PROTON STRUCTURE
THE LAST LIGHT PARTON

Gavin Salam, CERN
including work with Aneesh Manohar, Paolo Nason and Giulia Zanderighi

Guido Altarelli Memorial Session
5th International Conference on New Frontiers in Physics, Crete, July 2016
WHAT DO ATLAS & CMS USE MOST FREQUENTLY?

Papers commonly cited by ATLAS and CMS (2014-2016)
as of 2016-06-10, excluding self-citations; all papers > 0.2

fraction of ATLAS & CMS papers that cite them

Plot by gp Sillam based on data from InspireHEP
WHAT DO ATLAS & CMS USE MOST FREQUENTLY?

fraction of ATLAS & CMS papers that cite them

Papers commonly cited by ATLAS and CMS (2014-2016)

Nearly all of it is QCD

as of 2016-06-10, excluding self-citations; all papers > 0.2

Plot by GP Salam based on data from InspireHEP
WHAT DO ATLAS & CMS USE MOST FREQUENTLY?

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The core of hadron-collider QCD is parton distribution functions (PDFs)
ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

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Received 12 April 1977

A novel derivation of the $Q^2$ dependence of quark and gluon densities (of given helicity) as predicted by quantum chromodynamics is presented. The main body of predictions of the theory for deep-inelastic scattering on either unpolarized or polarized targets is re-obtained by a method which only makes use of the simplest tree diagrams and is entirely phrased in parton language with no reference to the conventional operator formalism.
Initial-state splitting

1st order analysis

Summary so far

- Collinear divergence for incoming partons not cancelled by virtuals.
- Real and virtual have different longitudinal momenta.
- Situation analogous to renormalization: need to regularize (but in IR instead of UV).
- Technically, often done with dimensional regularization.
- Physical sense of regularization is to separate (factorize) proton non-perturbative dynamics from perturbative hard cross section.
- Choice of factorization scale, $\mu^2$, is arbitrary between $1 \text{ GeV}^2$ and $Q^2$.
- In analogy with running coupling, we can vary factorization scale and get a renormalization group equation for parton distribution functions.

Dokshizer Gribov Lipatov Altarelli Parisi equations (DGLAP)
In analogy with running coupling, we can make physical sense of regularization by separating non-perturbative dynamics from perturbative hard cross sections. The situation is analogous to renormalization: we need to take care of infrared (IR) and ultraviolet (UV) divergences. Collinear divergence for incoming partons is not cancelled, but instead of UV, we use IR regularization.

First-order analysis is given by the renormalization group equation

\[
\frac{d q^i(x, t)}{dt} = \frac{\alpha(t)}{2\pi} \int_1^1 \frac{dy}{y} \left[ \sum_{j=1}^{2f} q^j(y, t) P_{qi} q^j \left( \frac{x}{y} \right) + G(y, t) P_{qi} G \left( \frac{x}{y} \right) \right],
\]

\[
\frac{d G(x, t)}{dt} = \frac{\alpha(t)}{2\pi} \int_1^1 \frac{dy}{y} \left[ \sum_{j=1}^{2f} q^j(y, t) P_{Gq} q^j \left( \frac{x}{y} \right) + G(y, t) P_{GG} \left( \frac{x}{y} \right) \right].
\]
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This probabilistic “picture”, so clear in the AP paper underpins the rest of QCD at LHC
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WHAT DO ATLAS & CMS USE MOST FREQUENTLY?

A summary of DGLAP’s influence at the LHC
impact of DGLAP evolution from $Q_0 = 2 \text{ GeV}$

$\text{gluon, } Q = 2 \text{ GeV}$

CT14nnlo

$LHC \ 13 \text{ TeV phys. region}$
impact of DGLAP evolution from $Q_0 = 2 \text{ GeV}$

$\times g(x, Q)$

$x$

$10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $0.1$ $0.3$ $0.5$ $0.7$ $0.91$

$Q = 3 \text{ GeV}$

CT14nnlo

LHC 13 TeV phys. region
impact of DGLAP evolution from $Q_0 = 2$ GeV

gluon, $Q = 4$ GeV

CT14nnlo

$LHC$ 13 TeV phys. region
impact of DGLAP evolution from $Q_0 = 2 \text{ GeV}$

$\text{gluon, } Q = 5 \text{ GeV}$

CT14nnlo

$LHC \ 13 \text{ TeV phys. region}$
impact of DGLAP evolution from $Q_0 = 2$ GeV

$g(x, Q) = 1000$

$g(x, Q) = 100$

$g(x, Q) = 10$

$g(x, Q) = 1$

$g(x, Q) = 0.1$

LHC 13 TeV phys. region

CT14nnlo
impact of DGLAP evolution from $Q_0 = 2 \text{ GeV}$

gluon, $Q = 20 \text{ GeV}$

CT14nnlo

LHC 13 TeV phys. region
impact of DGLAP evolution from $Q_0 = 2$ GeV

gluon, $Q = 50$ GeV

CT14nnlo

LHC 13 TeV phys. region
impact of DGLAP evolution from $Q_0 = 2$ GeV

$\text{gluon, } Q = 100 \text{ GeV}$

CT14nnlo

$LHC \ 13 \text{ TeV phys. region}$
impact of DGLAP evolution from $Q_0 = 2$ GeV

DGLAP evolution changes parton distributions by factors $\sim 10$.

Higgs cross section (13 TeV) would be 6x smaller without DGLAP nowadays, used at NNLO, thanks to Moch, Vermaseren & Vogt.
EXPERIMENTAL PRECISION TODAY CAN REACH 1%
**WHAT ACCURACY DO WE NEED? E.G. FOR LONG-TERM HIGGS PRECISION**

Naive extrapolation suggests LHC has long-term potential to do Higgs (and much other) physics at **1% accuracy**.
how well do we know the parton distributions?
PDF uncertainties (Q = 100 GeV)

core partons (up, down, gluon) are quite well known
PDF uncertainties (Q = 100 GeV)

➤ core partons (up, down, gluon) are quite well known ~2%

➤ strangeness ~10%
The core partons (up, down, gluon) are quite well known ~2%

➤ strangeness ~10%

➤ one other parton, the photon, is debated. The only model-independent determination (NNPDF23qed) has $O(100\%)$ uncertainty
IT MATTERS FOR DI-LEPTON, DI-BOSON, TTBAR, EW HIGGS, ETC.

**di-lepton spectrum**

\[ \frac{d\sigma}{dM_{ll}} [\text{fb} / \text{TeV}] \]

\( \sqrt{s} = 13 \text{ TeV} \)

Accomando et al, 1606.06646

\[ M_{ll} \text{ [TeV]} \]

normal DY contribution

photon-induced contribution and uncertainty [NNPDF23]
## PHOTON PDF ESTIMATES (not exhaustive)

<table>
<thead>
<tr>
<th>Model</th>
<th>Elastic</th>
<th>Inelastic</th>
<th>In LHAPDF?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluck Pisano Reya 2002</td>
<td>dipole</td>
<td>model</td>
<td>✗</td>
</tr>
<tr>
<td>MRST2004qed</td>
<td>✗</td>
<td>model</td>
<td>✓</td>
</tr>
<tr>
<td>NNPDF23qed</td>
<td>no separation; fit to data</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>CT14qed</td>
<td>✗</td>
<td>model (data-constrained)</td>
<td>✓</td>
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<td>CT14qed_inc</td>
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*elastic: Budnev, Ginzburg, Meledin, Serbo, 1975*
YOU SHOULDN’T NEED A MODEL
ep scattering (i.e. structure functions) contains all info about proton’s EM field
to extract it, we’ll study a hypothetical (“BSM”) heavy–neutral lepton production process
Manohar, Nason, GPS & Zanderighi, to appear
STEP 1
work out a cross section (exact) in terms of $F_2$ and $F_L$ struct. fns.

\[ \sigma = \frac{1}{4p \cdot k} \int \frac{d^4q}{(2\pi)^4} e_{ph}^2(q^2) \left[ 4\pi W_{\mu\nu} L^{\mu\nu}(k, q) \right] \times 2\pi \delta((k - q)^2 - M^2) \]
STEP 2
work out same cross section in terms of a photon distribution

\[ \hat{\sigma}_\gamma \left( \frac{M^2}{xS}, \mu^2 \right) \]

\[ f_{\gamma/p}(x, \mu^2) \]

\[ \sigma = c_0 \sum_a \int \frac{dx}{x} \hat{\sigma}_a \left( \frac{M^2}{xS}, \mu^2 \right) x f_{a/p}(x, \mu^2) \]
equate them to deduce the photon distribution (LUXqed)

\[
x f_{\gamma/p}(x, \mu^2) = \frac{1}{2\pi \alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{Q_{\text{min}}^2}^{Q_{\text{max}}^2} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \right. \\
\left[ \left( 2 - 2z + z^2 + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) \right. \\
- z^2 F_L \left( \frac{x}{z}, Q^2 \right) \left. \right] - \alpha^2(\mu^2) z^2 F_2 \left( \frac{x}{z}, \mu^2 \right) \right\},
\]

Result is in MSbar scheme & consistent with 2015 de Florian, Rodrigo, Sborlini O(\alpha_s) P_{yx} QED split.fns.
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</tr>
<tr>
<td>LUXqed 2016</td>
<td>data</td>
<td>data</td>
<td>soon</td>
</tr>
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</table>
DATA SOURCES – various fits to F2, FL & elastic form factors

- high $Q^2$ continuum region (PDFs: PDF4LHC15_nnlo_100)
- low $Q^2$ continuum region (Hermes GD11-P)
- resonance region (CLAS/CB)
- elastic (A1)
DATA SOURCES – various fits to F2, FL & elastic form factors

Figure 1: Elastic form factors (ratio to standard dipole form) as fitted by the A1 collaboration $[B_{14}]$. Left: electric. Right: magnetic.

Figure 2: Elastic contribution to $F_2/p(x, Q^2)$ with various fits for the form factors, normalised to the result obtained with the A1 world fit, including polarised data. The ratio freezes above $x=0.9$ because the A1 fits extends only up to $Q^2=10 GeV^2$ and beyond that scale we simply extrapolate the results for $G_E/M(U)$ using the standard-dipole shape, normalised to $G_E/M(10 GeV^2)$.

[Should we try to do this better? Maybe $x>0.9$ not so critical for now.]
The results

Ratio of some widely used PDFs to LUXqed (red)
PHOTON UNCERTAINTY (1−2%) COMPARED TO OTHER FLAVOURS

PDF uncertainties (Q = 100 GeV)

- **photon** (LUXqed)
- **strange** (PDF4LHC15)
- **up** (PDF4LHC15)
$\gamma\gamma$ luminosity for $E_{CM} = 13$ TeV

$dL_{\gamma\gamma} / d\ln M^2$

M [TeV]

- LUXqed
- NNPDF30
**APPLICATION TO HIGGS PHYSICS**

<table>
<thead>
<tr>
<th>Process Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow H W^+ (\rightarrow l^+\nu) + X$ at 13 TeV</td>
<td>$91.2 \pm 1.8$ fb</td>
</tr>
<tr>
<td>Non-photon induced contributions</td>
<td></td>
</tr>
<tr>
<td>Photon-induced contribs (NNPDF23)</td>
<td>$6.0^{+4.4}_{-2.9}$ fb</td>
</tr>
<tr>
<td>Photon-induced contribs (LUXqed)</td>
<td>$4.4 \pm 0.1$ fb</td>
</tr>
</tbody>
</table>

*non-photon numbers from LHCHXSWG*
➤ LHC physics would be unrecognisable without Guido’s contributions, first and foremost the simple physical picture contained in the DGLAP equations.

➤ Parton distribution functions are among the crucial inputs to LHC physics, with significant open problems still to solve today.

➤ More generally, Guido’s dedication, his combination of breadth and attention to detail, all serve as a model for what a physicist may aspire to.
extra slides
Elena Accomando,1, 2, * Juri Fiaschi,1, 2, † Francesco Hautmann,2, 3, ‡ Stefano Moretti,1, 2, § and C.H. Shepherd-Themistocleous1, 2, ¶

Photon-initiated production of a di-lepton final state at the LHC: 

\( \Delta PDF / d\sigma [%] \)

\( M_{ll} [\text{GeV}] \)

\( \sqrt{s} = 13 \text{ TeV} \)
where 

obtains corrections of order 

isation scale. We stress that Eq. (1) is accurate up to 

tonic tensor. We define the physical QED coupling 

parton distribution functions (PDFs) 

ways of writing the heavy-lepton production cross section 

ric particle production at 

part by Drees and Zeppenfeld’s study of supersymmet-

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SEPARATE CONTRIBUTIONS TO PHOTON PDF

LUXqed, $\mu = 100$ GeV

without MS conversion

PDFs

continuum data

resonances

elastic magnetic

elastic electric

$Q = 1$ GeV

$Q^2/T^2 < 100$ GeV. There is a sizeable

$Q^2/T^2$ vanishes as

$Q^2/T^2 = 0$. The CLAS fit

because of the rapid drop-o

$Q^2/T^2$ that we use in each region.

$Q^2/T^2$ is available

$Q^2/T^2$ from all sources we have considered, and their total sum

$Q^2/T^2$ in quadrature shown as a black line.

$Q^2/T^2$ PDF, from all sources we have considered, and their total sum

$Q^2/T^2$ with

$Q^2/T^2$ from

$Q^2/T^2$ estimated size of the two-photon exchange contribution

$Q^2/T^2$ the uncertainty on the elastic form factors, equal to the

$Q^2/T^2$ to scales

$Q^2/T^2$ standard 68%CL uncertainties on the PDFs, applied

$Q^2/T^2$ for the uncertainty on

$Q^2/T^2$ have to be included. Furthermore, inelastic contributions

$Q^2/T^2$ that we have considered and are shown in Fig. 2

$Q^2/T^2$ for the accuracy we are aiming at, all contri-

$Q^2/T^2$ to structure functions, but including the full elastic contri-

$Q^2/T^2$ with

$Q^2/T^2$.

$Q^2/T^2$ photons PDF as a function of

$Q^2/T^2$ 5 GeV

$Q^2/T^2$ 100 GeV. There is a sizeable

$Q^2/T^2$ CB resonance fits are constrained by photoproduction

$Q^2/T^2$ and CB 

$Q^2/T^2$ Christy and Bosted (CB) 

$Q^2/T^2$ also consider an alternative fit, to the world data, by

$Q^2/T^2$ W

$Q^2/T^2$ breaks the inelastic part of the ( 

$Q^2/T^2$ thanks to a long history of

$Q^2/T^2$ fits [39–41] together with the known massless NNLO co-

$Q^2/T^2$ The leading twist contribution to

$Q^2/T^2$ also behaves sensibly there. (Very low

$Q^2/T^2$ data, i.e. they extend down to

$Q^2/T^2$ the ALLM parametric form [37]. Both the GD11-P and

$Q^2/T^2$ also

$Q^2/T^2$ contributions arising from the elastic contribution, with an important magnetic com-

$Q^2/T^2$ scale choice of

$Q^2/T^2$ e fits [39–41] together with the known massless NNLO co-

$Q^2/T^2$ .
One needs the photo-disintegration to have the photon PDF as a function of $x$, $Q^2$. At high $Q^2$, the elastic contribution to the photon PDF is known for $x, Q^2$. The PDF has been multiplied by $1 + 1/F_2$; at low $Q^2$, the PDF would be the dashed blue line without the continuum conversion term.

The leading twist contribution to $F_2$ for which we use the HERMES parametrization [36]. Also consider an alternative fit, to the world data, by CLAS [34], and GD11-P fit by Hermes [36] based on the ALLM parametric form [37]. Both the GD11-P and CLAS are related by $Q^2 = m^2$.

The inelastic components of $F_2$ are related by $(1 + R)/(1 + T)$ = 0. The CLAS fit vanishes as $|x, Q^2| < 9$ GeV. There is a sizeable uncertainty on elastic component (E); an estimate of the uncertainty in the resonance region taken as the difference between the CLAS fit and the GD11-P fit by the HERMES parametrization [36].

For the uncertainty on $F_1$, one needs an estimate of the uncertainty in the resonance region. In Fig. 1 we show the various contributions to our determination of $F_1$. The inelastic components of $F_2$ is suppressed by $|x, Q^2| > 100$ GeV. There is a sizeable error on elastic component (E); a conservative estimate of the uncertainty in the resonance region taken as the difference between the CLAS fit and the GD11-P fit by the HERMES parametrization [36].

The uncertainty on our calculation of the photon parton density function from all sources we have considered, and their total sum in quadrature shown as a black line.

In Fig. 3 we show the sources contributing to the uncertainties on $R$ (R), higher orders (HO), and pdf errors (PDF). The PDF would be the dashed blue line without the overall normalization uncertainty (PDF); a conservative estimate of the uncertainty in the resonance region (RES) and in the matching PDF and fits (M). The twist 4 correction to $R$ in PDF (T) is negligible. We have to be included. Furthermore, inelastic contributions arising from the photo-disintegration region of all the PDF, from all sources we have considered, and their total sum in quadrature as shown in Fig. 3.
$\gamma\gamma$ luminosity for $E_{CM} = 8$ TeV

$\frac{dL_{\gamma\gamma}}{d\ln M^2}$

- LUXqed
- NNPDF30