The PDFLattice2017 workshop: a summary report

XXV International Workshop on Deep-Inelastic Scattering and Related Subjects

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Rudolf Peierls Centre for Theoretical Physics - University of Oxford

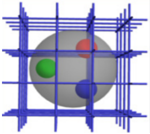
University of Birmingham – April 4 2017

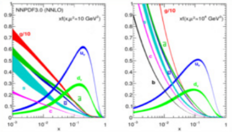
PDFLattice 2017

Parton Distributions and Lattice Calculations in the LHC era

22 -24 March 2017, Balliol College, Oxford, UK

http://www.physics.ox.ac.uk/confs/PDFlattice2017/index.asp





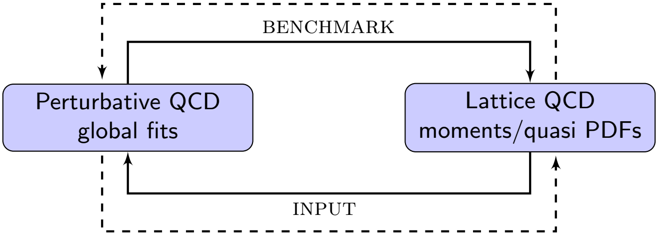
A first joint workshop between global-fitting and lattice PDF communities

Huey-Wen Lin (MSU), Emanuele R. Nocera (Oxford), Fred Olness (SMU), Kostas Orginos (W&M & JLab), Juan Rojo (VU Amsterdam and NIKHEF)

"The goal of this workshop is to **bring together the global PDF analysis and lattice-QCD PDF communities** *in order to explore ways to improve current PDF determinations. In particular, we plan to* **set precision goals for lattice-QCD calculations** *so that these calculations, together with the experimental input, can achieve improved determinations of PDFs. We discuss what impact such improved determinations of PDFs will have on future new-physics searches."*

Bridging two families together

LHC era broadly denotes high-energy precision physics,
not bound only to the LHC physics program, but including also RHIC, JLAB, ...



LHC (precision physics)	RHIC, JLAB (hadron physics)
Higgs boson characterisation	Spin physics, nucleon structure
Precision SM measurements (*e.g.* M_W)	Large-x behaviour
BSM searches, SUSY	Nuclear modifications

PERTURBATIVE AND LATTICE QCD INTERPLAY IN PDF DETERMINATIONS

Conscious focus on collinear unpolarised and longitudinally polarised PDFs only

Workshop format

Workshop by invitation only, a total of 28 participants: 14 pQCD/14 lQCD

Alberto Accardi (Hampton & JLab)
Constantia Alexandrou (Cyprus)
Alessandro Bacchetta (Pavia)
Gunnar Bali (Regensburg)
Giuseppe Bozzi (Pavia)
Jiunn-Wei Chen (Taiwan)
Sara Collins (Regensburg)
Amanda Cooper-Sarkar (Oxford)
Martha Constantinou (Temple)
Luigi del Debbio (Edinburgh)
Michael Engelhardt (New Mexico)
Jeremy Green (Mainz)
Rajan Gupta (Los Alamos)
Lucian Harland-Lang (UCL)
Tomomi Ishikawa (SJTU)
Aleksander Kusina (LPSC Grenoble)
Huey-Wen Lin (MSU)
Keh-Fei Liu (Kentucky)
Simonetta Liuti (Virginia)
Christopher Monahan (Rutgers)
Pavel Nadolsky (SMU)
Emanuele Nocera (Oxford)
Fred Olness (SMU)
Kostas Orginos (W&M and JLab) Juan Rojo (VU Amsterdam and NIKHEF)
Ingo Schienbein (LPSC Grenoble)
Gerrit Schierholz (DESY)
Werner Wogelsang (Tuebingen)

Wednesday afternoon: introductory overview talks

Thursday, all day: dedicated talks to specific topics (morning lQCD/afternoon pQCD)

Friday, sess. 1: open discussions on floor-nominated/selected topics from Thursday talks

Friday, sess. 2: white paper organization (structure, assignments, format, deadline)

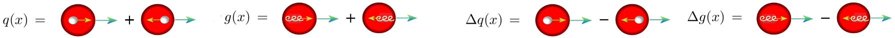
The outcome of the workshop will be compiled in a joint-community white paper including specific deadlines and precision goals for physics impact

Precedent: muon g-2, now the highest priority in the US (money and computational resources)

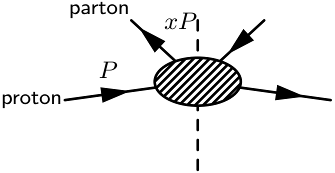
Parton distribution functions [Rev.Mod.Phys. 67 (1995) 157]

1. The densites of partons $f = q, \bar{q}\,(q = u, d, s, c, b), g$ with momentum fraction x

$$f(x) \equiv f^{\uparrow}(x) + f^{\downarrow}(x) \qquad\qquad \Delta f(x) \equiv f^{\uparrow}(x) - f^{\downarrow}(x)$$



2. Allow for a proper field-theoretic definition as matrix elements of bilocal operators



collinear transition of a massles proton h
into a massless parton i
with fractional momentum x
local OPE $\Longrightarrow$ lattice formulation

$$\begin{aligned} q(x) &= \frac{1}{4\pi}\int dy^- e^{-iy^- xP^+}\langle P|\bar{\psi}(0, y^-, \mathbf{0}_\perp)\gamma^+\psi(0)|P\rangle \\ \Delta q(x) &= \frac{1}{4\pi}\int dy^- e^{-iy^- xP^+}\langle P, S|\bar{\psi}(0, y^-, \mathbf{0}_\perp)\gamma^+\gamma^5\psi(0)|P, S\rangle \end{aligned}$$

with light-cone coordinates

$$y = (y^+, y^-, \mathbf{y}_\perp)\,, \quad y^+ = (y^0 + y^z)/\sqrt{2}\,, \quad y^- = (y^0 - y^z)/\sqrt{2}\,, \quad \mathbf{y}_\perp = (v^x, v^y)$$

3. All these definitions have ultraviolet divergences which must be renormalized

PDFs from the perturbative QCD perspective

1. Factorisation of physical observables
a variety of sufficiently inclusive processes allow for a factorised description

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

2. Evolution of parton distributions
perturbative QCD corrections lead PDFs to depend on μ according to DGLAP

$$\frac{\partial}{\partial \ln \mu^2} f_i(x,\mu^2) = \sum_j^{n_f} \int_x^1 \frac{dz}{z} P_{ji}\left(z,\alpha_s(\mu^2)\right) f_j\left(\frac{x}{z},\mu^2\right)$$

3. Parametrisation of PDFs
a sufficiently general, smooth and flexible form at an initial scale Q_0

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

4. A prescription to determine/compute expectation values and uncertainites
Monte Carlo: $\mathcal{P}(\Delta f|data) \longrightarrow \{\Delta f_k\}$ Maximum likelihood: $\mathcal{P}(\Delta f|data) \longrightarrow \Delta f_0$

Final PDFs result from a careful balance of data, theory and methodology

PDFs from the perturbative QCD perspective: open issues

Unpolarised PDFs

1. The gluon PDF at small x
   large uncertainties below $x \sim 10^{-4}$, charm production from LHCb [Juan's talk]
2. The gluon PDF at large x
   large uncertainties above $x \sim 0.5$, inclusive jet and $t\bar{t}$ production from ATLAS and CMS
3. The light sea quark asymmetry
4. The strange PDF (and its suppression w.r.t. the light sea quark asymmetry)
5. The PDF ratio d_V/u_V at large x

Polarised PDFs

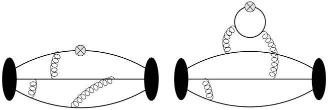
1. The polarised strange PDF and its connection with a potential SU(3) breaking
   what is the sign of Δs^+?
2. The polarised sea quark PDFs
   sea asymmetry positive, with large uncertainties, SIDIS and $W^\pm$ production at RHIC
3. The gluon polarisation at small x
   polarised gluon unconstrained below $x \sim 0.03$, need for an EIC
4. The ratio of total polarised to unpolarised PDFs, $\Delta u^+/u^+$ and $\Delta d^+/d^+$, at large x
   large uncertainties, no real discrimination among models, JLAB data may help

PDFs from the lattice QCD perspective

Moments of parton distributions

$$f_a^J(\mu_F^2) = \int dz\, z^{J-1} f_a(z,\mu_F^2) \qquad \langle P|[\mathcal{O}_a^J]|P\rangle = \int dx\, x^{J-1}[f_a(x,\mu^2) + f_{\bar{a}}(x,\mu^2)]$$

example: axial-vector operator $\mathcal{O}_A^0 = \bar{\psi}(x)\gamma^+\gamma_5\psi(x)$ related to g_A



need to renormalise the operators on the lattice
full control of systematics on the lowest couple of moments (operator mixing, renormalization)
moments involving connected contributions only are easier to compute

Moments of structure functions

$$C_a^J(Q^2/\mu_F^2,\alpha_s) = \int dz\, z^{J-1} C_a(z, Q^2/\mu_F^2,\alpha_s) \qquad \sum_a C_a^J(Q^2)\langle P|[\mathcal{O}_a^J]|P\rangle = F^{J-1}(Q^2)$$

compute $F_1(x,Q^2)$, $F_2(x,Q^2)$, $g_1(x,Q^2)$, $g_2(x,Q^2)$ from the Compton amplitude
possible extensions to some lattice cross sections

PDFs from the lattice QCD perspective

DIRECT x-DEPENDENCE: QUASI PDFs [PRL 110 (2013) 262002]

Quark bilinear slightly away from the (space-like) light-cone in the proton rest frame
One can find a frame where the quark bilinear is of equal time but the proton is moving

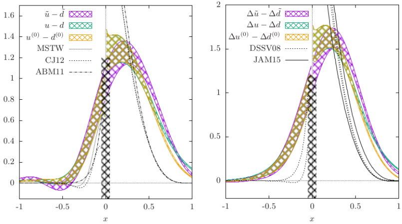
$$\tilde{q}(x,\mu,P_z) = \int \frac{dz}{4\pi} e^{-ixzP_z} \langle P|\bar{\psi}(0)\lambda\cdot\gamma\Gamma\psi(z\lambda)|P\rangle, \quad \lambda^\mu = (0,0,0,1)$$

The light-cone distribution is an effective field theory of the quasi PDF, in which there are large logarithms $\ln P_z$ in perturbation theory, which can be transformed into the standard renormalization scale dependence in the light-cone distribution through matching conditions

$$\tilde{q}(x,\mu^2,P_z) = C_F\frac{\alpha}{2\pi}\left\{\frac{x}{(1-x)^2}\frac{\Lambda}{P_z} + \frac{1+x^2}{1-x}\ln\frac{\Lambda P^z}{\lambda^2}\right\} \qquad \Lambda = \sqrt{\mu^2+(1-x)^2(P^z)^2} - (1-x)P^z$$

$P_z \to \infty$ recover Altarelli-Parisi kernel; $\mu^2 \to \infty$ first term is linear divergent

$$\tilde{q}(x,\mu^2,P_z) = \int_x^1 \frac{dy}{y} Z\left(\frac{x}{y},\frac{\mu}{P_z}\right) q(y,\mu^2)$$



Unpolarised valence and sea quarks at large x

Perturbative QCD

Valence unpol. quarks at large x relatively well known from fixed-target DIS experiments
Sea unpol. quarks at large x poorly known from lack of direct constraints

$$(U-D)(Q^2) = \int_0^1 dx\, x \left[u(x,Q^2) - d(x,Q^2)\right] \qquad (\bar{U}-\bar{D})(Q^2) = \int_0^1 dx\, x \left[\bar{u}(x,Q^2) - \bar{d}(x,Q^2)\right]$$

		$(U-D)(Q^2)$			$(\bar{U}-\bar{D})(Q^2)$	
$Q = 100$ GeV	PDF c.v.	PDF err.	shift w.r.t NNPDF3.0	PDF c.v.	PDF err.	shift w.r.t NNPDF3.0
NNPDF3.0	0.102	2.4%	—	-0.0038	51%	—
CT14	0.104	3.2%	+2.4%	-0.0055	25%	+43%
MMHT14	0.101	2.6%	-1.5%	-0.0060	14%	+57%

Triplet combination of pol. quarks related to the baryon decay constants

$$g_A = \int_0^1 dx \left[\Delta u(x,Q^2) + \Delta\bar{u}(x,Q^2) - \Delta d(x,Q^2) - \Delta\bar{d}(x,Q^2)\right]$$

$g_A = 1.2701 \pm 0.0025$ (fixed) $\qquad g_A = 1.19 \pm 0.22$ (fitted)

Lattice QCD

$\langle x\rangle_{u^+-d^+}(Q^2) \qquad \langle x^2\rangle_{u^--d^-}(Q^2) \qquad \langle 1\rangle_{\Delta u^+-\Delta d^+}(Q^2)$

Combined accurate computation of moments may provide insight
on unpol. sea quarks and pol. g_A once used in a global pQCD fit
Also, useful input on the ratios $\Delta u^+/u^+$ and $\Delta d^+/d^+$ at large x

Unpolarised and polarised strangeness

Perturbative QCD

Currently some controversy about how large the unpol. strangeness in the proton is

$$(S+\bar{S})(Q^2) = \int_0^1 dx\, x\left[s(x,Q^2)+\bar{s}(x,Q^2)\right]$$

$Q=5$ GeV	PDF c.v	PDF err.	shift w.r.t NNPDF3.0
NNPDF3.1	0.46	6%	—
CT14	0.43	18%	-7%
MMHT14	0.43	16%	-7%

Polarised strangeness determined from octet barion decays
(though SU(3) can be broken at least up to 30%)

$$a_8 = \int_0^1 dx\, x\left[\Delta u(x,Q^2)+\Delta\bar{u}(x,Q^2)+\Delta d(x,Q^2)+\Delta\bar{d}(x,Q^2)-2\Delta s(x,Q^2)-2\Delta\bar{s}(x,Q^2)\right]$$

$a_8 = 0.585 \pm 0.025(\pm 0.176)$ (fixed) the fit (DIS only) does not converge (a_8 fitted)

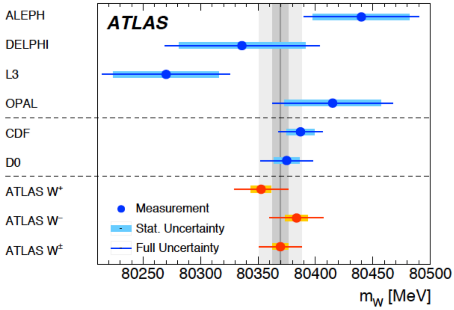
Lattice QCD

$$\langle x\rangle_{s^+}(Q^2) \qquad \langle x^2\rangle_{s^-}(Q^2) \qquad \langle 1\rangle_{s^+}(Q^2) \qquad \langle x\rangle_{s^-}(Q^2)$$

Large PDF uncertainties imply that lattice QCD could have an impact here
In principle, lattice can provide a handle on the separation between $s/\bar{s}$ and $\Delta s/\Delta\bar{s}$
Also, indications from lattice QCD about whether unpol. strangeness is suppressed w.r.t. light unpol. sea quarks would be most valuable

Opportunities: the W mass [from J. Rojo's talk]

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0



The recent measurement of the W mass at 7 TeV by ATLAS is dominated by PDF uncertainties

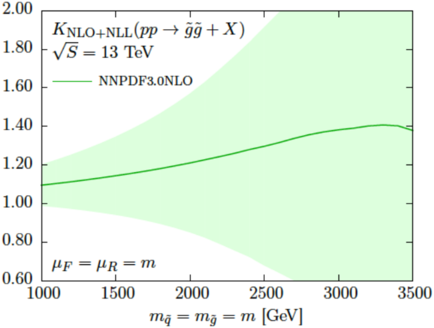
Can lattice QCD have an impact here? Can we define an accuracy target for the reduction of PDF uncertainties in W mass measurements?

Note that this is a decisive indirect probe of BSM physics

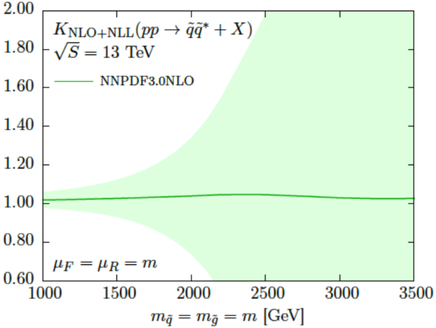
Opportunities: high-mass BSM particle production

Direct sensitivity to high-mass BSM particle production (squarks) at the LHC

Beenakker, Borchensky, Kramer, Kulesza, Laenen, Marzani, Rojo 15



PDF uncertainties in gluino pair production



PDF uncertainties in squark pair production

Large PDF errors driven by lack of knowledge of gluon and anti-quark PDFs at large x

Possible lattice QCD accuracy target
high-mass BSM cross sections with few-percent PDF uncertainties

Outcomes

1. Setting a common language
   - Benchmark moments of collinear unpol. and long. pol. PDFs ($\overline{\mathrm{MS}}$, $Q^2 = 4$ GeV)

$$\langle x\rangle_{u^+-d^+}(\mu^2)\Big|_{\mu^2=Q^2} = \int_0^1 dx\, x\left\{u(x,Q^2)+\bar{u}(x,Q^2)-d(x,Q^2)-\bar{d}(x,Q^2)\right\}$$

$$\langle x^2\rangle_{u^--d^-}(\mu^2)\Big|_{\mu^2=Q^2} = \int_0^1 dx\, x^2\left\{u(x,Q^2)-\bar{u}(x,Q^2)-d(x,Q^2)+\bar{d}(x,Q^2)\right\}$$

$$\langle 1\rangle_{\Delta u^+-\Delta d^+}(\mu^2)\Big|_{\mu^2=Q^2} = \int_0^1 dx\left\{\Delta u(x,Q^2)+\Delta\bar{u}(x,Q^2)-\Delta d(x,Q^2)-\Delta\bar{d}(x,Q^2)\right\}$$

$$\langle x\rangle_{\Delta u^--\Delta d^-}(\mu^2)\Big|_{\mu^2=Q^2} = \int_0^1 dx\, x\left\{\Delta u(x,Q^2)-\Delta\bar{u}(x,Q^2)-\Delta d(x,Q^2)+\Delta\bar{d}(x,Q^2)\right\}$$

   - Agreement on presenting quasi-PDFs plots separately for quarks and antiquarks
   - Recommendation to use the most updated pQCD and lQCD results for comparisons

2. Need of a full characterisation of lattice systematics
   - contamination from excited states
   - nonperturbative renormalization of bilinear operators
   - finite volume effects
   - chiral extrapolation to physical m_u and m_d
   - extrapolation to the continuum limit
   - $Z\left(\frac{x}{y}, \frac{\mu^2}{P_z^2}\right)$ computed in perturbative QCD at one loop

     subtraction of power divergences? matching to which scheme?

     large physical P_z are needed, fine lattices? noisy observables?

Summary: towards a joint-community White Paper

There is an undeniable progress in the determination of PDFs on both pQCD and lQCD sides

Opportunity to gain further knowledge by increasing the cross-talk between the two communities

A first basic light document aiming at setting a common framework for future developments

1. Introduction and Motivation
2. Theory review
   - Lattice QCD (moments methods, x-dependence methods)
   - Perturbative QCD global fits (data, theory, methodology)
3. Collection and benchmark of current results
   - Fixing common notation and conventions
   - Extensive comparison of moments and x-dependent PDFs
4. Potential impact of future projections
   - Assume target precision for lattice computations in ~ 5 years
   - Use lattice pseudodata to gauge their impact in a global PDF fit (Bayesian reweighting/Hessian profiling)
   - Focus on LHC phenomenology (*e.g.* high-mass BSM, M_W, heavy Higgs, ...)
   - Focus on spin issues (*e.g.* SU(3) breaking, strangeness, large-x behaviour, ...)

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Thank you

Extra material

Moments - additional definitions

Additional moments (not benchmark quantities)

$$\langle x \rangle_{q^+=u^+,d^+,s^+,c^+}(\mu^2)\Big|_{\mu^2=Q^2} = \int_0^1 dx\, x\left\{q(x,Q^2)+\bar{q}(x,Q^2)\right\}$$

$$\langle x^2 \rangle_{q^-=u^-,d^-,s^-,c^-}(\mu^2)\Big|_{\mu^2=Q^2} = \int_0^1 dx\, x^2\left\{q(x,Q^2)-\bar{q}(x,Q^2)\right\}$$

$$\langle x \rangle_{g}(\mu^2)\big|_{\mu^2=Q^2} = \int_0^1 dx\, x\, g(x,Q^2)$$

$$\langle 1 \rangle_{q^+=\Delta u^+,\Delta d^+,\Delta s^+,\Delta c^+}(\mu^2)\Big|_{\mu^2=Q^2} = \int_0^1 dx\left\{\Delta q(x,Q^2)+\Delta\bar{q}(x,Q^2)\right\}$$

$$\langle x \rangle_{\Delta q^-=\Delta u^-,\Delta d^-,\Delta s^-,\Delta c^-}(\mu^2)\Big|_{\mu^2=Q^2} = \int_0^1 dx\, x\left\{\Delta q(x,Q^2)-\Delta\bar{q}(x,Q^2)\right\}$$