MSHT20 PDFs
review and recent developments

Thomas Cridge

DESY

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PDF4LHC Meeting, CERN

In collaboration with S. Bailey, L.A. Harland-Lang, A.D. Martin, J. McGowan, and R.S. Thorne.

MSHT20

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

- MSHT20 - New PDF set for precision LHC era - arXiv:2012.04684 .
- Significant developments on all three fronts:.
  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 $2\ \text{GeV}^2 \lesssim Q^2 \lesssim 10^6\ \text{GeV}^2$.

Outline

- MSHT20 - culmination of several years of effort to produce our most accurate, reliable and precise PDF set. - 2012.04684.
- Nearly two years since then and we have investigated several topics:

1. Strong Coupling and Heavy Quark Masses - 2106.10289.
2. QED PDFs - MSHT20QED - 2111.05357.
3. New data - Dijets, Seaquest, EIC pseudodata.
4. Approximate N3LO and Theoretical Uncertainties - MSHT20aN3LO - 2207.04739. (↑ Robert's talk)
5. Summary

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

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.*

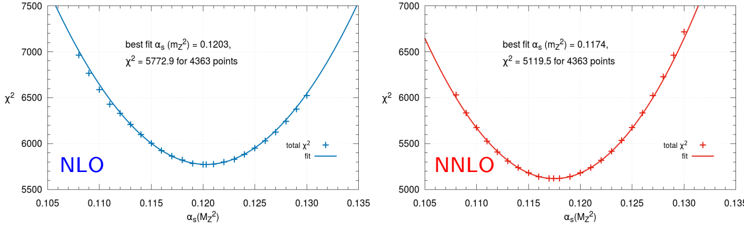
MSHT20 α_S dependence

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

- 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 at NLO and NNLO are:

$\alpha_{S,\mathrm{NNLO}}(M_Z^2) < \alpha_{S,\mathrm{NLO}}(M_Z^2)$ 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 ✓

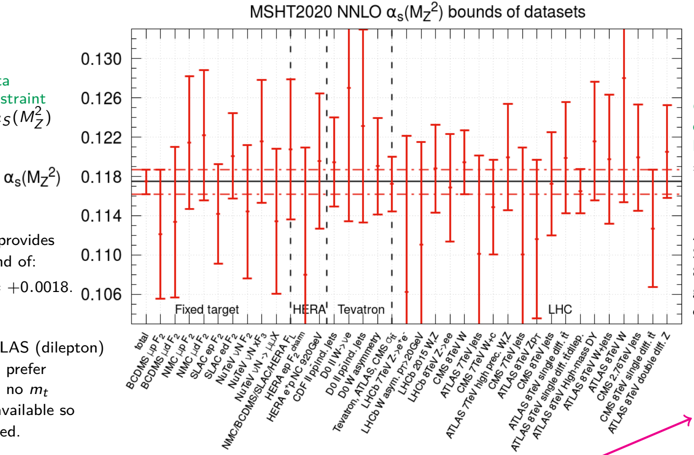
- Also now investigated at aN3LO $\Rightarrow$ see later slides.

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: $\Delta\chi^2_{\rm global} = 17$.

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

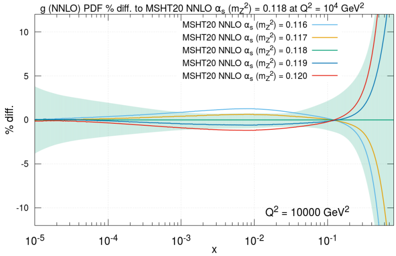
$$\alpha_{S,\rm NNLO}(M_Z^2) = 0.1174 \pm 0.0013$$

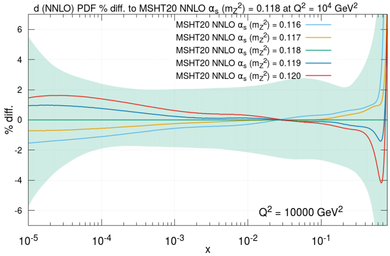
Consistent with World Average of 0.1179 ± 0.0009.

MSHT20 PDF α_S dependence - gluon

- Correlations between PDFs and α_S.

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

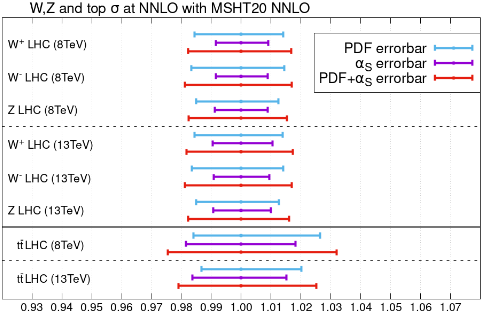




- Gluon anti-correlated with $\alpha_S(M_Z^2)$ for $x \lesssim 0.1$ as maintains product $\alpha_S g$ for structure functions.
- Gluon therefore correlated with $\alpha_S(M_Z^2)$ at high $x \gtrsim 0.1$ due to momentum sum rule.
- High/low x quarks reduced/enhanced with increasing α_S as increases quark/gluon splitting.

MSHT20 σ α_S dependence - W, Z

- PDF-α_S correlations mean there are indirect effects on cross-sections.
- Have both direct α_S uncertainty on σ and indirect α_S uncertainty from change of PDF effect on σ.

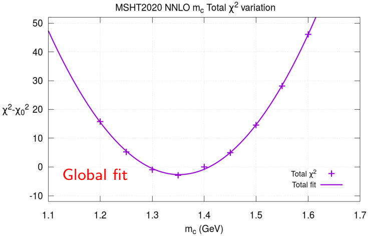


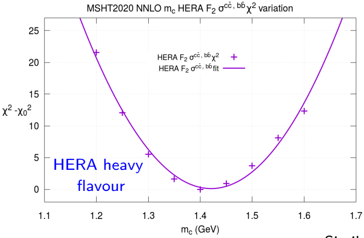
N.B. "Direct" α_S uncertainty $=$ direct effect of α_S on xsec. "Indirect" α_S uncertainty $=$ effect of α_S on PDFs and through them onto xsec.

- W, Z - Direct α_S uncertainty very small. Indirect α_S uncertainty is much larger as quarks increase below $x \lesssim 0.1$ with increasing α_S.
- Top - Direct α_S uncertainty $\sim 2\%$. Indirect α_S uncertainty reduces this as gluon anti-correlated with α_S below $x \sim 0.1$.

MSHT20 m_c, m_b dependence

- Default charm/bottom (pole) mass $m_c, m_b = 1.4, 4.75$ GeV.
- Assume all perturbative heavy flavour, i.e. no fitted/intrinsic part.





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

Similar plots for bottom mass in backup slides.

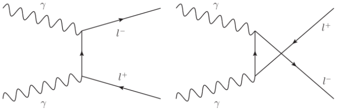
- Overall global fit favours (left) $m_c, m_b \approx 1.35, 4.5\mathrm{GeV}$.
- HERA heavy flavour combined charm and bottom (right) prefer charm/bottom mass close to our default $m_c, m_b = 1.4, 4.75\mathrm{GeV}$.
- Very low values of m_c and m_b disfavoured, in contrast to MMHT14.
- Also now investigated at aN3LO $\Rightarrow$ see later slides.

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:

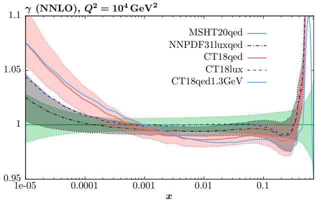
- With NNLO QCD now standard, noting that $\alpha_{\text{QED}}(M_Z) \sim \alpha_S^2(M_Z)$:
  $\Rightarrow$ important to consider EW effects, QED corrections are a key part.
- MSHT20 include EW corrections for:
  - Drell-Yan
  - inclusive jets
  - top
  - DIS.



Photon-Initiated contributions to Drell-Yan.

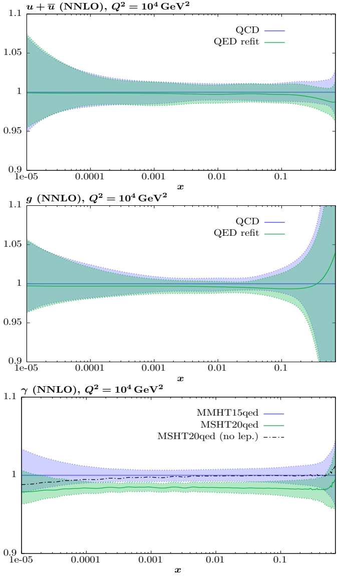
- QED corrections enter via QED modifications to DGLAP evolution, included at $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha\alpha_S)$, $\mathcal{O}(\alpha^2)$ and via photon PDF.
- Obtain photon PDF, $\gamma(x, Q^2)$ with %-level uncertainties, from measured NC proton structure functions.
- General consistency compared to NNPDF, CT.
- Low x difference reflects differing charge-weighted singlet.

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

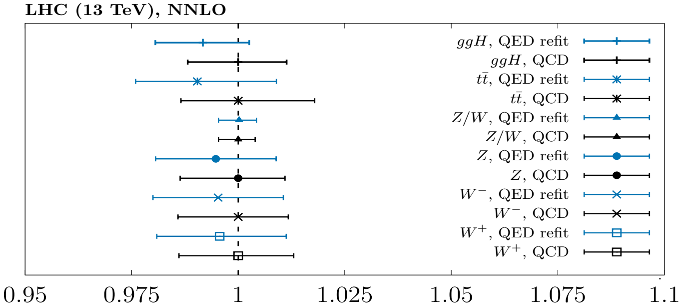


QED effects on PDFs:

- MSHT20qed has reduced $u + \bar{u}$ at high x from $q \to q\gamma$ splitting.
- Effect on down quarks (not shown) smaller due to smaller charge.
- 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 $\lesssim$ PDF uncertainties for these processes.
- Uncertainties generally similar in QED case to QCD only case.

New data added on top of MSHT20

New data - Dijets vs Inclusive Jets - Fit Quality (NNLO)

- 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.

Also investigated at aN3LO ⇒ see later!

Dijets:

Dataset	$N_{\rm pts}$	$\chi^2/N_{\rm pts}$
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	$N_{\rm pts}$	$\chi^2/N_{\rm pts}$
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

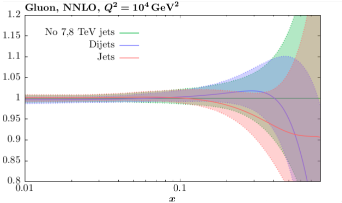
- Fit quality of dijets - 1.12, better than inclusive jets - 1.50.
- Clear improvement with order, NNLO needed for precise LHC data.

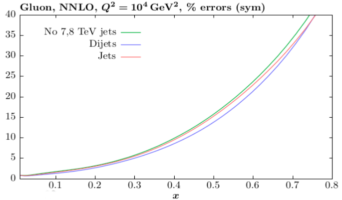
Dataset	$N_{\rm pts}$	NLO	NNLO
ATLAS 7 TeV dijets	90	1.10	1.05
CMS 7 TeV dijets	54	1.71	1.43
CMS 8 TeV dijets	122	5.30	1.04
Total dijets	266	3.15	1.12

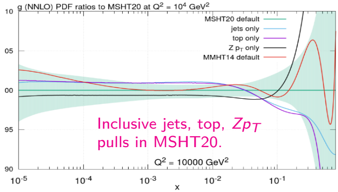
Dataset	$N_{\rm pts}$	NLO	NNLO
ATLAS 7 TeV jets	140	1.69	1.53
ATLAS 8 TeV jets	171	2.37	1.45
CMS 7 TeV jets	158	1.38	1.22
CMS 8 TeV jets	174	1.65	1.80
Total inclusive jets	643	1.78	1.50

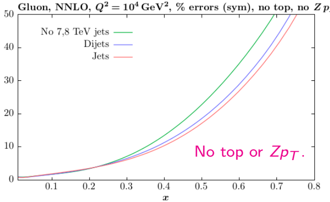
New data - Dijets vs Inclusive Jets - PDFs (NNLO)

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









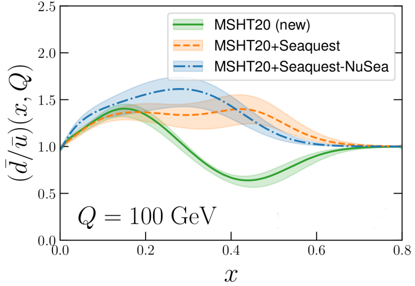
N.B. This is all Leading Colour, we have looked preliminarily at Full Colour and not found significant changes.

- 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

Again note added on NNLO fit here.

- 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.



Also investigated. at aN3LO $\Rightarrow$ see later!

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

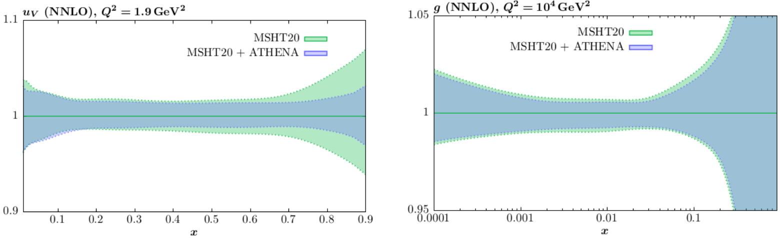
- NuSea χ^2/N_{pts}: 0.65 $\rightarrow$ 1.27, when Seaquest added.

- 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.

New data - EIC Pseudodata

Again note added on NNLO fit here.

- Investigated impact of simulated EIC pseudodata with colleagues from ATHENA/EIC.
- Effects on unpolarised proton PDFs from high x lower Q^2 sensitivity.



- Effect on up valence larger due to charge-squared coupling of virtual photon in DIS $\Rightarrow$ reduction in u_V uncertainty above $x \sim 0.5$.
- Smaller impact on other partons, gluon uncertainty nonetheless reduced across range of x.

Theoretical Uncertainties and N3LO in MSHT20 - MSHT20aN3LO

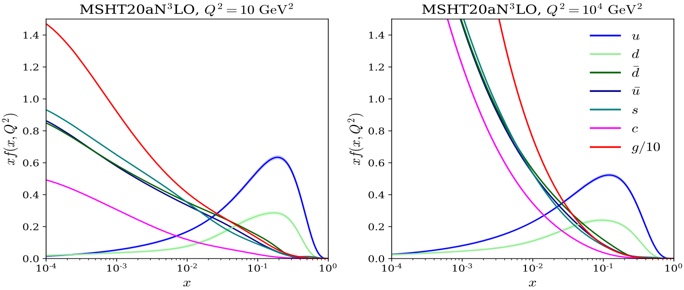
More information in article: Jamie McGowan, TC, Lucian Harland-Lang, Robert Thorne, 2207.04739, and in Robert's talk later.

Overview MSHT20aN3LO PDFs

Available on LHAPDF and UCL website:
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).

  $\Rightarrow$ we can address both in one go! $\Rightarrow$ **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).

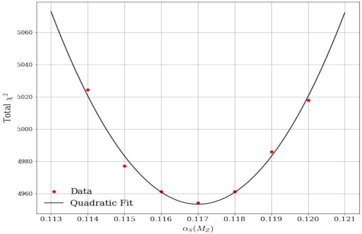


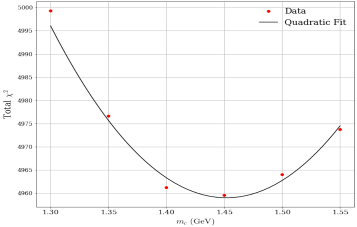
More information in Robert's talk!

MSHT20aN3LO PDFs - Strong Coupling, Charm Mass

- 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	≈ 0.1170





- 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.

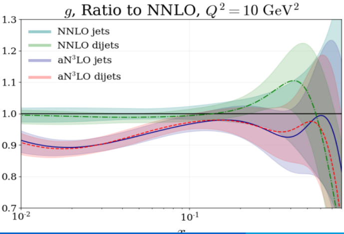
Dijet data aN3LO vs NNLO:

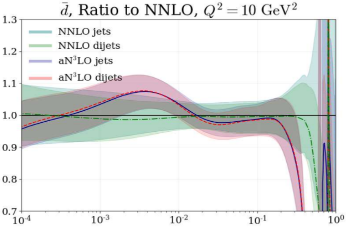
Preliminary!

- Obtain better fit quality at NNLO and aN3LO than jets.
- Dijet fit quality improves further slightly at aN3LO, unlike for jets.

.	N_{pts}	χ^2/N_{pts} NNLO	χ^2/N_{pts} aN3LO	.	N_{pts}	χ^2/N_{pts} NNLO	χ^2/N_{pts} aN3LO
ATLAS 7 TeV jets	140	1.58	1.54	ATLAS 7 TeV dijets	90	1.05	1.12
CMS 7 TeV jets	158	1.11	1.18	CMS 7 TeV dijets	54	1.43	1.39
CMS 8 TeV jets	174	1.50	1.56	CMS 8 TeV dijets	122	1.04	0.83
Total (jets)	472	1.39	1.43	Total (dijets)	266	1.12	1.04
Total	4363	1.17	1.14	Total	4157	1.14	1.10

- Effect of jets vs dijets on PDFs and rest of data similar at NNLO and aN3LO, and no significant change in uncertainty.

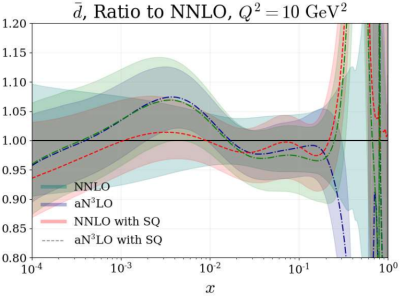


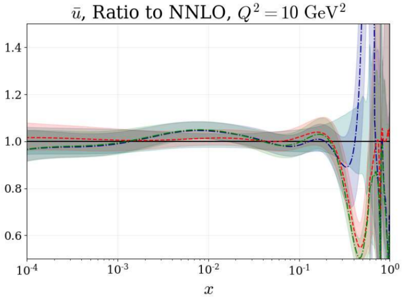


N.B. This is all Leading Colour, we have looked preliminarily at Full Colour and not found significant changes.

MSHT20aN3LO PDFs - Seaquest

- At aN3LO, the $\bar{d}$ become negative above $x \sim 0.5$ with a minimum at $x \sim 0.6$. Nonetheless remains positive within uncertainties.
- Like at NNLO, adding the Seaquest data raises the $\bar{d}/\bar{u}$.





- Adding Seaquest $\Rightarrow$ NNLO and aN3LO $\bar{d}$, $\bar{u}$ again very similar.
- Effect on fit quality of adding Seaquest similar to NNLO, $\Delta\chi^2 = +6$ in rest of data, NuSea χ^2/N doubles from ~ 0.6 to ~ 1.3.

Availability and Summary

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 $\Rightarrow$ 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.
  - New data examined - dijets and Seaquest mainly.
  - World-first approximate N3LO PDFs with theoretical uncertainties - see Robert's talk.
- All PDFs available for public usage - LHAPDF and MSHT website.
- This will all be supplemented by further ongoing work driving our knowledge of PDFs forward.

Backup Slides

Note: For some of the more recent work, this project (via TC) has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 101002090 COLORFREE).

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.

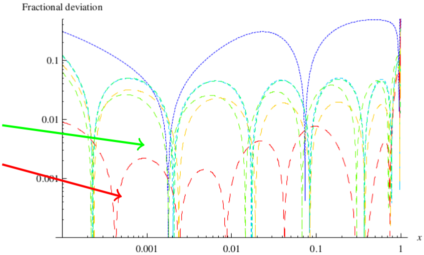
Clear preference for NNLO in new precision LHC data, NLO no longer sufficient.

- 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 $\bar{d}/\bar{u} \to \text{constant}$ 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.

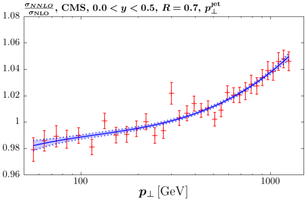
MSHT20: 2012.04684

Theoretical Developments - NNLO QCD

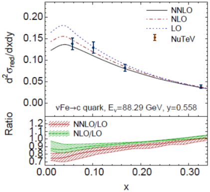
- Nearly all data now full NNLO in QCD, typically via k-factors relative to NLO grids. ↗Work on NNLO by Czakon et al, 2011.01011, JHEP 06 (2021) 100.
- Exception is CMS 7 TeV $W + c$ data only have NLO theory.
- Fit quality shows clear preference for NNLO over NLO now.

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.

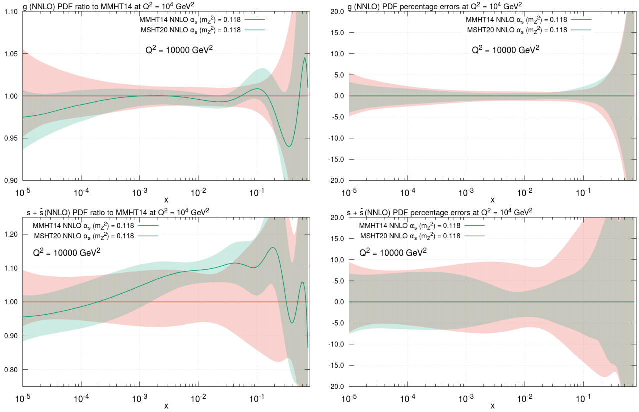
Greater theoretical accuracy.

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.)

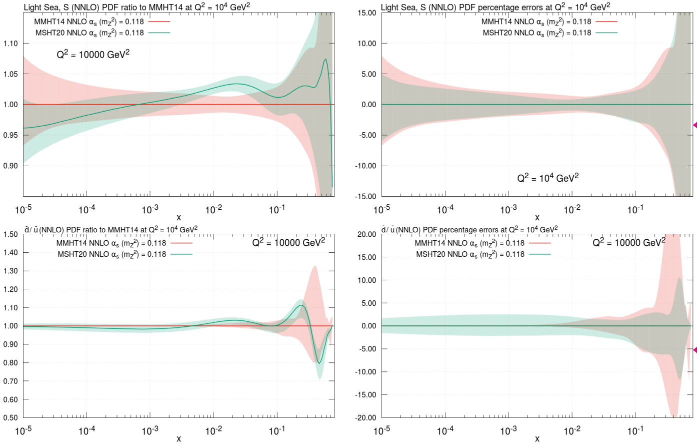
More information in our MSHT20 paper: arXiv:2012.04684, *Eur.Phys.J.C 81 (2021) 4, 341*

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.

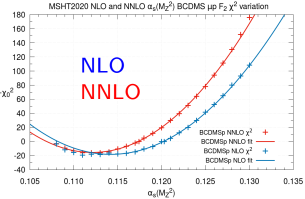
- Broadly consistent between MSHT20 and MMHT14.

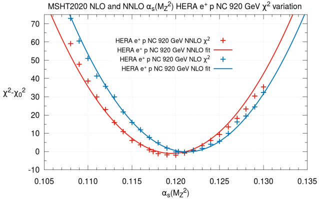
More information in our MSHT20 paper: arXiv:2012.04684, *Eur.Phys.J.C 81 (2021) 4, 341*

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.

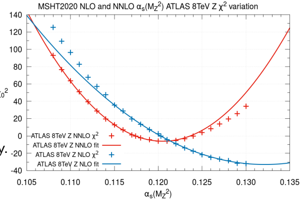


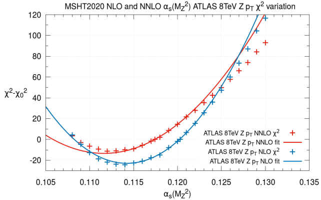


Broadly consistent with α_S pulls seen in MMHT14 study for older datasets.

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.

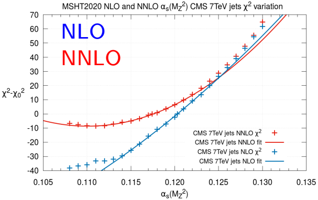
(More datasets in backup slides.)

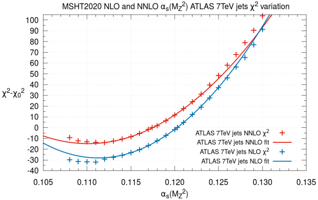
- Must do within global fit to capture α_S PDF correlations.
- Different datasets favour different $\alpha_S(M_Z^2)$ in global fit.
- Datasets with direct/indirect sensitivity to α_S prefer lower/higher α_S.

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.

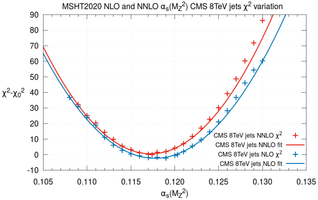
CMS 7 TeV jets prefers lower α_S, better quadratic profile at NNLO.

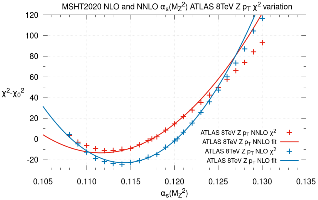




ATLAS 7 TeV jets prefers lower α_S.

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





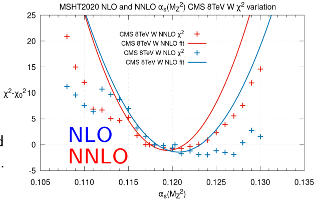
ATLAS 8 TeV Zp_T prefers lower α_S, allows increased high x gluon.

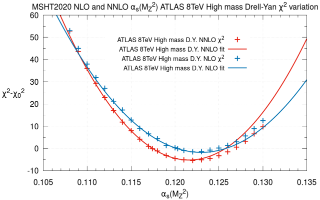
- Jets, Zp_T datasets have direct sensitivity to α_S, prefer lower α_S.

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.

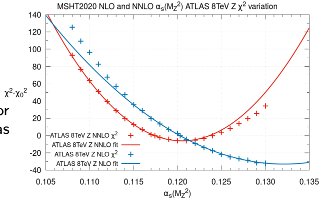
CMS 8 TeV W prefers slightly raised α_S, likely through its effects on q evolution and xsec normalisation.

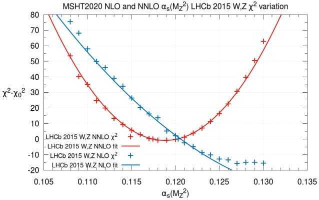




ATLAS 8 TeV High Mass DY prefers raised α_S.

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).

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:

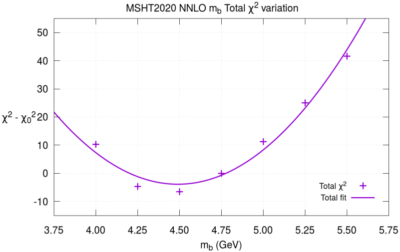
Quadrature as whilst central values correlated errors uncorrelated. CT: 1004.4624.

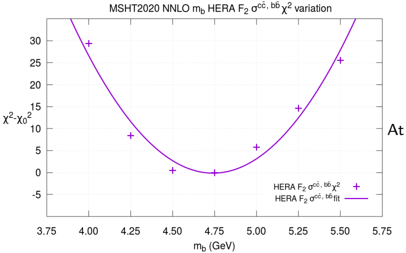
$$\Delta\sigma = \sqrt{(\Delta\sigma_{\mathrm{PDF}})^2 + (\Delta\sigma^2_{\alpha_S(M_Z^2)})}$$

- 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 $4.0\text{GeV} \leq m_b \leq 5.5\text{GeV}$ and examine fit qualities.





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

- Overall global fit dependence (left) centred on $m_b \approx 4.5\text{GeV}$.
- HERA heavy flavour combined charm and bottom (right) prefer bottom mass very close to our default $m_b = 4.75\text{GeV}$.
- 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:

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

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

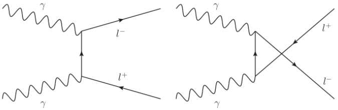
- QED corrections enter via QED modifications to DGLAP evolution:

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

$\Rightarrow$ 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.



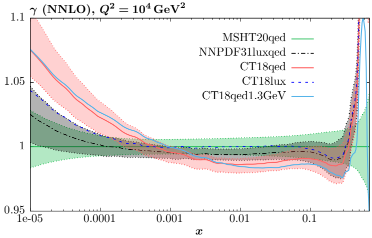
PI contributions to Drell-Yan.

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)*.

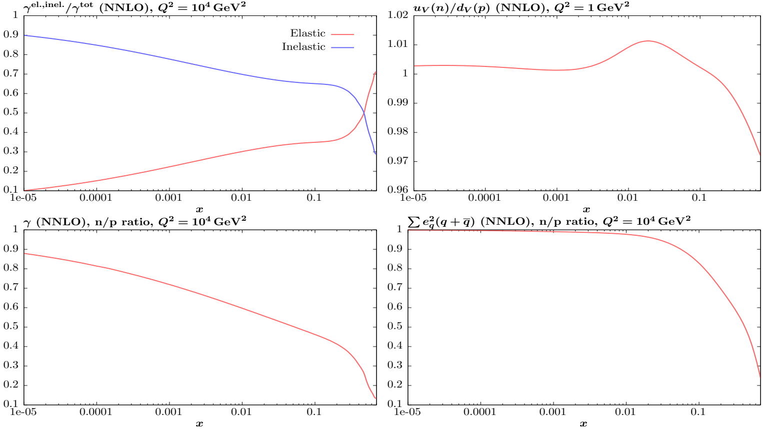
$$x\gamma(x,Q_0^2) = \frac{1}{2\pi\alpha(Q_0^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2m_p^2}{1-z}}^{Q_0^2}\frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[\left(zP_{\gamma,q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2)\right.\right.$$
$$\left.\left. -z^2F_L(x/z,Q^2)\right] - \alpha^2(Q_0^2)\left(z^2+\ln(1-z)zP_{\gamma,q}(z)-\frac{2x^2m_p^2z}{Q_0^2}\right)F_2(x/z,Q_0^2)\r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

- $\gamma(x,Q_0^2)$ 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 $\Rightarrow \gamma(p) \neq \gamma(n)$.



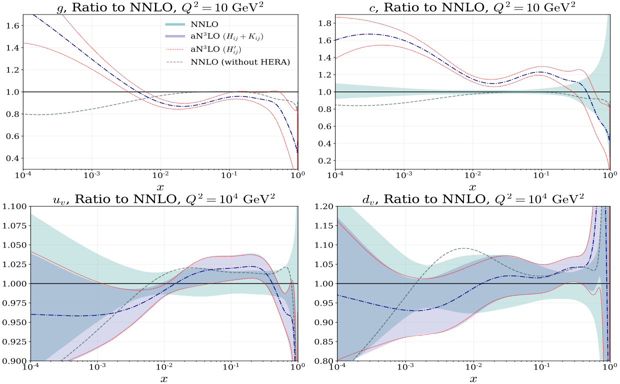
MSHT20aN3LO PDFs - Fit quality

- 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

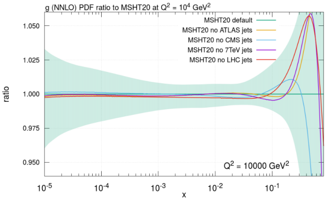
MSHT20aN3LO PDFs - PDF changes



- 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.

New data - Dijets - Introduction

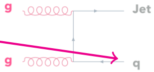
- High x gluon is of interest in PDFs, with tensions between datasets.
- MSHT20 - data on inclusive jets from ATLAS, CMS at 7 and 8 TeV, sensitive to high-x gluon. Different pulls.
- Known issues with systematic correlations in ATLAS 7, 8 TeV inclusive jets (latter therefore not included in MSHT20).



- 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: $\frac{d\sigma}{dp_T^{\text{avg}} dy^* dy_b}$.

CMS 8 TeV dijets

Dijets when triple differential more sensitive to x-dependence.

New data - EIC Pseudodata

EIC: Future Constraints?

- Recent study presented at DIS22:

- Detailed simulation work to optimise resolutions throughout phase-space
→ 5 bins per decade in x and Q^2

- Kinematic coverage: $Q^2 > 1$ GeV^2, $0.01 < y < 0.95$, $W > 3$ GeV

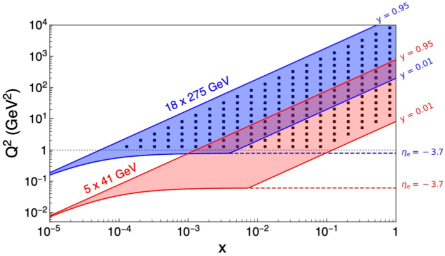
- Lower y accessible in principle, but easier to rely on overlaps between data at different $\sqrt{s}$

- Highest x bin centre at x=0.815

e-beam E	p-beam E	$\sqrt{s}$ (GeV)	inte. Lumi. (fb^{-1})
18	275	140	15.4
10	275	105	100.0
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4

- CC data also included for highest $\sqrt{s}$

5



- Including sensible projections for main uncertainty sources.

→ 1.5-2.5% point-to-point uncorrelated
→ 2.5% normalisation (uncorrelated between different $\sqrt{s}$)

P. Newman, DIS22