Unpolarised Parton Distribution Functions today: needs, achievements and challenges

Thirteenth Conference

on the Intersections of Particle and Nuclear Physics

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Indian Wells – 1^{st} June 2018

Outline

1. Needs
   - Accuracy and precision
2. Achievements
   - Data: impact of latest LHC measurements
   - Theory: NNLO QCD corrections, fitting charm, the photon PDF, resummed PDFs
3. Challenges
   - Theory: including missing higher order uncertainties in a fit
   - Methodology: tools for compression, visualisation and minimisation
4. Conclusions

DISCLAIMER

I will focus on collinear, unpolarised parton distribution functions

Emphasis on recent achievements and on topics which I've worked on recently

Apologies in advance for not discussing your favourite subject

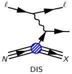
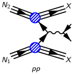
For an extensive review of topics not addressed in this talk, please see

[Phys.Rept. 742 (2018) 1; WG1 summary talk at DIS2018]

1. Needs

Factorisation of physical observables [Adv.Ser.Direct.HEP 5 (1988) 1]

$$\mathcal{O}_I = \sum_{f=q,\bar{q},g} C_{If}(x,\alpha_s(\mu^2)) \otimes f(x,\mu^2) + \text{p.s. corrections} \qquad f\otimes g = \int_x^1 \frac{dy}{y} f\left(\frac{x}{y}\right) g(y)$$

Process	Reaction	Subprocess	PDFs probed	x
	$\ell^\pm\{p,n\} \to \ell^\pm + X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
	$\ell^\pm n/p \to \ell^\pm + X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
	$\nu(\bar{\nu})N \to \mu^-(\mu^+) + X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
	$\nu N \to \mu^-\mu^+ + X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
	$\bar{\nu} N \to \mu^+\mu^- + X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
	$e^\pm p \to e^\pm + X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
	$e^+ p \to \bar{\nu} + X$	$W^+\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
	$e^\pm p \to e^\pm c\bar{c} + X$	$\gamma^* c \to c, \gamma^* g \to c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.1$
	$e^\pm p \to jet(s) + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
	$pp \to \mu^+\mu^- + X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
	$pn/pp \to \mu^+\mu^- + X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
	$p\bar{p}(pp) \to jet(s) + X$	$gg, qg, qq \to 2jets$	g, q	$0.005 \lesssim x \lesssim 0.5$
	$p\bar{p} \to (W^\pm \to \ell^\pm \nu) + X$	$ud \to W^+, \bar{u}\bar{d} \to W^-$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
	$pp \to (W^\pm \to \ell^\pm \nu) + X$	$u\bar{d} \to W^+, d\bar{u} \to W^-$	$u, d, \bar{u}, \bar{d}, (g)$	$x \gtrsim 0.001$
	$p\bar{p}(pp) \to (Z \to \ell^+\ell^-) + X$	$uu, dd(u\bar{u}, d\bar{d}) \to Z$	$u, d(g)$	$x \gtrsim 0.001$
	$pp \to (W + c) + X$	$gs \to W^- c, g\bar{s} \to W^+ \bar{c}$	$s, \bar{s}$	$x \sim 0.01$
	$pp \to t\bar{t} + X$	$gg \to t\bar{t}$	g	$x \sim 0.01$

A global determination of parton distribution functions

A mathematically ill-posed problem: determine a set of functions from a finite set of data

METHODOLOGY

1. Parametrisation: general, smooth, flexible at an initial scale Q_0^2

$$xf_i(x,Q_0^2) = A_{f_i}\, x^{a_{f_i}}\,(1-x)^{b_{f_i}}\,\mathscr{F}(x,\{c_{f_i}\})$$

small x: $xf_i(x,Q^2) \xrightarrow{x\to 0} x^{a_{f_i}}$

$\mathscr{F}(x,\{c_{f_i}\}) \xrightarrow[x\to 1]{x\to 0} \text{finite}$ — smooth interpolation in between

large x: $xf_i(x,Q^2) \xrightarrow{x\to 1} (1-x)^{b_{f_i}}$

2. A prescription to determine/compute expectation values and uncertainties

$$E[\mathcal{O}] = \int \mathcal{D}\Delta f \mathcal{P}(\Delta f|data)\mathcal{O}(\Delta f) \qquad V[\mathcal{O}] = \int \mathcal{D}\Delta f \mathcal{P}(\Delta f|data)[\mathcal{O}(\Delta f) - E[\mathcal{O}]]^2$$

Monte Carlo: $\mathcal{P}(\Delta f|data) \longrightarrow \{\Delta f_k\}$

$$E[\mathcal{O}] \approx \frac{1}{N}\sum_k \mathcal{O}(\Delta f_k)$$

$$V[\mathcal{O}] \approx \frac{1}{N}\sum_k [\mathcal{O}(\Delta f_k) - E[\mathcal{O}]]^2$$

Maximum likelihood: $\mathcal{P}(\Delta f|data) \longrightarrow \Delta f_0$

$$E[\mathcal{O}] \approx \mathcal{O}(\Delta f_0)$$

$$V[\mathcal{O}] \approx \text{Hessian}, \Delta\chi^2 \text{envelope}, \dots$$

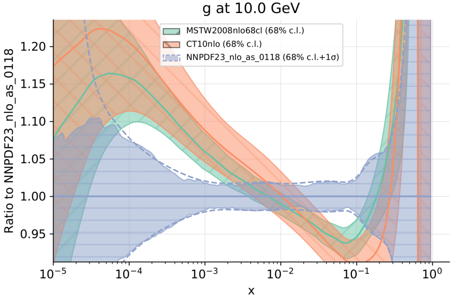
3. A self-validating procedure (closure test, dynamic tolerance)

COMBINED WITH THEORY AND DATA TO FIND BEST-FIT PDFs

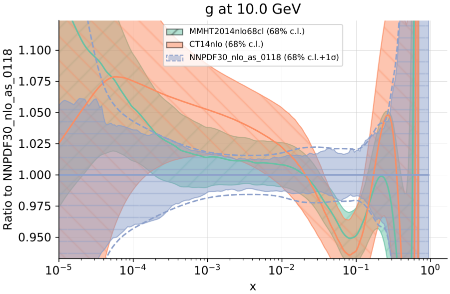
theory: NNLO QCD, GM-VFNS, charm, photon, . . . data set: as global as possible

Example: the gluon PDF

circa 2012



circa 2015



incompatible results from different groups

benchmarking exercise largely inconclusive

recommendation:
ignore individual group uncertainties
take the envelope of individual determinations

compatible results from different groups

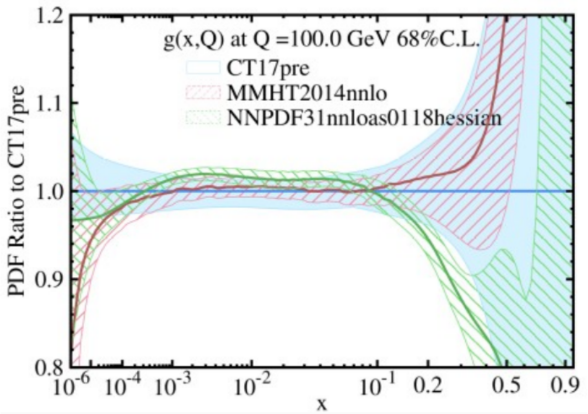
PDF uncertainties become meaningful

recommendation (PDF4LHC):
combine individual group uncertainties
into a statistically meaningful set

Agreement keeps improving
residual differences among groups can be explained in terms of differences
in the data set, details of the QCD analysis and methodology [PRD 86 (2012) 074017]

Example: the gluon PDF

circa 2018



[Tie-Jiun Hou, DIS 2018]

Agreement keeps improving

residual differences among groups can be explained in terms of differences in the data set, details of the QCD analysis and methodology [PRD 86 (2012) 074017]

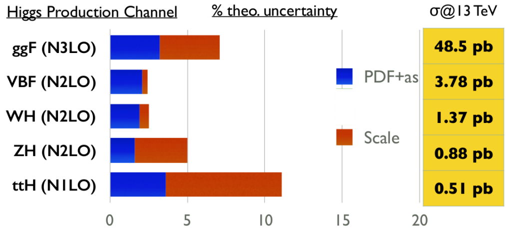
Overview of recent PDF determinations

	NNPDF3.1	MMHT2014	CT14	HERAPDF2.0	CJ15	ABMP16
Fixed target DIS	✓	✓	✓	✗	✓	✓
JLAB	✗	✗	✗	✗	✓	✗
HERA I+II	✓	(✓)	(✓)	✓	(✓)	✓
HERA jets	✗	✓	✗	✗	✗	✗
Fixed target DY	✓	✓	✓	✗	✓	✓
Tevatron W, Z	✓	✓	✓	✗	✓	✓
Tevatron jets	✓	✓	✓	✗	✓	✗
LHC jets	✓	✓	✓	✗	✗	✗
LHC vector boson	✓	✓	✓	✗	✗	✓
LHC top (incl.)	✓	✗	✗	✗	✗	✗
LHC (diff.)	✓	✗	✗	✗	✗	✗
statistical treatment	Monte Carlo	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2 = 1$	Hessian $\Delta\chi^2 = 1.645$	Hessian $\Delta\chi^2 = 1$
parametrisation	Neural Network (259 pars)	Chebyschev pol. (37 pars)	Bernstein pol. (30-35 pars)	polynomial (14 pars)	polynomial (24 pars)	polynomial (15 pars)
HQ scheme	FONLL	TR$'$	ACOT-χ	TR$'$	ACOT-χ	FFN
latest update	EPJ C77 (2017) 663	EPJ C75 (2015) 204	PRD 89 (2014) 033009	EPJ C75 (2015) 580	PRD 93 (2016) 114017	PRD 96 (2017) 014011

See also recommendations for PDF usage
in computations of (LHC) high-energy processes [JPG 43 (2016) 023001, EPJC 76 (2016) 471]

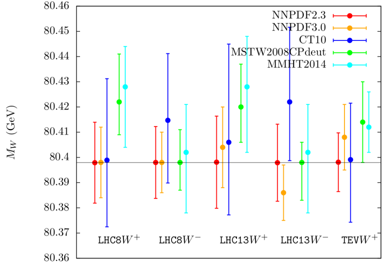
The role of PDF uncertainties

[CERN Yellow report, 1610.07922]

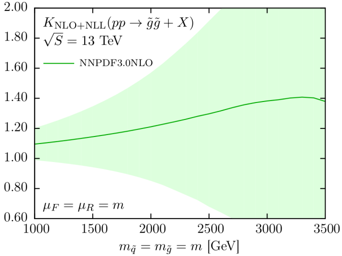


1. Higgs boson characterisation
   PDF uncertainty often dominant contribution to theory uncertainty
2. Determination of SM parameters
   PDF uncertainty largest theoretical uncertainty in M_W determination
3. BSM gluino production
   the larger the mass of the final state the larger the PDF uncertainty

[PRD 91 (2015) 113005]



[EPJ C76 (2016) 53]



2. Achievements

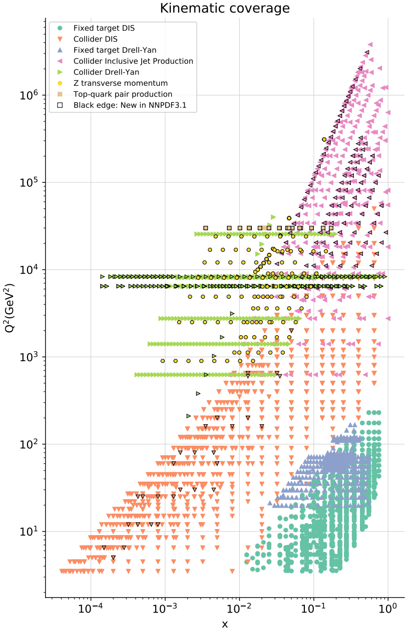
A plethora of new data

1. GLUON
   inclusive jets and dijets (medium/large x)
   isolated photon and γ+jets (medium/large x)
   top pair production (large x)
   high p_T V production (small/medium x)

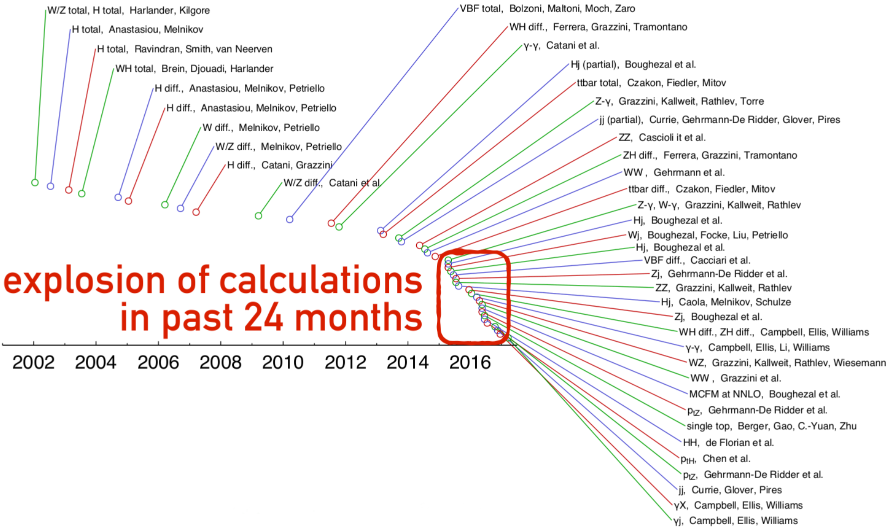
2. QUARKS
   high $p_T W$(+ jets) ratios (medium/large x)
   W and Z production (medium x)
   low and high mass DY (small and large x)
   $W + c$ (strange at medium x)

3. PHOTON
   low and high mass DY
   WW production

4. Great progress also in interface NLO (NNLO) codes to PDF fitting codes
   APPLgrid [EPJ C66 (2010) 503]
   FASTNLO [Kluge et al., 2010]
   aMCfast [JHEP 1408 (2014) 166]
   MCgrid [CPC 185 (2014) 2115]
   APFELgrid [CPC 212 (2017) 205]

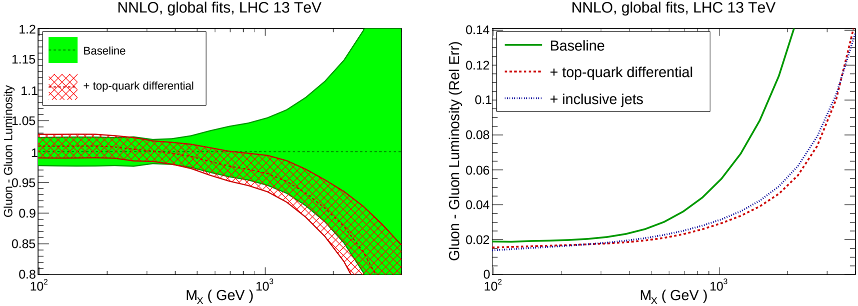


A wealth of new NNLO calculations



[Slide: courtesy of G. Salam, updated April 2017]

The gluon PDF at large x: $t\bar{t}$ differential distributions



ATLAS and CMS rapidity distributions at $\sqrt{s} = 8$ TeV

Significant reduction of gg luminosity uncertainties at $M_X \geq \mathcal{O}(1)$ TeV

e.g., at $M_X \sim 2$ TeV, uncertainties decrease from 13% to 5%

Impact of $t\bar{t}$ differential data similar to that of jet data

though jet data analysed neglecting NNLO QCD corrections in the matrix element

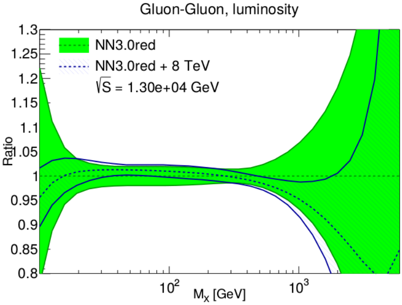
A precision determination of the gluon PDF at large x is now possible at NNLO

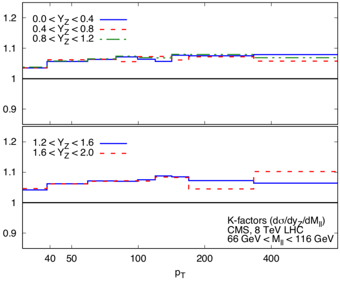
the situation should only improve thanks to the recent NNLO jet calculation

$t\bar{t}$ differential distributions are included in the NNPDF3.1 PDF release

[see JHEP 1704 (2017) 044 and EPJ C77 (2017) 663 for details]

The gluon PDF at medium x: the Z-boson p_T distribution





ATLAS and CMS p_T distributions at $\sqrt{s} = 8$ TeV
in various rapidity bins in the Z-peak region

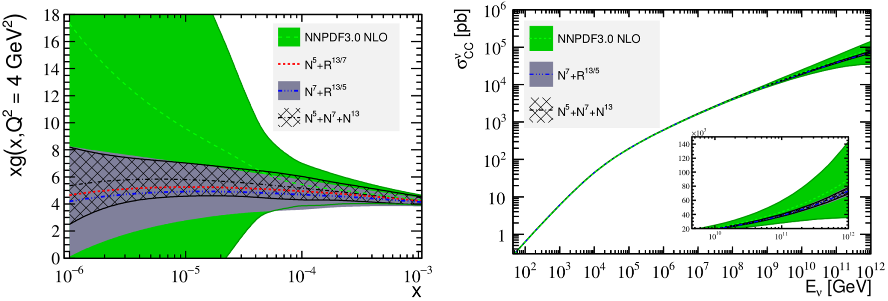
NNLO/NLO K-factors 5%-10% depending on the rapidity/invariant mass region
challenge: measurements have sub-percent experimental errors

Complementary information on the gluon PDF
e.g., at $M_X \sim 2$ TeV, uncertainties decrease from 13% to 8%

Z p_T distributions are included in the NNPDF3.1 PDF release

[see JHEP 1707 (2017) 130 and EPJ C77 (2017) 663 for details]

The gluon PDF at small x: forward charm production



D meson production from LHCb at different center-of-mass energies

$$N_X^{ij} = \frac{d^2\sigma(X\ \text{TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(X\ \text{TeV})}{dy_{\text{ref}}^D d(p_T^D)_j} \qquad R_{13/X}^{ij} = \frac{d^2\sigma(13\ \text{TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(X\ \text{TeV})}{dy_i^D d(p_T^D)_j}$$

Gluon PDF errors are reduced by up to a factor 10 below $x \sim 10^{-5}$

robust w.r.t theoretical uncertainties (charm mass, scale variations, alternative reference bins)

Combine result with future LHeC measurements of F_L

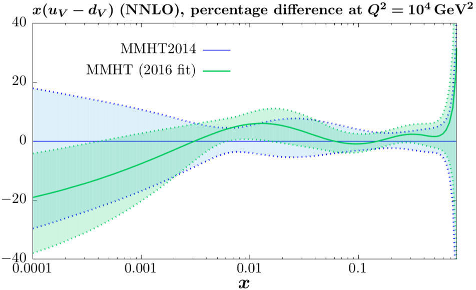
test for BFKL resummations and non-linear QCD dynamics

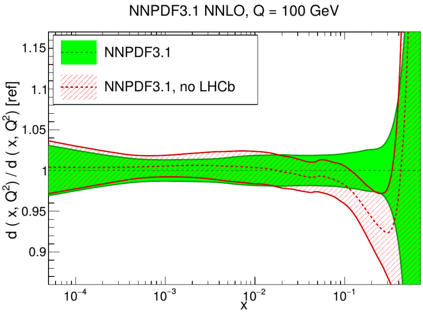
Application: ultra high-energy (UHE) neutrino-nucleus cross-sections

NLO QCD provides a prediction accurate to $\lesssim 10\%$ at $E_\nu \simeq 10^{12}$ GeV

[see PRL 118 (2017) 072001 for details]

Quark flavour separation from LHC data





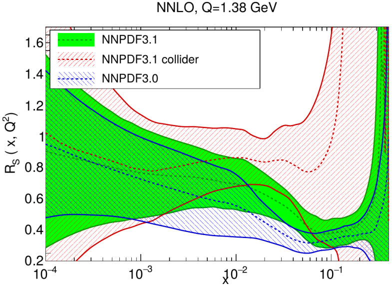
High-precision W and Z production data from ATLAS, CMS and LHCb
handle on quark/antiquark flavour separation

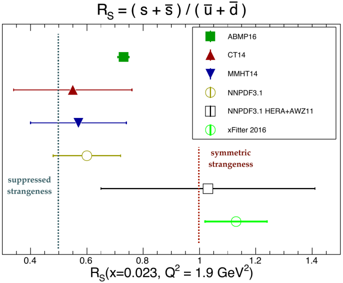
Largest impact on light quarks at large x provided by LHCb data
error reduction by a factor 2 in NNPDF3.1 at $x \sim 0.1$

Combined effect of (LHC) CMS, LHCb and (Tevatron) D0 W, Z data
improved determination of $x(u_V - d_V)$

[see R. Thorne's talk at DIS2017 and EPJ C77 (2017) 663 for details]

The strange PDF from collider data





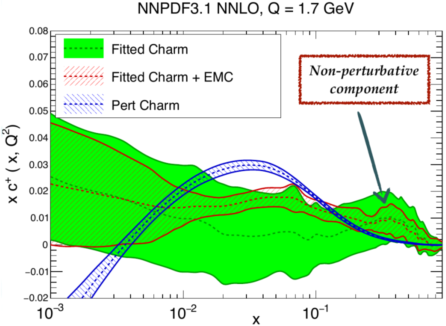
In most PDF fits the strange PDF is suppressed w.r.t up and down sea quark PDFs
effect mostly driven by neutrino dimuon data

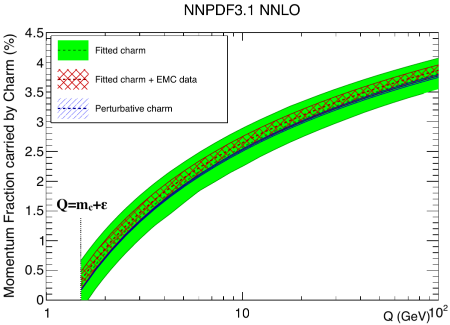
A symmetric strange sea PDF is preferred by collider data
in particular by ATLAS W, Z rapidity distributions (2011) [EPJ C77 (2017) 367]

$$R_s(x, Q^2) = \frac{s(x, Q^2) + \bar{s}(x, Q^2)}{\bar{u}(x, Q^2) + \bar{d}(x, Q^2)} \begin{cases} \sim 0.5 \text{ from neutrino and CMS } W + c \text{ data} \\ \sim 1.0 \text{ from ATLAS } W, Z \end{cases}$$

The ATLAS data can be accommodated in the global fit
increased strangeness, though not as much as in a collider-only fit
some tension remains between collider and neutrino data
Suppressed strangeness confirmed by recent $W + c$ CMS analysis [CMS PAS SMP-17-014]

The charm PDF: perturbative vs fitted [EPJ C76 (2016) 647, see also M. Guzzi]





Parametrise the $c^+(x, Q_0^2)$, quark and gluon PDFs on the same footing

stabilise the dependence of LHC processes upon variations of m_c

quantify the nonperturbative charm component in the proton (BHPS? sea-like?)

take into account massive charm-initiated contribution to the DIS structure functions

Fitted charm found to differ from perturbative charm at scales $Q \sim m_c$ in NNPDF3.1

preference for a BHPS-like shape

shape driven by LHCb W, Z data + EMC data

At $Q = 1.65$ GeV charm carry 0.26 ± 0.42 % of the proton momentum

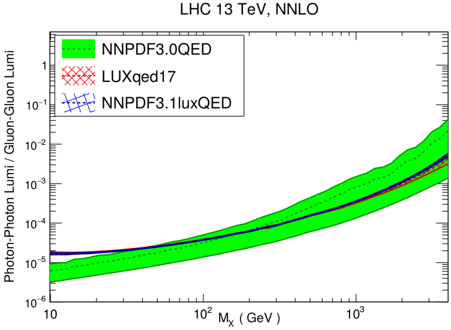
but it is affected by large uncertainties, especially if no EMC data are included

The photon PDF: how bright is the proton?

The photon PDF $\gamma(x,Q)$ *in* ***LUXqed***

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

Good agreement with NNPDF3.0QED, model-independent fit from LHC DY data



NNPDF3.0QED: model-independent determination of $\gamma(x,Q)$ from LHC W,Z data

affected by large uncertainties, $\mathcal{O}(100\%)$ due to limited experimental information

LUXQED: compute $\gamma(x,Q)$ in terms of inclusive structure functions F_2 and F_L

significant improvement in the PDF uncertainty

implications for high-mass processes for BSM searches, *e.g.* DY production at the TeV scale

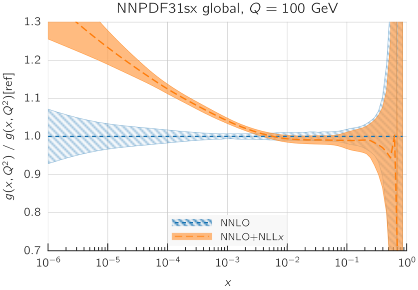
NNPDF3.1LUXQED: consistent NNPDF fit with LUXQED constraint

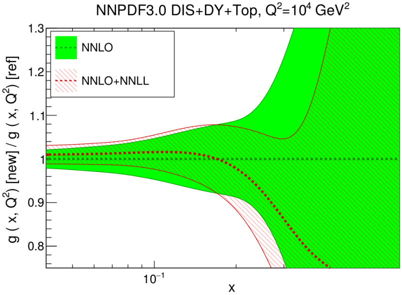
good agreement, but smaller uncertainties

sizable impact on precision physics: *e.g.* associated Higgs production with W

[See NPB 877 (2013) 290; arXiv:1606.07130; PRL 117 (2016) 242002; arXiv:1712.07053]

Beyond fixed-order accuracy





small x: $\frac{1}{x}\ln^k x$

high-energy gluon emission: single logs

large x: $\left(\frac{\ln^k(1-x)}{(1-x)}\right)_+$

soft gluon emission: double logs

Large logs $\alpha_s \ln \sim 1$ spoil the convergence of the perturbative series

PDFs with threshold resummation [JHEP 1509 (2015) 191] (only DIS, DY Z/γ, total $t\bar{t}$ + evol.)

suppression in PDFs partially or totally compensates enhancements in partonic cross-sections

accuracy of the resummed fit competitive with the fixed-order fit, except for the large-x gluon

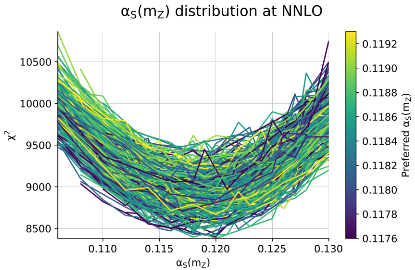
large uncertainties for MSSM particle resummed cross-sections [EPJ C76 (2016) 53]

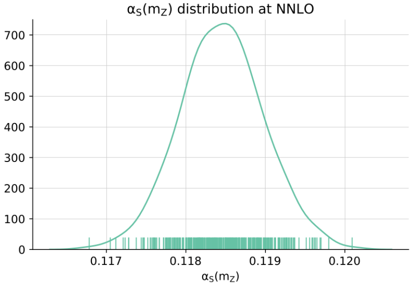
PDFs with high-energy resummation [EPJ C78 (2018) 321] (only DIS + evol.)

Resummed PDFs enhanced at small x, uncertainties reduced

Large effects for future colliders, or b production at LHC

The correlated replica method and α_s [EPJ C78 (2018) 408]



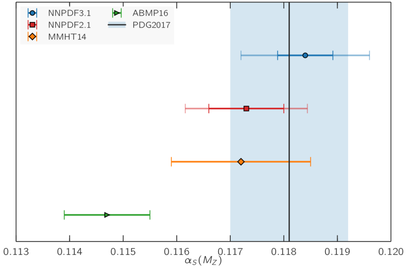


How can we take into account PDF/α_s correlations in a Monte Carlo way?

for each data sample (replica), perform a scan in α_s

each replica has a preferred value of the α_s (the minimum of each parabola)

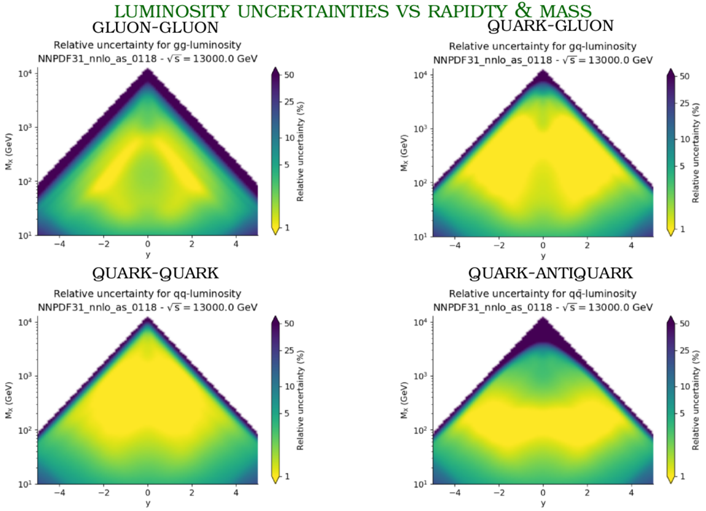
these preferred values form a Monte Carlo distribution



$$\alpha_s^{\rm NNLO}(M_Z) = 0.1185 \pm 0.0005^{\rm exp} \pm 0.0001^{\rm meth} \pm 0.0011^{\rm th} = 0.1185 \pm 0.0012 (1\%)$$

3. Challenges

Towards 1% PDF uncertainties



Typical PDF uncertainty in data region of order 1%
Can we believe in 1% PDF uncertainties? What are the consequences?

Higher data precision, more fit challenges

Example 1: ATLAS 7 TeV jets [EPJ C78 (2018) 248]

Each rapidity bin can be fitted with $\chi^2/d.o.f. \sim 1$, best-fit PDFs indistinguishable

If all bins are fitted simultaneously, $\chi^2/d.o.f. \sim 3$

$\Longrightarrow$ misestimated correlations?

Example 2: The CMS double differential DY 2011 [EPJ C77 (2017) 663]

from 2011 to 2012, uncorrelated ucnertainties down to sub-permille

2011: $\chi^2/d.o.f. \sim 1$; 2012: impossible to fit better than $\chi^2/d.o.f. \sim 3$

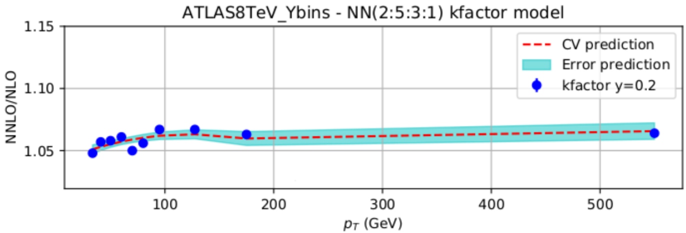
$\Longrightarrow$ pathological behaviour of covariance matrix, what is the uncertainty on it?

Example 3: The ATLAS 7 TeV p_T distribution [EPJ C77 (2017) 663]

uncorrelated statistical uncertainties at permille level

large NNLO corrections $\sim 10\%$, but nominal K-factor uncertainties very small

$\Longrightarrow$ fit only possible with estimate of theory uncertainties

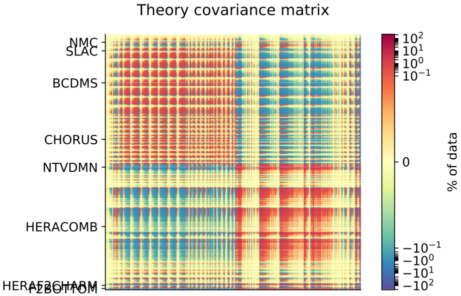


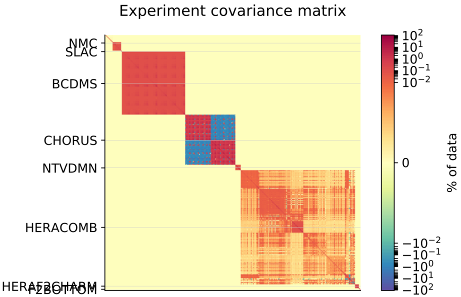
Including the theory covariance matrix in a fit

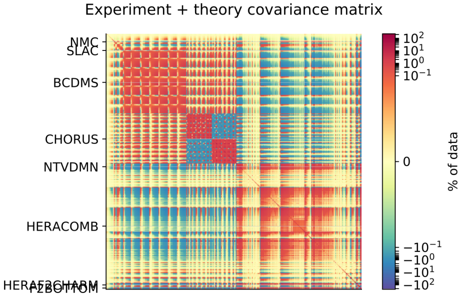
Very preliminary

$$\mathcal{O}_i(\mu_R, \mu_F),\ i = 1, N_{\rm dat}$$
$$\Delta_i^+ = \mathcal{O}_i(\mu_R, \mu_F) - \mathcal{O}_i(2\mu_R, 2\mu_F)$$
$$\Delta_i^- = \mathcal{O}_i(\mu_R, \mu_F) - \mathcal{O}_i(\tfrac{1}{2}\mu_R, \tfrac{1}{2}\mu_F)$$

$$\text{Cov}_{\rm th}[\mathcal{O}_i, \mathcal{O}_j] = \Delta_i^+\Delta_j^+ - \Delta_i^-\Delta_j^-$$
$$\text{Cov}_{\rm tot} = \text{Cov}_{\rm exp} + \text{Cov}_{\rm th}$$







Computational efficiency

Issue 1: PDF fits are computationally expensive

Can modern optimisation tools (evolutionary strategies, analytical gradients) help?

CMA-ES [arXiv:1711.09991]; IMC [PRD 94 (2016) 114004]

Assess the impact of the data without refitting

Bayesian reweighting [NPB 855 (2012) 608] and Hessian profiling [JHEP 12 (2014) 100]

Issue 2: Monte Carlo sets are delivered in terms of a large number of replicas

Option1: compression [EPJ C75 (2015) 474]

select a subset of replicas whose statistical features are as close as possible to those of the prior

Option2: Monte Carlo to Hessian conversion [EPJ C75 (2015) 369]

sample the replicas on a discrete grid, select the eigenvectors of the ensuing covariance matrix

Issue 3: PDF sets are not optimised for specific processes

Tools for visualising sensitivity of PDFs to (hadronic) data

SMPDF [EPJ C76 (2016) 205] and PDFSense [arXiv:1803.02777]

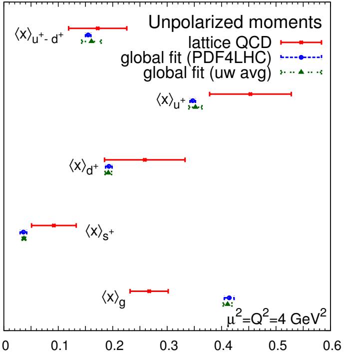
select subset of the covariance matrix correlated to a given set of processes

perform single value decomposition on the covariance matrix and select dominant eigenvector

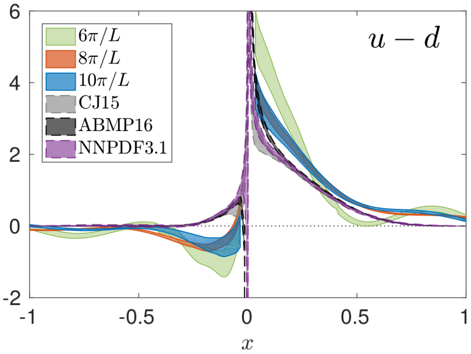
project out orthogonal subspace and iterate until desired accuracy reached

Input from Lattice QCD [Prog.Part.Nucl.Phys. 100 (2018) 107; see K.-F. Liu]

Moments



Quasi-PDFs



Various lattice QCD methods to determine PDF-related quantities

Need for a rigorous characterisation of the systematic uncertainties

Promising results, but still not competitive with global QCD analyses

4. Conclusions

Summary and outlook

1. The impact of the data
   - LHC data have now the dominant impact on PDFs (gluon and flavour separation) although collider-only fits are still not competitive
   - Methodology and theory must adapt accordingly
2. The (limits of the) methodology
   - statistical analysis tools necessary to cope with data accuracy
   - PDF uncertainties are faithful, but not optimised
3. The theory frontier
   - with sub-percent data uncertainties, theory uncertainties become dominant
   - resummation advantageous, electroweak corrections mandatory
4. Beyond the frontier
   - NNPDF `http://nnpdf.mi.infn.it/`
   - N3PDF `http://n3pdf.mi.infn.it/`

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Thank you