MSHT20 PDFs
review and recent developments

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Outline

1. MSHT20 PDFs - Introduction
2. Strong Coupling and Heavy Quark Masses
3. QED PDFs - MSHT20QED
4. Theoretical Uncertainties and N3LO - MSHT20aN3LO ⟶ Jamie's talk!
5. New data
6. PDF4LHC21
7. Conclusions

In collaboration with MSHT group: Shaun Bailey, Lucian Harland-Lang, Alan Martin, Jamie McGowan and Robert Thorne.

Introduction to MSHT20

More information in article: TC et al, 2012.04684, *Eur.Phys.J.C 81 (2021) 4, 341.*

MSHT20

Most accurate, precise PDF set yet, with reduced uncertainties.

- MSHT20 - New PDF set from MSTW/MMHT/MSHT group for precision LHC era. arXiv:2012.04684 , very extensive paper.
- Significant developments on all three fronts - theoretical, experimental, methodological.
  1. Theoretical - Vast majority of processes included have full NNLO QCD theory, with NLO EW where relevant.
  2. Experimental - Many new datasets, more precise, more channels, more differential.
  3. Methodological - Extended parameterisation to allow fitting accuracy to $< 1\%$ if data allows, better knowledge of central values (52 PDF parameters) and uncertainties (64 eigenvector directions).
- Global fit $\Rightarrow$ 61 different datasets - 10 Structure Function, 6 neutrinos, 2 fixed target DY, 8 HERA, 8 Tevatron, 27 LHC.
- More than 4000 datapoints included over wide range of (x, Q^2): $10^{-4} \lesssim x \lesssim 0.8$ and $2\ \mathrm{GeV}^2 \lesssim Q^2 \lesssim 10^6\ \mathrm{GeV}^2$.

MSHT20 New data - Mainly LHC

- Significant new data in MSHT20 fit - Drell-Yan, inclusive jets, top, W+jets, $W + c$, HERA final combination and heavy quarks:

High x quarks - u_V, d_V.

Flavour Decomposition - e.g. strangeness.

High x gluon - jets, top, Zp_T.

Low/intermediate x - quarks, antiquarks, and gluon, e.g. LHCb and HERA data.

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)
ATLAS 8 TeV W^+W^- + jets	30	1.13 (1.13)	0.60 (0.57)
CMS 7 TeV $W + c$	10	0.82 (0.85)	0.86 (0.84)
LHCb 7+8 TeV $W + Z$	67	1.71 (2.35)	1.48 (1.55)
LHCb 8 TeV $Z \to ee$	17	2.29 (2.89)	1.54 (1.78)
CMS 8 TeV W	22	1.05 (1.79)	0.58 (1.30)
ATLAS 7 TeV $W + Z$	61	5.00 (7.62)	1.91 (5.58)
ATLAS 8 TeV W^+W^-	22	3.85 (13.9)	2.61 (5.25)
ATLAS 8 TeV double differential Z	59	2.67 (3.26)	1.45 (5.16)
ATLAS 8 TeV high-mass DY	48	1.79 (1.99)	1.18 (1.26)
CMS 2.76 TeV jets	81	1.53 (1.59)	1.27 (1.39)
CMS 7 TeV jets $R = 0.7$	158	1.27 (1.32)	1.11 (1.17)
ATLAS 7 TeV jets $R = 0.6$	140	1.62 (1.59)	1.59 (1.68)
CMS 8 TeV jets $R = 0.7$	174	1.64 (1.73)	1.50 (1.59)
ATLAS 8 TeV Z p_T	104	2.26 (2.31)	1.81 (1.59)
$\sigma_{t\bar{t}}$	17	1.34 (1.39)	0.85 (0.87)
ATLAS 8 TeV $t\bar{t} \to l + j$ sd	25	1.56 (1.50)	1.02 (1.15)
ATLAS 8 TeV $t\bar{t} \to l^+l^-$ sd	5	0.94 (0.82)	0.68 (1.11)
CMS 8 TeV $(d\sigma_{\bar{t}t}/dp_{T,t}dy_t)/\sigma_{\bar{t}t}$	15	2.19 (2.20)	1.50 (1.48)
CMS 8 TeV $d\sigma_{\bar{t}t}/dy_t$	9	1.43 (1.02)	1.47 (2.14)
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)

New data χ^2/N_{pts} MSHT20 fit qualities (MMHT14 prediction central fit qualities).

More information to determine PDFs.

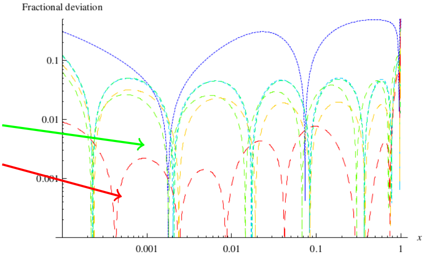
Clear preference for NNLO in new precision LHC data, NLO no longer sufficient.

- Overall good fit quality achieved, including for individual datasets.

More information in our MSHT20 paper: arXiv:2012.04684, *Eur.Phys.J.C 81 (2021) 4, 341*

MSHT20 extension of parameterisation

- MSHT use Chebyshev polynomials $T_i(1-2x^{0.5})$ to parameterise PDFs.
- MMHT used 4 Chebyshevs, MSHT now uses 6 Chebyshevs $\Rightarrow$ enables fitting to $< 1\%$ if data allows.
- Parameterise $\bar{d}/\bar{u}$ instead of $\bar{d}-\bar{u}$, with $\bar{d}/\bar{u} \to$ constant as $x \to 0$.



MMHT: 1211.1215.

New parameterisation:

$u_v(x,Q_0^2) = A_u(1-x)^{\eta_u}x^{\delta_u}(1+\sum_{i=1}^{6} a_{i,u}T_i(1-2x^{\frac{1}{2}}))$; A_u fixed by $\int_0^1 u_v\,dx = 2$

$d_v(x,Q_0^2) = A_d(1-x)^{\eta_d}x^{\delta_d}(1+\sum_{i=1}^{6} a_{i,d}T_i(1-2x^{\frac{1}{2}}))$; A_d fixed by $\int_0^1 d_v\,dx = 1$

$sea(x,Q_0^2) = A_S(1-x)^{\eta_S}x^{\delta_S}(1+\sum_{i=1}^{6} a_{i,S}T_i(1-2x^{\frac{1}{2}}))$;

$s^+(x,Q_0^2) = A_s(1-x)^{\eta_s}x^{\delta_S}(1+\sum_{i=1}^{6} a_{i,s}T_i(1-2x^{\frac{1}{2}}))$; ($a_{i,s} \neq a_{i,S}, i = 5,6$)

$(\bar{d}/\bar{u})(x,Q_0^2) = A_{\rm rat}(1-x)^{\eta_{\rm rat}}(1+\sum_{i=1}^{6} a_{i,{\rm rat}}T_i(1-2x^{\frac{1}{2}}))$;

$g(x,Q_0^2) = A_g(1-x)^{\eta_g}x^{\delta_g}(1+\sum_{i=1}^{4} a_{i,g}T_i(1-2x^{\frac{1}{2}})) - A_{g_-}(1-x)^{\eta_{g_-}}x^{\delta_{g_-}}$;

$s^-(x,Q_0^2) = A_{s_-}(1-x)^{\eta_{s_-}}(1-x_o/x)x^{\delta_{s_-}}$. x_0 fixed by $\int_0^1 s^-\,dx = 0$, δ_{s_-} fixed.

51 parton parameters

(36 in MMHT14)

7 extra eigenvectors

- 1 extra in each of PDFs, except in s^-, 2 extra in s^+.

Net $\Delta\chi^2_{\rm global} = -73$.

More accurate and precise description.

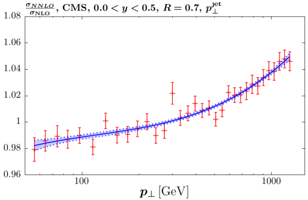
MSHT20: 2012.04684

Theoretical Developments - NNLO QCD

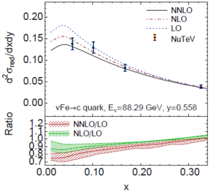
- Nearly all data now full NNLO in QCD, typically via k-factors relative to NLO grids. ↗Work on NNLO by Czakon et al, 2011.01011, JHEP 06 (2021) 100.
- Exception is CMS 7 TeV $W + c$ data only have NLO theory.
- Fit quality shows clear preference for NNLO over NLO now.

Data	N_{pts}	NLO χ^2/N_{pts}	NNLO χ^2/N_{pts}
Total, LHC data in MSHT20	1328	1.79	1.33
Total, non-LHC data in MSHT20	3035	1.13	1.10
Total, all data	4363	1.33	1.17

- K-factors smoothed with fit including adding MC error (MSHT20).
- Some data starting to be provided with NNLO grids - e.g. $t\bar{t}$.



Harland-Lang et al 1711.05757, Eur.Phys.J.C 78 (2018) 3, 248.



Thorne et al 1907.08147, PoS DIS2019 (2019) 036.

Greater theoretical accuracy.

Strong Coupling $\alpha_S(M_Z^2)$ and Heavy quark Masses m_c, m_b in MSHT20

More information in article: TC et al, 2106.10289, *Eur.Phys.J.C 81 (2021) 8, 744.*

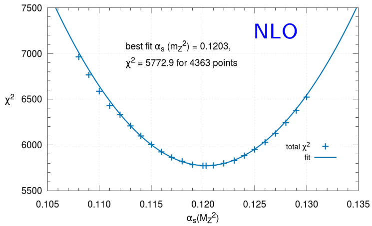
MSHT20 α_S dependence

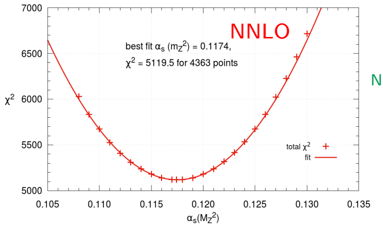
More information in article: TC et al, arXiv: 2106.10289, *Eur.Phys.J.C 81 (2021) 8, 744.*

- Default PDFs provided at standard fixed value of $\alpha_S(M_Z^2) = 0.118$.
- Can also allow α_S to be a free parameter in the fit.
- Global fit nature of PDFs $\Rightarrow$ can provide a precise, accurate determination of α_S.
- Individual datasets have different dependences on α_S, but robust determination utilising all datasets.
- The best fit values are found to be:

$\alpha_{S,\mathrm{NNLO}}(M_Z^2) < \alpha_{S,\mathrm{NLO}}(M_Z^2)$ as NNLO corrections +ve, so fitting same data $\Rightarrow$ lower α_S.

$$\alpha_{S,\mathrm{NLO}}(M_Z^2) = 0.1203 \qquad \alpha_{S,\mathrm{NNLO}}(M_Z^2) = 0.1174$$





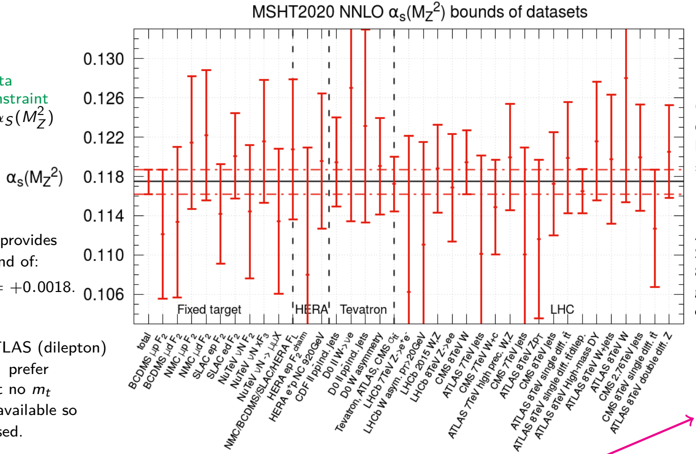
Nice Quadratic χ^2 profile ✓

MSHT20 α_S bounds - NNLO

BCDMSp data strongest constraint upwards: $\Delta\alpha_S(M_Z^2) = +0.0012$.

SLACp data provides upwards bound of: $\Delta\alpha_S(M_Z^2) = +0.0018$.

CMS and ATLAS (dilepton) $t\bar{t}$ single diff. prefer lower α_S but no m_t dependence available so bound not used.



CMS 8 TeV W data gives lower bound: $\Delta\alpha_S(M_Z^2) = -0.0013$.

ATLAS 8 TeV Z, SLACd, ATLAS 8 TeV High-mass DY give lower bounds of $\Delta\alpha_S(M_Z^2) = -0.0017, -0.0018, -0.0019$

Corresponds to: $\Delta\chi^2_{\mathrm{global}} = 17$.

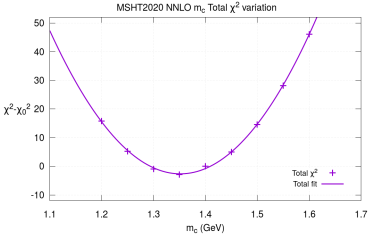
- Therefore upper and lower bounds are $+0.0012$ and -0.0013.

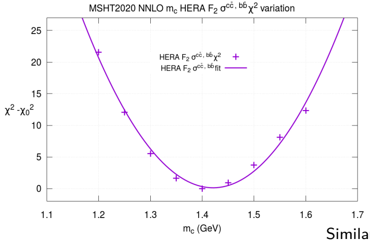
$$\alpha_{S,\mathrm{NNLO}}(M_Z^2) = 0.1174 \pm 0.0013$$

Consistent with World Average of 0.1179 ± 0.0009.

MSHT20 m_c, m_b dependence

- Default charm/bottom (pole) mass $m_c, m_b = 1.4, 4.75$ GeV, examine variation and sensitivity around this within global fit.
- Assume all perturbative heavy flavour, i.e. no intrinsic non-perturbative component ⇒ neither fitted nor intrinsic charm.





At fixed $\alpha_S(M_Z^2) = 0.118$

Similar plots for bottom mass in backup slides.

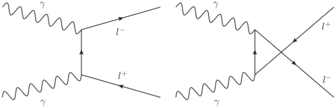
- Overall global fit favours (left) $m_c, m_b \approx 1.35, 4.5\mathrm{GeV}$.
- HERA heavy flavour combined charm and bottom (right) prefer charm/bottom mass close to our default $m_c, m_b = 1.4, 4.75\mathrm{GeV}$.
- Very low values of m_c and m_b disfavoured, in contrast to MMHT14.

QED effects in MSHT20 - MSHT20qed PDFs

More information in article: T.C. et al., 2111.05357, *Eur.Phys.J.C 82 (2022) 1, 90*.

Inclusion of QED effects:

- With NNLO QCD now standard, noting that $\alpha_{\rm QED}(M_Z) \sim \alpha_S^2(M_Z)$:
  $\Rightarrow$ important to consider EW effects, QED corrections are a key part.
- MSHT20 include EW corrections for:
  - Drell-Yan
  - top
  - inclusive jets
  - DIS.

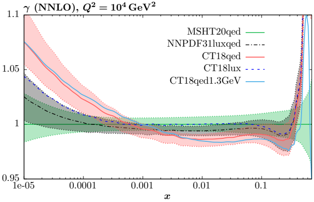


Photon-Initiated contributions to Drell-Yan.

- QED corrections enter via QED modifications to DGLAP evolution, included at $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha\alpha_S)$, $\mathcal{O}(\alpha^2)$ and via photon PDF.
- Obtain photon PDF, $\gamma(x, Q^2)$ with %-level uncertainties, from measured NC proton structure functions, à la LUXQED.

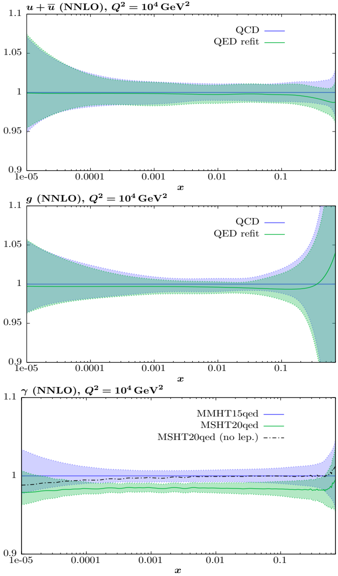
Manohar et al, 1708.01256,*JHEP 12, 046 (2017)*.

- General consistency compared to NNPDF, CT.
- Low x difference reflects differing charge-weighted singlet.
- High x difference may relate to inherent differences in methodology.

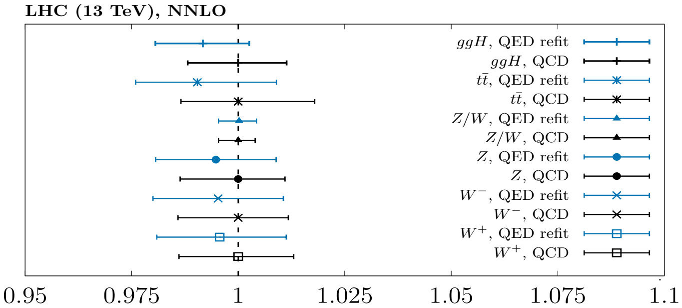


QED effects on PDFs:

- MSHT20qed has reduced $u + \bar{u}$ at high x from quark to photon splitting, $q \to q\gamma$.
- Up valence (not shown) similarly reduced at intermediate/high x.
- Gluon reduced across almost entire x range due to momentum sum rule. $\Rightarrow$ Need to accommodate γ carrying extra momentum.
- Photon reduced relative to MMHT2015qed due to inclusion of lepton-loops in $P_{\gamma\gamma}$.
- Photon breakdown into elastic and inelastic components also provided, as are neutron PDFs (see backup).



QED effects on Benchmark Cross-sections:



- Gluon-initiated processes, e.g. $gg \to H$ and top production, lower by $\sim 1\%$ due to lower gluon in QED fit.
- W, Z production also reduced (albeit slightly less) by lower quarks from $q \to q\gamma$ splitting, W/Z ratio remains stable.
- Effect of QED inclusion is smaller than but of similar order to PDF uncertainties.
- Uncertainties generally similar in QED case to QCD only case.

Theoretical Uncertainties and N3LO in MSHT20 - MSHT20aN3LO

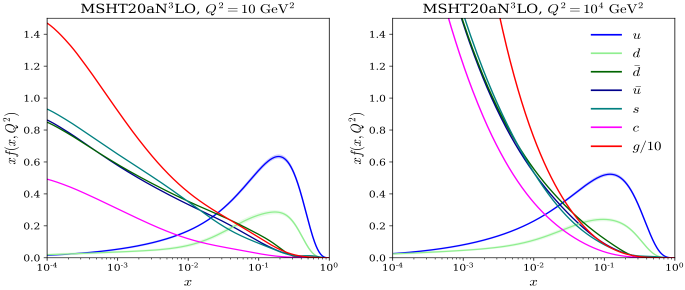
More information in article: Jamie McGowan, TC, Lucian Harland-Lang, Robert Thorne, 2207.04739, and in Jamie's talk on Tuesday.

Overview MSHT20aN3LO PDFs

Available on LHAPDF (soon) and UCL website (now): `http://www.hep.ucl.ac.uk/msht/`

- As PDFs become more precise two issues are more pressing:
  1. Inclusion of theoretical uncertainties.
  2. Moving to higher orders (N3LO).

  ⇒ we can address both in one go! ⇒ **MSHT20aN3LO PDFs.**
- Idea is to include known N3LO effects already into PDFs and to parameterise remaining unknown pieces via nuisance parameters.
- Variation of these remaining unknown N3LO pieces then provides a theoretical uncertainty within an approximate N3LO fit (aN3LO).



More information in Jamie's talk!

(More also in backup slides.)

New data added on top of MSHT20

New data - Dijets vs Inclusive Jets - Fit Quality

- Fit either 7+8 TeV inclusive jets or dijets on MSHT20 baseline.
- Inclusive jets have issues with systematic correlations and theoretical questions, e.g. scale choice, non-unitary nature, etc.
- Dijets may resolve some such issues, and triple differential measurement is more sensitive to PDF x-dependence.

High-x gluon. sensitive to these jets/dijets data.

Dijets:

Dataset	N_{pts}	χ^2/N_{pts}
ATLAS 8 TeV Zp_T	104	1.65
Top differential data total	54	1.24
ATLAS 7 TeV dijets	90	1.05
CMS 7 TeV dijets	54	1.43
CMS 8 TeV dijets	122	1.04
Total dijets	266	1.12

Inclusive Jets:

Dataset	N_{pts}	χ^2/N_{pts}
ATLAS 8 TeV Zp_T	104	1.85
Top differential data total	54	1.12
ATLAS 7 TeV jets	140	1.53
ATLAS 8 TeV jets	171	1.45
CMS 7 TeV jets	158	1.22
CMS 8 TeV jets	174	1.80
Total inclusive jets	643	1.50

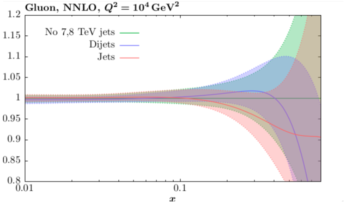
- Fit quality of dijets - 1.12, better than inclusive jets - 1.50.
- Clear improvement with order, NNLO needed for precise LHC data.

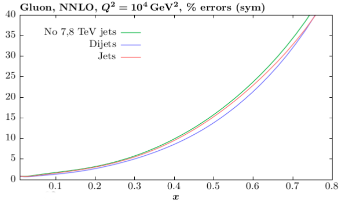
Dataset	N_{pts}	NLO	NNLO
ATLAS 7 TeV dijets	90	1.10	1.05
CMS 7 TeV dijets	54	1.71	1.43
CMS 8 TeV dijets	122	5.30	1.04
Total dijets	266	3.15	1.12

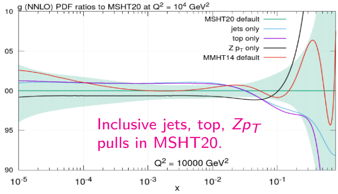
Dataset	N_{pts}	NLO	NNLO
ATLAS 7 TeV jets	140	1.69	1.53
ATLAS 8 TeV jets	171	2.37	1.45
CMS 7 TeV jets	158	1.38	1.22
CMS 8 TeV jets	174	1.65	1.80
Total inclusive jets	643	1.78	1.50

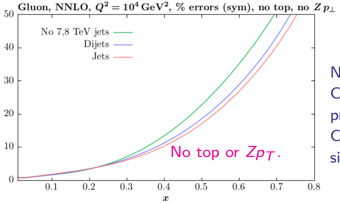
New data - Dijets vs Inclusive Jets - PDFs

- Impact on gluon PDF at high x, consistent but different pulls.
- Dijets have more impact on reducing gluon uncertainty at high x.









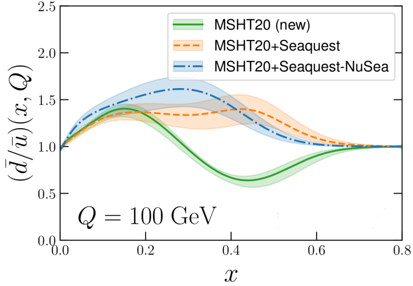
N.B. This is all Leading Colour, we have looked preliminarily at Full Colour and not found significant changes.

- Dijets increases high-x gluon, like Zp_T, inclusive jets reduces high x gluon, like top data. $\Rightarrow$ Interplay with other data.
- Without Zp_T or top, inclusive jets has greater impact on uncertainty.

New data - Seaquest

Preliminary!

- Seaquest (E906) fixed target DY data - sensitivity to high x q, $\bar{q}$: $\Rightarrow \sigma_D/\sigma_H \sim 1 + \bar{d}/\bar{u}$. Direct measurement of $\bar{d}/\bar{u}$ at high x.
- Various models for $\bar{d}/\bar{u}$ at high x: Pauli blocking, pion cloud, etc.
- Previous questions of NuSea (E866) data preferring $\bar{d} < \bar{u}$ at $x \approx 0.4$.
- Clearly raises high x $\bar{d}/\bar{u}$. Tension with NuSea which pulls it down.



Dataset	$N_{\rm pts}$	MSHT20	New
Seaquest	6	-	8.2
NuSea	15	9.8	19.0
Total (without Seaquest or NuSea)	4348	5102.3	5112.1

- NuSea $\chi^2/N_{\rm pts}$: $0.65 \rightarrow 1.27$, when Seaquest added.

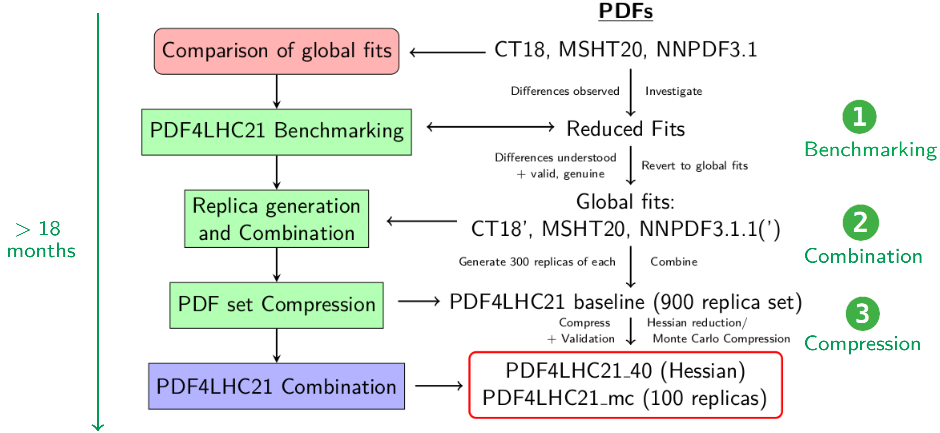
- Rest of data also worsens in χ^2 by 9 points, with 4.5 in E866 absolute DY (rather than ratio), 4.4 in NMC n/p, 4.3 in DØ W asymmetry.

PDF4LHC21 - CT18, MSHT20, NNPDF3.1 Combined

More information in article: PDF4LHC Working Group, 2203.05506, *J.Phys.G 49 (2022) 8, 080501*.

PDF4LHC21 Introduction

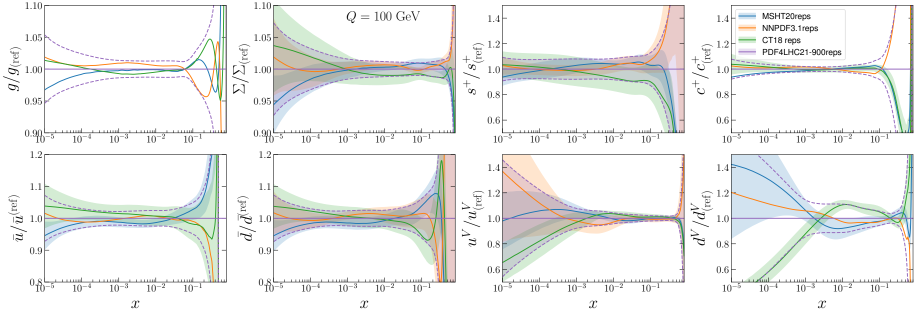
- Combination of CT18, MSHT20 and NNPDF3.1 PDFs into a single combined set ⇒ PDF4LHC21.



- Output Combined PDF sets `PDF4LHC21_40` (40 member Hessian set) and `PDF4LHC21_mc` (100 member Monte Carlo set set).

PDF4LHC21 Combination

- Compare input PDF sets (300 replicas each) with baseline (900 replica) combination:

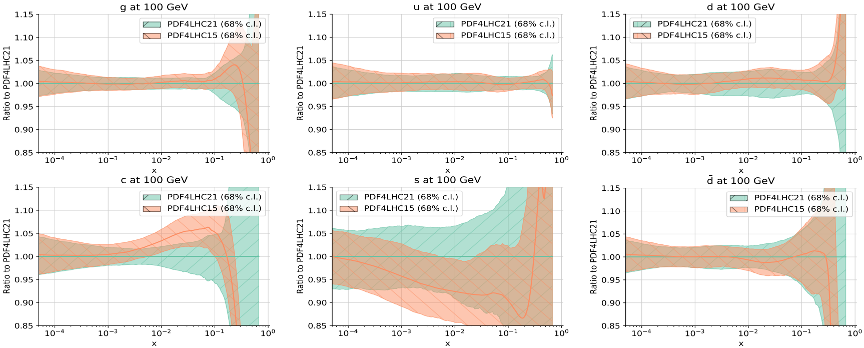


- Consistency within PDF4LHC21 combined (baseline) uncertainties across all flavours and all x.
- Combination central value is average of three input PDFs.
- PDF4LHC21 combination uncertainties reflect both:

  1. Uncertainties of 3 input PDFs.
  2. Offsets in their central values.

Due to differences in approach, data, etc.

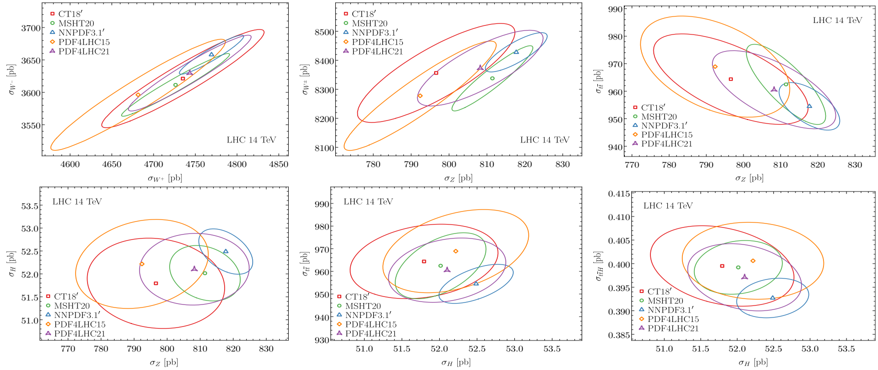
PDF4LHC21 vs PDF4LHC15*: PDF Central Values



*Note this is a comparison of the baseline 900 replica sets.

- Consistent for all flavours and x values.
- High x gluon differs due to new data, lowered but within errorbands.
- Strange quark raised for $x \gtrsim 10^{-3}$ due to ATLAS precision W, Z data.
- Charm raised at (very) high x by NNPDF3.1' fitted charm. $\longrightarrow$ In PDF4LHC15 all groups had perturbative charm.
- PDF4LHC21 PDF uncertainties generally similar to PDF4LHC15.

PDF4LHC21 vs PDF4LHC15: Inclusive Cross-sections



- Shows 1σ error ellipses for pairs of inclusive cross-sections.
- In all cases error ellipses of PDF4LHC21 and PDF4LHC15 overlap with central value of latter (almost) within ellipse of former.
- Error ellipses of PDF4LHC21 systematically reduced in size cf PDF4LHC15 $\Rightarrow$ more precise for LHC cross-sections.

Availability and Conclusions

MSHT PDF sets available

All available at https://www.hep.ucl.ac.uk/msht/, and most also on LHAPDF.

- Overview of available MSHT20 PDF sets (this is a small selection!):

LHAPDF6 grid name	Order	$n_f^{\max}$	N_{mem}	$\alpha_S(m_Z^2)$	Description
MSHT20nnlo_as118	NNLO	5	65	0.118	Default NNLO set
MSHT20nlo_as120	NNLO	5	65	0.118	Default NLO set
MSHT20lo_as130	NNLO	5	65	0.118	Default LO set
MSHT20nnlo_as_largerange	NNLO	5	23	0.108-0.130	$\alpha_S(M_Z^2)$ variation NNLO set
MSHT20nlo_as_largerange	NLO	5	23	0.108-0.130	$\alpha_S(M_Z^2)$ variation NLO set
MSHT20nnlo_mcrange_nf5	NNLO	5	9	0.118	Charm mass variation (1.2-1.6 GeV) NNLO set
MSHT20nnlo_mbrange_nf5	NNLO	5	7	0.118	Bottom mass variation (4.0-5.5 GeV) NNLO set
MSHT20nnlo_nf3,4	NNLO	3, 4	65	0.118	NNLO set with max. 3 or 4 flavours
MSHT20qed_nnlo	NNLO	5	77	0.118	NNLO set with QED effects and γ PDF
MSHT20qed_nnlo_(in)elastic	NNLO	5	77	0.118	NNLO set with QED effects and (in)elastic γ
MSHT20qed_nnlo_neutron	NNLO	5	77	0.118	NNLO neutron set with QED effects and γ
MSHT20an3lo_as118	aN3LO	5	105	0.118	Approximate N3LO set with theoretical uncertainties also included
MSHT20an3lo_as118_KCorr	aN3LO	5	105	0.118	Approximate N3LO set with theoretical uncertainties also included, K-factors correlated
PDF4LHC21	NNLO	5	901	0.118	Baseline PDF4LHC21 set
PDF4LHC21_mc	NNLO	5	101	0.118	Replica compressed PDF4LHC21 set
PDF4LHC21_40	NNLO	5	41	0.118	Hessian compressed PDF4LHC21 set

Selection of some of the MSHT PDF sets available in LHAPDF format. Many more online!

Key:

- Default - $\alpha_S, m_{c,b}$ - QED - aN3LO - PDF4LHC21

- Feel free to contact us with questions about usage.

Conclusions

- MSHT20 was a significant step forward ⇒ our most accurate, precise PDF set yet.
- Many subsequent developments:
  - Strong coupling and heavy quark mass sensitivity.
  - MSHT20qed PDF sets with QED effects and photon PDF.
  - World-first approximate N3LO PDFs with theoretical uncertainties - see Jamie's talk.
  - New data examined - dijets and Seaquest mainly.
  - PDF4LHC21 combined PDF includes MSHT20 along with CT18 and NNPDF3.1 sets.
- All PDFs available for public usage.
- This will all be supplemented by further ongoing work driving our knowledge of PDFs forward.

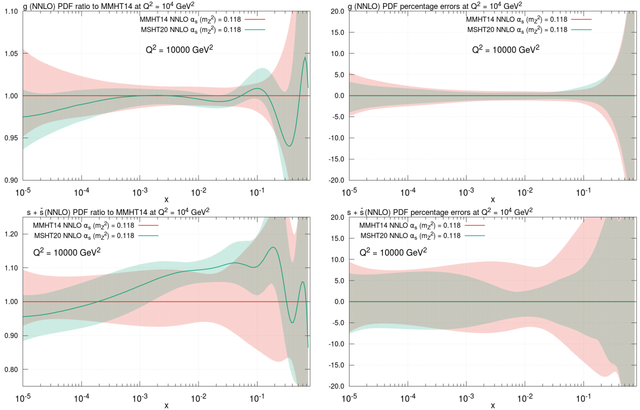
Backup Slides

MSHT20 vs MMHT14

- New data + theoretical developments + extended parameterisation $\Rightarrow$ many changes in the PDFs + reduced uncertainties.

Gluon

Strange-ness



Changes in high x gluon
Reduced uncertainty
← More data here - Jets, top, Zp_T.

More accurate PDFs with reduced uncertainties.

Increased Strangeness
Reduced uncertainty
← Both due to new ATLAS 7, 8 TeV W, Z data.

- Broadly consistent between MSHT20 and MMHT14.

(Other PDFs in backup slides.)

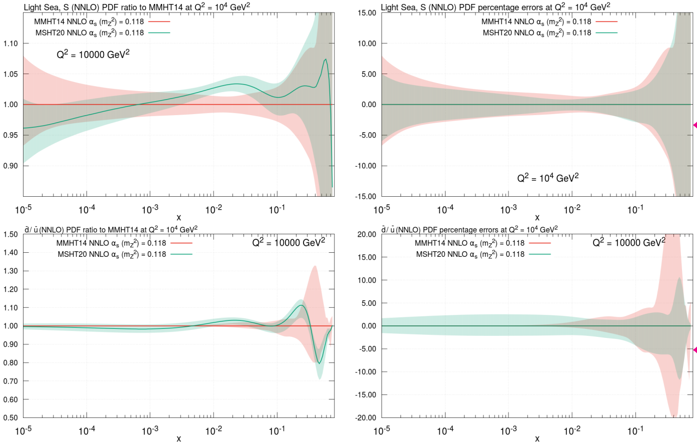
More information in our MSHT20 paper: arXiv:2012.04684, *Eur.Phys.J.C 81 (2021) 4, 341*

MSHT20 vs MMHT14

- New data + theoretical developments + extended parameterisation $\Rightarrow$ many changes in the PDFs + reduced uncertainties.

Light Sea

$\bar{d}/\bar{u}$



Changes in light sea
Reduced uncertainty

Changes in $\bar{d}/\bar{u}$.
Reduced uncertainty at high x.
Increased uncertainty at low x - driven by parameterisation.

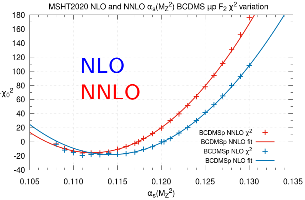
- Broadly consistent between MSHT20 and MMHT14.

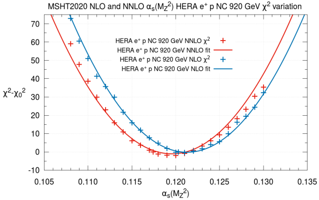
More information in our MSHT20 paper: arXiv:2012.04684, *Eur.Phys.J.C 81 (2021) 4, 341*

MSHT20 Individual dataset α_S dependence

- Perform fits for range $0.108 < \alpha_S(M_Z^2) < 0.130$ in steps of 0.001, and examine individual dataset α_S dependence via fit quality.

BCDMSp prefers lower α_S to slow fall of structure function with Q^2.

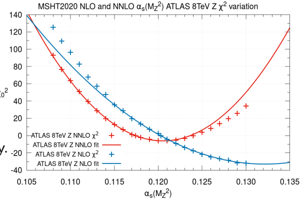


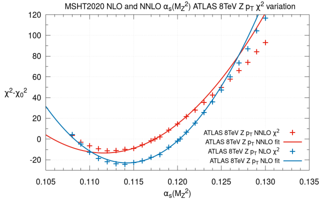


Broadly consistent with α_S pulls seen in MMHT14 study for older datasets.

HERA has limited sensitivity to α_S compared to large no. of points.

ATLAS 8 TeV Z prefers raised α_S, particularly for NLO, but this has poor fit quality.





ATLAS 8 TeV Zp_T prefers lower α_S, allows increased high x gluon.

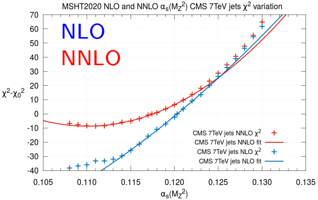
(More datasets in backup slides.)

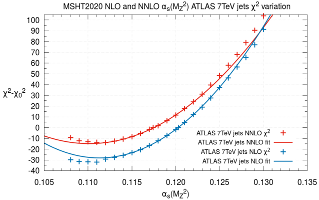
- Must do within global fit to capture α_S PDF correlations.
- Different datasets favour different $\alpha_S(M_Z^2)$ in global fit.
- Datasets with direct/indirect sensitivity to α_S prefer lower/higher α_S.

MSHT20 dataset α_S dependence - Jets/Zp_T

- Perform fits for range $0.108 < \alpha_S(M_Z^2) < 0.130$ in steps of 0.001, and examine individual dataset α_S dependence via fit quality.

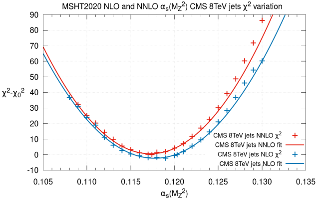
CMS 7 TeV jets prefers lower α_S, better quadratic profile at NNLO.

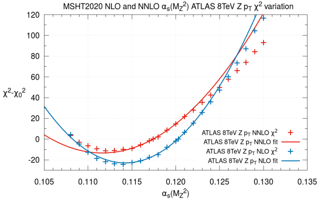




ATLAS 7 TeV jets prefers lower α_S.

CMS 8 TeV jets prefers α_S near best fit. Weak dependence around min, perhaps gluon moderates.





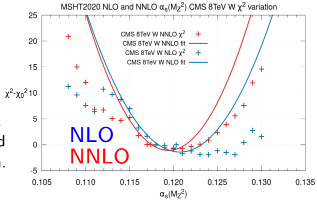
ATLAS 8 TeV Zp_T prefers lower α_S, allows increased high x gluon.

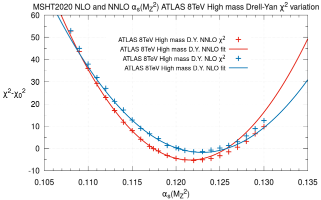
- Jets, Zp_T datasets have direct sensitivity to α_S, prefer lower α_S.

MSHT20 dataset α_S dependence - W, Z

- Perform fits for range $0.108 < \alpha_S(M_Z^2) < 0.130$ in steps of 0.001, and examine individual dataset α_S dependence via fit quality.

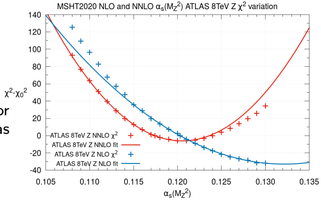
CMS 8 TeV W prefers slightly raised α_S, likely through its effects on q evolution and xsec normalisation.

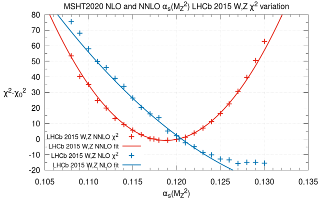




ATLAS 8 TeV High Mass DY prefers raised α_S.

ATLAS 8 TeV Z prefers raised α_S, particularly for NLO, but NLO has poor fit quality.





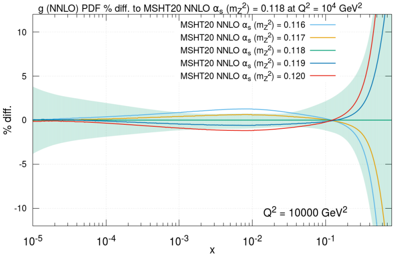
LHCb 8 TeV W, Z prefers raised α_S at NLO, but at NNLO prefers near best fit α_S.

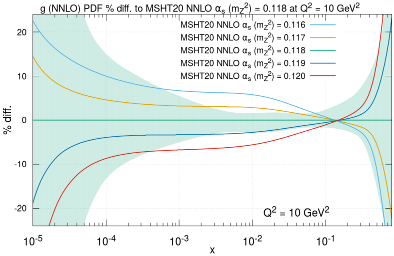
- High precision W, Z data have indirect sensitivity to α_S through their precision, generally prefer higher α_S values (but not always).

MSHT20 PDF α_S dependence - gluon

- Correlations between PDFs and α_S.

Changes of PDFs generally within PDF uncertainties, certainly at larger scales for $\Delta\alpha_S(M_Z^2) = \pm 0.001$.



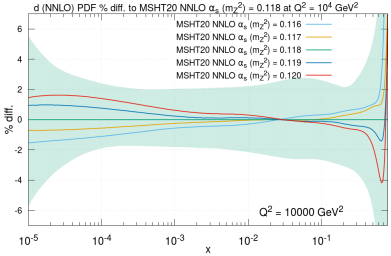


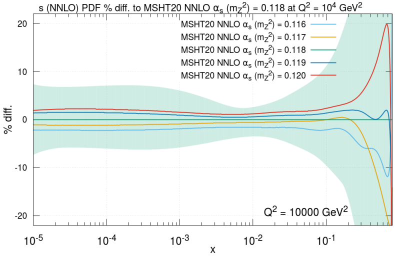
- Gluon anti-correlated with $\alpha_S(M_Z^2)$ for $x \lesssim 0.1$ as maintains product $\alpha_S g$ for structure functions.
- Gluon therefore correlated with $\alpha_S(M_Z^2)$ at high $x \gtrsim 0.1$ due to momentum sum rule.
- Larger effect at low Q^2 as less evolution distance.

MSHT20 PDF α_S dependence - quarks

- Correlations between PDFs and α_S.

Changes of PDFs generally within PDF uncertainties, certainly at larger scales for $\Delta\alpha_S(M_Z^2) = \pm 0.001$.





- High x quarks reduced with increasing α_S as increases splitting.
- Small x quarks increase with α_S as reinforced by gluon splitting.
- Strange relatively insensitive to α_S, partly due to compensation in BR $B(D \to \mu)$ which can change normalisation.
- High x strange raised as poorly determined and compensates for reduction in u, d. Low x strange raised by gluon splitting with α_S.

Procedure for combining PDF and α_S dependence

- Within Hessian approach to PDF uncertainties, correct manner to determine combined PDF+$\alpha_S(M_Z^2)$ uncertainty for any quantity, including correlations between PDFs and α_S is:

  1. Take PDFs determined at $\alpha_S(M_Z^2) \pm \Delta\alpha_S(M_Z^2)$ and treat as additional pair of eigenvectors.
  2. Determine quantity to obtain $\Delta\sigma_{\alpha_S}$.
  3. Combine uncertainties in quadrature:

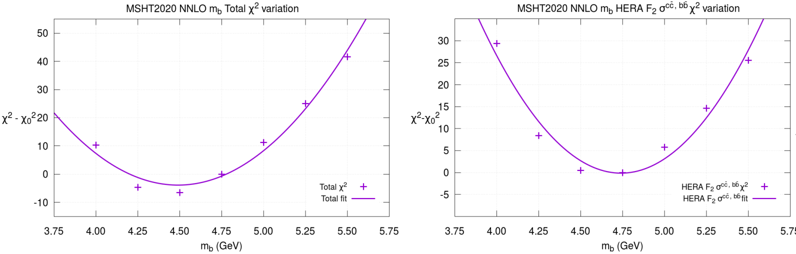
Quadrature as whilst central values correlated errors uncorrelated. CT: 1004.4624.

$$\Delta\sigma = \sqrt{(\Delta\sigma_{\mathrm{PDF}})^2 + (\Delta\sigma^2_{\alpha_S(M_Z^2)})}$$

- Works provided central PDFs are best fit PDFs with $\alpha_S(M_Z^2)$ free.
- Choice of $\Delta\alpha_S(M_Z^2)$ up to user but recommended to be close to our 1σ bounds, e.g. ± 0.001 for simplicity and near that of world average.

MSHT20 m_b dependence

- Default bottom (pole) mass $m_b = 4.75$ GeV, vary in steps of 0.25GeV in range $4.0\mathrm{GeV} \leq m_b \leq 5.5\mathrm{GeV}$ and examine fit qualities.



At fixed $\alpha_S(M_Z^2) = 0.118$

- Overall global fit dependence (left) centred on $m_b \approx 4.5\mathrm{GeV}$.
- HERA heavy flavour combined charm and bottom (right) prefer bottom mass very close to our default $m_b = 4.75\mathrm{GeV}$.
- Very low values of m_b clearly disfavoured, in contrast to MMHT14.

Motivation for inclusion of QED effects:

- With NNLO QCD now standard, noting that:

$$\alpha_{\text{QED}}(M_Z) \sim \alpha_S^2(M_Z)$$

$\Rightarrow$ important to consider EW effects, QED corrections are a key part.

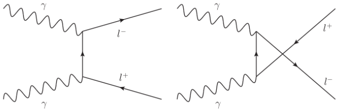
- QED corrections enter via QED modifications to DGLAP evolution:

$$P_{ij}^{\text{QED}} = \frac{\alpha}{2\pi} P_{ij}^{0,1} + \frac{\alpha\alpha_S}{(2\pi)^2} P_{ij}^{1,1} + \frac{\alpha^2}{(2\pi)^2} P_{ij}^{0,2} + \ldots$$

$\Rightarrow$ Include $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha\alpha_S)$, $\mathcal{O}(\alpha^2)$ corrections.

- Requires also introduction of photon PDF, photon-initiated (PI) channels provide important QED corrections.

- MSHT20 include EW corrections for:
  - Drell-Yan
  - top
  - inclusive jets
  - DIS.



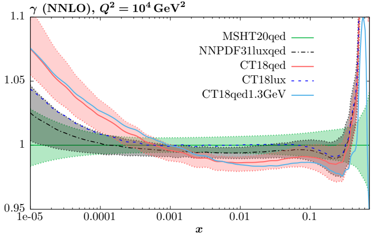
PI contributions to Drell-Yan.

Photon PDF in MSHT20qed:

- Obtain photon from experimentally well-measured NC proton structure functions, à la LUXQED. Manohar et al, 1708.01256,*JHEP 12, 046 (2017).*

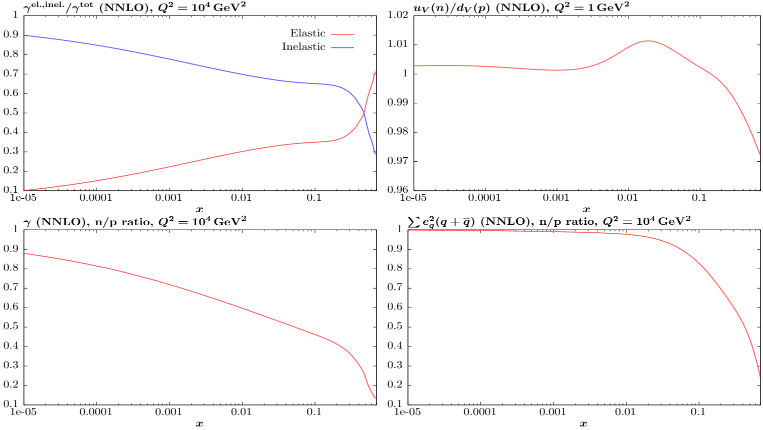
$$x\gamma(x,Q_0^2) = \frac{1}{2\pi\alpha(Q_0^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2 m_p^2}{1-z}}^{Q_0^2} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[\left(zP_{\gamma,q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2)\right.\right.$$
$$\left.\left. -z^2F_L(x/z,Q^2)\right] - \alpha^2(Q_0^2)\left(z^2+\ln(1-z)zP_{\gamma,q}(z)-\frac{2x^2m_p^2 z}{Q_0^2}\right)F_2(x/z,Q_0^2)\right\},$$

- $\gamma(x,Q_0^2)$ extracted from experimental data and then evolved in QED-modified DGLAP $\Rightarrow$ $\gamma(x,Q^2)$ with %-level uncertainties.
- General consistency compared to NNPDF, CT.
- Low x difference reflects differing charge-weighted singlet.
- High x difference may relate to inherent differences in methodology.



MSHT20qed - elastic/inelastic and neutron PDFs

- Breakdown of photon into elastic and inelastic pieces also provided, former dominates except at high x and low Q^2 (upper left).
- Neutron PDFs also provided as QED corrections lead to isospin violation: $u_V(p) \neq d_V(n)$, $u_V(n) \neq d_V(p)$, etc $\Rightarrow \gamma(p) \neq \gamma(n)$.



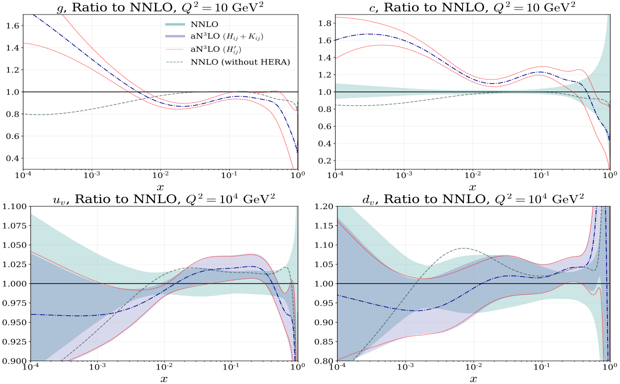
MSHT20aN3LO PDFs - Fit quality

- Smooth improvement and convergence in fit quality with increasing order.
- Fit quality improves by $\Delta\chi^2 = -172.5$ for 20 extra parameters.
- Reduction in tension between low and high x, HERA and fixed target fit better.
- ATLAS 8 TeV Zp_T improves significantly, reduction in tension with other data.
- Jets are only class of data with worsening of χ^2, looks better with dijet data (preliminary).

Order	LO	NLO	NNLO	aN3LO
χ^2/N_{pts}	2.57	1.33	1.17	1.13

Data set	Points	MSHT20aN3LO χ^2	$\Delta\chi^2$ from NNLO
HERA e^+p CC	39	51.8	-0.1
HERA e^-p CC	42	66.3	-3.8
HERA e^+p NC 820GeV	75	83.8	-6.0
HERA e^-p NC 460GeV	209	247.4	-0.9
HERA e^+p NC 920GeV	402	476.7	-36.0
HERA e^-p NC 575GeV	259	248.0	-15.0
HERA e^-p NC 920GeV	159	243.3	-1.0
CCFR $\nu N \to \mu\mu X$	86	69.2	+1.5
NuTeV $\nu N \to \mu\mu X$	84	55.3	-3.1
CMS double diff. DY	132	137.1	-7.4
ATLAS 7 TeV W, Z	61	110.5	-6.2
ATLAS 8 TeV W	22	55.1	-2.3
ATLAS 8 TeV Z	59	80.8	-4.8
ATLAS 8 TeV Zp_T	104	105.8	-82.7
CMS 7 TeV $W + c$	10	12.3	+3.7
ATLAS 8 TeV W+jets	30	19.1	+0.9
ATLAS 7 TeV jets	140	214.5	-7.1
CMS 7 TeV jets	158	189.8	+14.1
CMS 8 TeV jets	174	272.6	+11.3
CMS 2.76 TeV jets	81	113.9	+11.1
DIS data (total)	2375	2585.2	-86.4
Jets data (total)	739	972.9	+30.8
Top data (total)	71	73.4	-5.9
DY data (total)	864	1044.8	-43.1
Total	4363	4948.6	-172.5

MSHT20aN3LO PDFs - PDF changes

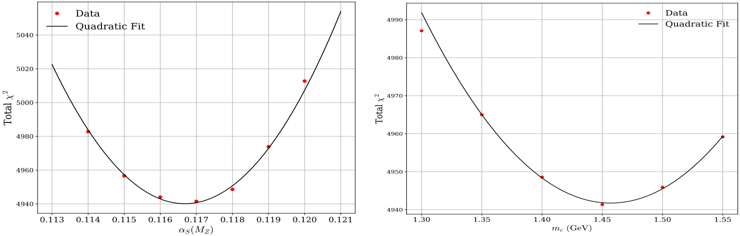


- Small-x low-Q^2 gluon enhanced due to large logs included at N3LO.
- Enhanced charm via enlarged $A_{Hg}^{(3)}$ and increased small-x gluon.
- Reduced quarks at large/small-x accommodate small-x gluon.
- High-Q^2, intermediate/large-x light quarks largely follow NNLO no HERA fit, demonstrating eased tension with smaller x HERA data.

MSHT20aN3LO PDFs - Strong Coupling, Charm Mass

- Can repeat strong coupling and charm mass variation now at aN3LO.
- Both $\alpha_S(M_Z^2)$ (left) and m_c (right) show good quadratic behaviour.
- Further slight reduction in best fit $\alpha_S(M_Z^2)$ relative to NNLO value:

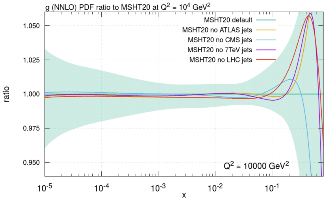
Order	NLO	NNLO	aN3LO
$\alpha_S(M_Z^2)$	0.1203 ± 0.0015	0.1174 ± 0.0013	≈ 0.1167



- m_c minimises around $m_c \approx 1.45\mathrm{GeV}$ at aN3LO cf $\approx 1.35\mathrm{GeV}$ at NNLO. Better agreement with world average: $m_c = 1.5 \pm 0.2\mathrm{GeV}$.
- Preferred $\alpha_S(M_Z^2)$ and m_c therefore suppress slightly gluon and charm relative to NNLO, partially mitigating aN3LO changes.

New data - Dijets - Introduction

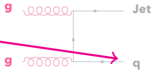
- High x gluon is of interest in PDFs, with tensions between datasets.
- MSHT20 - data on inclusive jets from ATLAS, CMS at 7 and 8 TeV, sensitive to high-x gluon. Different pulls.
- Known issues with systematic correlations in ATLAS 7, 8 TeV inclusive jets (latter therefore not included in MSHT20).



- Theoretical issues: scale choice, non-unitary nature of inclusive jets.
- Dijets also allow triple differential measurement, cf double differential for single inclusive jets. Schematically at LO:

$$x = \frac{p_T}{\sqrt{s}}(e^{y_j} + e^{y_{j'}})$$

Integrated over in inclusive jet case.



$\Rightarrow$ Single inclusive jets: $\frac{d\sigma}{dp_T^j d|y^j|}$, dijets: $\frac{d\sigma}{dp_T^{\rm avg} dy^* dy_b}$.

CMS 8 TeV dijets

Dijets when triple differential more sensitive to x-dependence.

PDF Benchmarking: Reduced Fit Settings

- Chosen subset of datasets fit by all 3 groups in (almost) the same way.
- Ensure enough datasets and variety of dataset types are fit to have some (but incomplete) constraints on all PDF flavours.
- Choose common theory settings wherever possible.

Reduced Fit dataset:

- BCDMS p, d DIS data.
- NMC d/p ratio in DIS.
- NuSea Drell-Yan pd/pp.
- NuTeV dimuon data.
- HERA I+II inclusive DIS.
- D0 Z rapidity distribution.
- ATLAS W, Z 7 TeV η distribution.
- CMS 7 TeV W asymmetry.
- CMS 8 TeV inclusive jet data.
- LHCb 7, 8 TeV W, Z η distributions.

Fixed target

HERA

Tevatron

LHC

Reduced Fit theory settings:

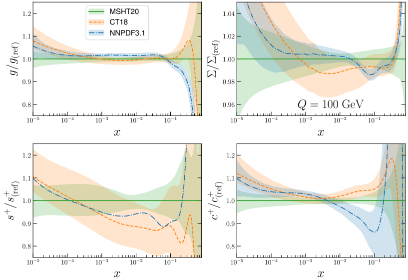
- Same heavy quark masses, m_c, m_b and strong coupling, $\alpha_S(M_Z^2)$.
- No strangeness asymmetry at input scale $(s - \bar{s})(Q_0) = 0$.
- Perturbative charm.
- Positive definite quark distributions (lack of constraint may allow negative fluctuations).
- No deuteron or nuclear corrections.
- Fixed branching ratio for charm hadrons to muons for dimuon data, $BR(D \to \mu)$.
- 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*.

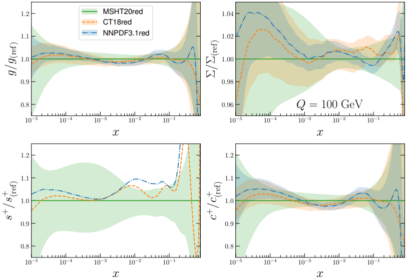
PDF Benchmarking: Reduced Fits

- Use fits to reduced common datasets and common theory settings.

Global Fits



Reduced Fits



- Agreement improved relative to global PDFs.
- Very good agreement within uncertainties, including gluon.
- More similar sized uncertainties in data regions, differences outside this, reflecting remaining methodological and other choices.
- Same data and theory settings $\rightarrow$ more consistent PDFs.
- Remaining differences, e.g. in errors, reflect methodological choices.

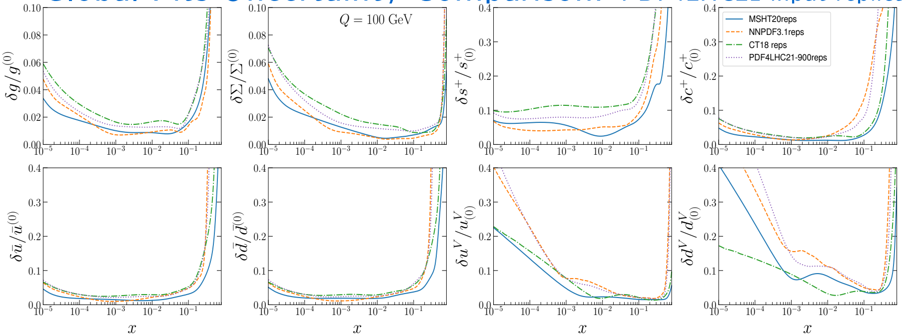
PDF4LHC21 Combination

- Differences in PDFs reflect genuine freedom in PDF determination from data, theory, methodology $\Rightarrow$ spread in PDFs should therefore contribute to a combined PDF uncertainty.
- Continue with PDF4LHC21 combination of ***global PDF fits***, with common $\alpha_S(M_Z^2) = 0.118$ and $m_c, m_b = 1.4, 4.75\mathrm{GeV}$. $\longrightarrow$ MSHT default values
- Each group determines their *own settings and datasets* for their global PDF fit contribution to combination. Several known, explained differences $\rightarrow$ high x gluon, (fitted) charm, strangeness.
- Combine **300 replicas of CT18', MSHT20, NNPDF3.1'** (aka NNPDF3.1.1) to give *baseline PDF4LHC21* set of 900 replicas.

CT18'	MSHT20	NNPDF3.1'
- CT18 global PDF set but with m_c, m_b changed to common values.	- Default, public MSHT20 global PDF set.	- Update of NNPDF3.1. - Common m_c, m_b set. - Global PDF set, version in between NNPDF3.1/4.0.

PDF4LHC21 input *global* PDF sets.

Global Fits Uncertainty Comparison: PDF4LHC21 input replicas



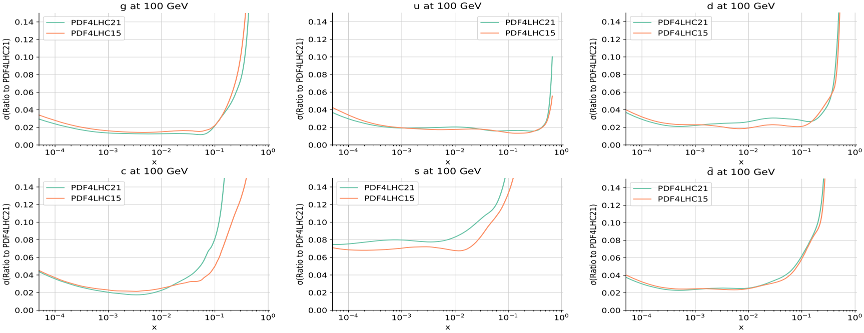
- Good general agreement with differences largely in extreme regions.
- Compare also with <u>*indicative*</u> PDF4LHC21 900 replica baseline combination uncertainties ⇒ see expected behaviour.
- Central value is average of those of the 3 global fits input.
- Central values agree closely ⇒ uncertainty is average of 3 groups:
- Central values spread ⇒ uncertainty has component from spread.

Compression/Reduction:

- Baseline PDF4LHC21 900 replica combined set is impractical $\Rightarrow$ wish to reduce its size for pheno applications, 2 methods:
  - Monte Carlo (MC) Compression - Extract subset of 900 replicas that reproduces statistical properties of baseline distribution.
  - Hessian Reduction - Convert 900 replica set to a Hessian set reproducing Gaussian features of baseline distribution.
- Examined and validated effects of compression/reduction on PDFs, PDF properties (mean, variance, correlations, etc) and on cross-sections to ensure faithful reproduction of baseline 900 replica distribution.

- Output is the PDF4LHC21 PDF sets for general usage:
  - `PDF4LHC21_mc` - Monte Carlo set with 100 replicas.
  - `PDF4LHC21_40` - Hessian set with 40 eigenvectors.

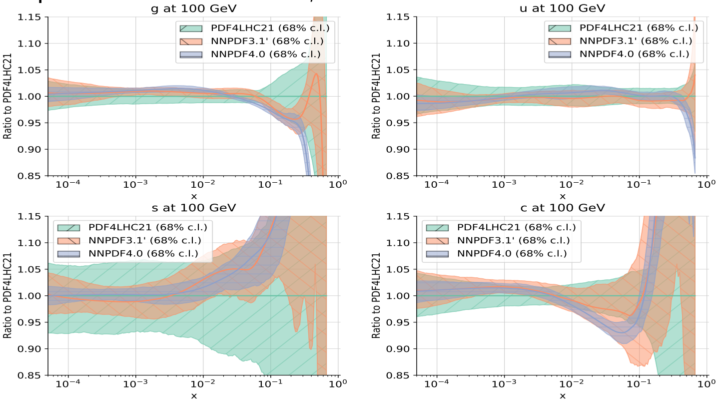
PDF4LHC21 vs PDF4LHC15: PDF Uncertainties



- PDF errorbands similar, reduced in some places, raised in others.
- Uncertainties reduced relative to PDF4LHC15 where three input sets agree as their individual uncertainties have reduced.
- Uncertainties increase where disagreement between three input sets have worsened, e.g. for strangeness or for charm at $x \gtrsim 10^{-2}$.
- Uncertainties more clearly reduced relative to PDF4LHC15 for PDF luminosities and cross-sections.

PDF4LHC21 and NNPDF4.0:

- NNPDF4.0 appeared relatively late in the PDF4LHC21 benchmarking/combination effort, therefore not included.
- Instead NNPDF3.1' (aka NNPDF3.1.1) is included which is intermediate between NNPDF3.1 and NNPDF4.0.
- Comparison of NNPDF3.1', NNPDF4.0 and PDF4LHC21 PDFs:



PDF4LHC21_mc vs PDF4LHC21_40:

- Both main PDF4LHC21 sets - `PDF4LHC21_mc`, `PDF4LHC21_40` reflect central values and uncertainties of three input PDF sets.
- Both carefully checked to ensure they reproduce excellently the baseline 900 replica combination, nonetheless small differences exist:

PDF4LHC21_mc	PDF4LHC21_40
➤ **Monte Carlo set** of 101 members (100 replicas + central value) ➤ Reproduces *non-Gaussian features* of combination as well as mean, variances, correlations, etc. ➤ Central value and replicas may go negative at large x. (In a few, limited cases.) Note this occurred also in PDF4LHC15.	➤ **Hessian set** of 41 members (40 symmetric eigenvectors + central value) ➤ Reproduces *Gaussian features* of combination - i.e. mean, variances, correlations. ➤ Positivity imposed, central value remains positive, although errorband may include negative values.

- Non-Gaussian features more relevant in regions where there are disagreements or lack of data, includes at high x.
- Positivity may be useful in certain applications, e.g. event generation.
- For each `PDF4LHC21_40...` set there is also a ‘`nopos`’ set.

N.B. See backup slides for more on positivity at large x.