







Parton Distributions and New Physics searches at the LHC

VU Amsterdam & Nikhef

Quark Confinement and the Hadron Spectrum XIII Maynooth University, 02/08/2018



Discovery through precision at hadron colliders

Outstanding questions in Particle Physics

The Higgs boson

Huge gap, **10**¹⁷, between **Higgs and Plank scales**

Elementary or composite? Additional Higgs bosons?

Coupling to **Dark Matter**? Role in cosmological phase transitions?

M Is the **vacuum state of the Universe** stable?

Quarks and leptons

Why three families? Can we explain masses and mixings?

✓Origin of Matter-Antimatter asymmetry in the Universe?

✓Are neutrinos Majorana or Dirac? CP violation in the lepton sector?

Weakly interacting massive particles? Sterile neutrinos? Extremely light particles (axions)?

Mathematical Standard Model particles?

What is the **structure of the Dark Sector**? Is Dark Matter self-interacting?

Outstanding questions in Particle Physics

Many of these crucial questions could be addressed at the Large Hadron Collider

For the next 20 years, LHC will be the forefront of the exploration of the high-energy frontier!

Juan Rojo

High-energy lepton colliders involve elementary particles without substructure

Clean initial state, well-behaved perturbative expansion ($\alpha_{\text{QED}} \gtrsim 0.01$)

Quantum Electrodynamics and lepton colliders are ideal for high-precision measurements

Juan Rojo

5

Hadron colliders offer excellent energy reach, but also very messy environment:

initial state: non-perturbative
proton's parton distributions

- initial state: non-perturbative
 proton's parton distributions
- quark-gluon hard-scattering:
 slow perturbative convergence

- initial state: non-perturbative
 proton's parton distributions
- quark-gluon hard-scattering:
 slow perturbative convergence
- parton showering and hadronization

- initial state: non-perturbative proton's parton distributions
- quark-gluon hard-scattering:
 slow perturbative convergence
- parton showering and hadronization
- plus lots of poorly understood non-perturbative effect:
 background noise such multiple parton intercations, pile-up....

Hadron colliders offer excellent energy reach, but also very messy environment:

- initial state: non-perturbative proton's parton distributions
- quark-gluon hard-scattering: slow perturbative convergence
- parton showering and hadronization
- plus lots of poorly understood non-perturbative effect:
 background noise such multiple parton interactions, pile-up....

Can we really aim for precision physics at LHC?

Hadron colliders offer excellent energy reach, but also very messy environment:

- initial state: non-perturbative proton's parton distributions
- quark-gluon hard-scattering: slow perturbative convergence
- parton showering and hadronization
- plus lots of poorly understood non-perturbative effect:
 background noise such multiple parton interactions, pile-up....

Can we really aim for precision physics at LHC?

Parton Distributions and BSM searches at the LHC

13

anatomy of hadronic collisions

In high-energy **hadron colliders** the collisions involve **composite particles** (protons) with internal substructure (quarks and gluons): the LHC is actually a **quark/gluon collider!**

Calculations of **cross-sections** in hadron collisions require the combination of **perturbative cross-sections** with **non-perturbative parton distribution functions (PDFs)**

the inner life of protons

Distribution of energy that **quarks and gluons carry inside proton** quantified by **Parton Distributions**

Extract from experimental data within a global analysis

Extract PDFs from lepton-proton collisions

Use PDFs to predict proton-proton cross-sections

the inner life of protons

Determine the PDFs at some low scale $Q_0 \simeq m_p \simeq 1 \text{ GeV}$

Juan Rojo

QCHS-XIII, Maynooth, 02/08/2018

The global QCD fit machinery

The global QCD fit machinery

from **O(40)** experiments,

some of them with $\approx 1\%$ errors,

yet still $\chi^2/N_{dat} \approx 1!$

PDFs and Higgs boson profiling

Within the **Standard Model**, the properties of the Higgs sector are **uniquely determined Any deviation** from the tight SM predictions would be a **smoking gun for Physics beyond the SM**

BSM model	Deviations in Higgs coupling to		
	W, Z weak bosons	bottom quarks	photons
New heavy Higgs boson	6%	6%	6%
Two-Higgs Doublet model	1%	10%	1%
Composite Higgs	-3%	-9%	-9%
New heavy top-like quark	-2%	-2%	+2%

A precision of a few percent in Higgs couplings measurements is the goal!

This precision required both in experimental data and in theory calculations of Higgs production

PDFs and Higgs boson profiling

PDF and α_s uncertainties are one of **dominant theory errors in Higgs cross-sections** The better we understand PDFs, the **more discriminating Higgs measurements** become

Higgs Cross-Section Working Group Yellow Report 4

LHC measurements of **SM cross-sections** provide unique information to strengthen the Higgs boson profiling efforts

PDFs and the SMEFT

If BSM physics is **too heavy and beyond the reach of the LHC**, its effects could still be present in kinematic distributions due to virtual corrections

Generic BSM scenarios can be parametrised in a **model-independent way** in terms of higherdimensional operators: the **SM Effective Field Theory** (SMEFT):

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

A large number of these operators can be directly probed at the LHC

For instance, some operators contributing to **inclusive jet**, **dijet**, **and multi-jet production** are:

$$g_s f^{abc} G^{\nu,a}_{\mu} G^{\rho,b}_{\nu} G^{\mu,c}_{\rho} = -\frac{Z}{2m_W^2} (D_\mu G^{\mu\nu,a})^2 \qquad \mathcal{Q}^{(1)}_{qq} \propto (\bar{q}_p \gamma_\mu q_r) (\bar{q}_s \gamma^\mu q_t)$$

Crucially, no **dedicated searches** are required: we can exploit all the excellent measurements that the LHC has (and will) produce, provided **theoretical calculations are up to par**

PDFs and the SMEFT

Several SMEFT operators lead to **corrections which grow with the energy**: enhanced sensitivity at the LHC via the **TeV tails of differential cross-sections**

$$\sigma(E) = \sigma_{SM}(E) \left(1 + \epsilon \frac{m_{SM}^2}{m_W^2} + \epsilon \frac{E^2}{m_W^2} + \dots \right)$$

... but PDF uncertainties blow up in the TeV region due to **limited experimental constraints at large x**

Improved PDFs allow extending the SMEFT parameter space accessible at the LHC

PDFs and the SMEFT

Several SMEFT operators lead to **corrections which grow with the energy**: enhanced sensitivity at the LHC via the **TeV tails of differential cross-sections**

$$\sigma(E) = \sigma_{SM}(E) \left(1 + \epsilon \frac{m_{SM}^2}{m_W^2} + \epsilon \frac{E^2}{m_W^2} + \dots \right)$$

Fully exploiting the SMEFT program only possible if PDF uncertainties under control

PDFs and high-mass BSM resonances

The production of **TeV-scale resonances**, expected in many BSM scenarios, also affected by **large PDF uncertainties**

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

Unless we *improve PDF uncertainties*, even if we discover New Physics, it will be extremely *difficult to characterise the underlying BSM model*

PDFs and precision EWK measurements

The SM is **over-constrained** once M_W , m_t and M_H have been determined **High-precision measurements of** m_t and M_H can be used to stress-test the SM

PDFs and precision EWK measurements

With improved PDFs, **direct measurements of the Weinberg mixing angle** at the LHC are expected to improve the current best bounds from LEP/SLD

NNPDF3.1 NNLO, Q = 100 GeV

Juan Rojo

QCHS-XIII, Maynooth, 02/08/2018

The Structure of the Proton in the LHC Precision Era

Jun Gao^a, Lucian Harland-Lang^b, Juan Rojo^{c,d}

^aInstitute of Nuclear and Particle Physics, Shanghai Key Laboratory for Particle Physics and Cosmology, School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China ^bDepartment of Physics and Astronomy, University College London, WC1E 6BT, United Kingdom ^cDepartment of Physics and Astronomy, VU University, De Boelelaan 1081, 1081HV Amsterdam, The Netherlands ^dNikhef, Science Park 105, NL-1098 XG Amsterdam, The Netherlands

Abstract

We review recent progress in the determination of the parton distribution functions (PDFs) of the proton, with emphasis on the applications for precision phenomenology at the Large Hadron Collider (LHC). First of all, we introduce the general theoretical framework underlying the global QCD analysis of the quark and gluon internal structure of protons. We then present a detailed overview of the hard-scattering measurements, and the corresponding theory predictions, that are used in state-of-the-art PDF fits. We emphasize here the role that higher-order QCD and electroweak corrections play in the description of recent high-precision collider data. We present the methodology used to extract PDFs in global analyses, including the PDF parametrization strategy and the definition and propagation of PDF uncertainties. Then we review and compare the most recent releases from the various PDF fitting collaborations, highlighting their differences and similarities. We discuss the role that QED corrections and photon-initiated contributions play in modern PDF analysis. We provide representative examples of the implications of PDF fits for high-precision LHC phenomenological applications, such as Higgs coupling measurements and searches for high-mass New Physics resonances. We conclude this report by discussing some selected topics relevant for the future of PDF determinations, including the treatment of theoretical uncertainties, the connection with lattice QCD calculations, and the role of PDFs at future high-energy colliders beyond the LHC.

Keywords: Parton Distributions, Quantum Chromodynamics, Large Hadron Collider, Higgs boson, Standard Model, Electroweak theory

170 pages, 82 figures, > 500 references (Physics Reports)

Only time for a very brief snapshot here!

28

Constraints from LHC data

LHC measurements have provided in the recent years a wealth of information on the PDFS

Illustrated by the **large-***x* **gluon**, now constrained by **three independent processes**: jets, top, Z p_T

Constraints from LHC data

Juan Rojo

QCHS-XIII, Maynooth, 02/08/2018

Parton Distributions with Theory Uncertainties

Free Theoretical uncertainties from perturbative **missing higher orders (MHO)** neglected in PDF fits

Solution Of the second second

Solidated with PDF fits with scale variations and with exact NLO => NNLO shift

New theory-induced correlations between experiments

Photon-initiated processes at the LHC

Free proton contains not only quarks and gluons, but also photons: the **LHC is also a photon collider!**

At high mass **PI contributions and NLO EW corrections have opposite sign**

Fhis seems to be the case for many processes: **once PI effects included**, **NLO EW corrections small**

NNPDF3.1_luxQED

Bertone, Carrazza, Pagani, Rojo, Vicini, Zaro (in preparation)

QCHS-XIII, Maynooth, 02/08/2018

Towards ultimate PDFs at hadron colliders

The HL-LHC with 3 ab⁻¹ will lead to a dramatic improvement of the PDF uncertainties

Process	Kinematics	$N_{\rm dat}$
$Z p_T$	$20 \text{ GeV} \le p_T^{ll} \le 3.5 \text{ TeV}$ $12 \text{ GeV} \le m_{ll} \le 150 \text{ GeV}$ $ y_{ll} \le 2.4$	338
high-mass Drell-Yan	$p_T^{l1(2)} \ge 40(30) \text{GeV}$ $ \eta^l \le 2.5, m_{ll} \ge 116 \text{GeV}$	32
top quark pair	$ y_t \le 2.4$	52
W+charm (central)	$p_T^{\mu} \ge 26 \mathrm{GeV}, p_T^c \ge 5 \mathrm{GeV}$ $ \eta^{\mu} \le 2.4$	12
W+charm (forward)	$p_T^{\mu} \ge 20 \text{ GeV}, \ p_T^c \ge 20 \text{ GeV}$ $p_T^{\mu+c} \ge 20 \text{ GeV}$ $2 \le \eta^{\mu} \le 5, \ 2.2 \le \eta^c \le 4.2$	12
Direct photon	$E_T^{\gamma} \lesssim 3 \text{ TeV}, \eta_{\gamma} \leq 2.5$	118
Forward W, Z	$p_T^l \ge 20 \text{ GeV}, \ 2.0 \le \eta^l \le 4.5$ $2.0 \le y_{ll} \le 4.5$ $60 \le m_{ll} \le 120 \text{ GeV}$	90
Inclusive jets	$ y \le 3, R = 0.4$	58

Abdul-Khalek, Bailey, Gao, Harland-Lang, JR to appear un the HL/HE-LHC Yellow Report

- Generated projections for HL-LHC pseudo-data
- Included them on PDF4LHC15 using Hessian profiling
- Study pheno implications for important processes such as **Higgs production**

Juan Rojo

Discovering ``New Physics" from the global QCD analysis

Juan Rojo

QCHS-XIII, Maynooth, 02/08/2018

Discovering New Physics within QCD

How we can ensure that we are not **``fitting way'' BSM effects** in the global PDF analysis? Our recent discovery of **BFKL effects in HERA data** illustrates how this can be achieved!

At small-x, logarithmically enhanced terms in 1/x become dominant and need to be resummed
BFKL/high-energy/small-x resummation can be matched to the DGLAP collinear framework
Until recently, no conclusive evidence for the onset of BFKL dynamics had been provided

$$\begin{array}{l} \begin{array}{l} \mbox{DGLAP} \\ \mbox{Evolution in } \mathbf{Q}^2 \end{array} & \mu^2 \frac{\partial}{\partial \mu^2} f_i(x,\mu^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z},\alpha_s(\mu^2)\right) f_j(z,\mu^2), \\ \\ \mbox{BFKL} \\ \mbox{Evolution in } \mathbf{x} \end{array} & -x \frac{d}{dx} f_+(x,\mu^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K\left(\frac{\mu^2}{\nu^2},\alpha_s\right) f_+(x,\nu^2) \end{array}$$

Within small-*x* resummation, the N^kLO fixed-order DGLAP splitting functions are complemented with the N^hLL*x* contributions from BKFL

$$P_{ij}^{\mathbf{N}^{k}\mathbf{LO}+\mathbf{N}^{h}\mathbf{LL}x}(x) = P_{ij}^{\mathbf{N}^{k}\mathbf{LO}}(x) + \Delta_{k}P_{ij}^{\mathbf{N}^{h}\mathbf{LL}x}(x),$$

ABF, CCSS, TW + others, 94-08

Evidence for BFKL dynamics in HERA data

In order to assess the impact of small-x resummation for the description of the small-x and Q^2 HERA data, compute the χ^2 removing data points in the region where resummation effects are expected

Evidence for BFKL dynamics in HERA data

Using NNLO+NLL*x* theory, the NNLO instability at small-*x* of the χ^2 disappears Excellent fit quality to inclusive and charm HERA data achieved in the entire (x,Q²) region

Juan Rojo

Science Life and Physics

Jon Butterworth

@jonmbutterworth Thu 28 Dec 2017 17.30 GMT

59

Jon Butterworth, The Guardian

After 40 years of studying the strong nuclear force, a revelation

This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force

In the mid 1970s, four Soviet physicists, Batlisky, Fadin, Kuraev and Lipatov, made some predictions involving the strong nuclear force which would lead to their initials entering the lore. "BFKL" became a shorthand for a difficult-to-

38

Juan Rojo

PDFs and BSM physics at the LHC

M Recent progress both from the **theoretical** and **experimental** sides have realised the dream of turning the **LHC into a high-precision experiment**

A detailed mapping of the proton structure is essential for a wide variety of BSM searches, both direct (high-mass resonances) and indirect (SMEFT, Higgs couplings, electroweak parameters)

The LHC provides unique opportunities to constrain the quark and gluon PDFs

O Parton distributions could be the key for **unravelling new physics at the LHC!**

Fascinating times to explore the high-energy frontier!

equipped with our high-precision QCD toolbox!

Juan Rojo

QCHS-XIII, Maynooth, 02/08/2018

Fascinating times to explore the high-energy frontier!

equipped with our high-precision QCD toolbox!

Juan Rojo

QCHS-XIII, Maynooth, 02/08/2018