHT reduced (AT7j only)	MSHT reduced (no jets)
χ^2/N	1.15	1.15	1.18	1.11	1.17	1.12
CMS 8 TeV jets (174)	243.6	247.2	249.9	-	-	-
CMS 7 TeV jets (158)	-	163.5	-	156.4	-	-
ATLAS 7 TeV jets (140)	-	-	225.7	-	210.4	-
p_t^T (8)	3.8	4.0	4.3	4.0	4.6	4.5
y_t (5)	8.4	7.3	7.3	6.4	5.5	5.2
y_{tt} (5)	12.5	9.8	10.2	7.2	5.2	6.6
m_{tt} (7)	6.4	6.4	7.0	6.4	6.4	7.4
$t\bar{t}$ total	31.2	27.5	28.8	24.0	21.6	23.8

- Tensions between CMS 8 TeV jets and ATLAS, CMS 7 TeV jets.
- Similar tensions with ATLAS 8 TeV $t\bar{t}$, specifically the rapidity distributions, which favour lower gluon.

* Note "uncorr" case shown, systematic correlations not included, same pattern observed in "corr" case.

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.

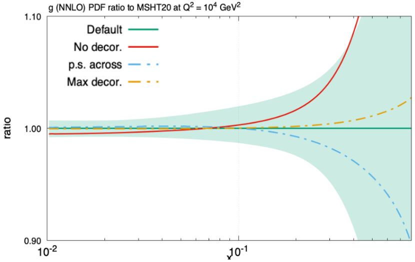
ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets: MSHT20*

- Assumption of full correlation of parton shower systematic can be relaxed, then a reasonable 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

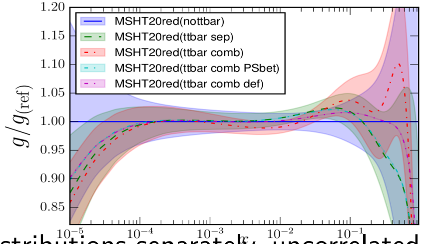


* S. Bailey & L.Harland-Lang 1909.10541 and MSHT20 2012.04684.

† T.-J. Hou et al, CT18 1912.10053.

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

- 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.