HERAFitter

an open source QCD fit framework

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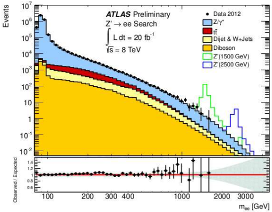
Outline

- Motivation
- Project overview
- Progress and plans
- QED-evolution in HERAFitter
- Summary

Motivation

- PDFs are essential for precision physics at the LHC

[ATLAS-CONF-2013-017]



Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	5%	NA	5%	NA
PDF variation	NA	15%	NA	15%
PDF choice	NA	17%	NA	17%
Scale	NA	-	NA	-
α_s	NA	4%	NA	4%
Electroweak corrections	NA	3%	NA	3%
Photon-induced corrections	NA	4%	NA	4%
Efficiency	-	-	6%	6%
Resolution	-	-	-	3% (7%)
W + jet and multi-jet background	NA	9%	NA	-
Diboson and ttbar extrapolation	NA	5%	NA	4%
Total	5%	26%	8%	25% (26%)

- PDF provided by main fitting groups (CTEQ, MSTW, NNPDF, HERAPDF, ABM, JR) may differ due to

  – fitted different data sets
  – method of best fit determination
  – uncertainty treatment
  – parametrization
  – heavy flavour treatment
  – PDF and α_s corellation

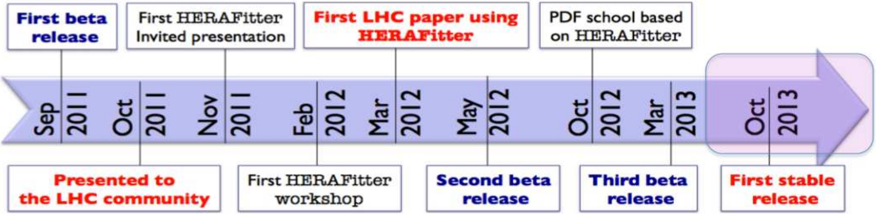
HERAFitter is an open source QCD platform which can be used for benchmarking and understanding such differences

HERAFitter

- Historically based on H1FITTER and ZEUSFITTER developments and now extended to LHC experiments
- Provides means for PDF extraction from experimental collider and/or fixed target data:
  - Theoretical predictions for a variety of processes (DIS, DY, top)
  - DGLAP evolution (QCDNUM)
  - LHAPDF-ready output, plots
- Flexible PDF parameterization
- Supports a variety of schemes of heavy flavour treatment in DGLAP formalism for DIS
- Elaborate uncertainty treatment:
  - Uncertainty correlations in the input data
  - Asymmetric errors
  - Different uncertainty treatments (Hessian, MC, regularization)

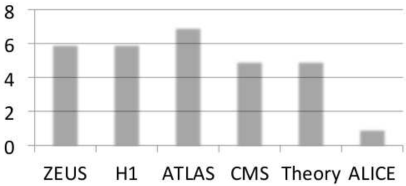
HERAFitter QCD Fit platform

HERAFitter Package is an open source QCD Fit platform ready to analyse new data



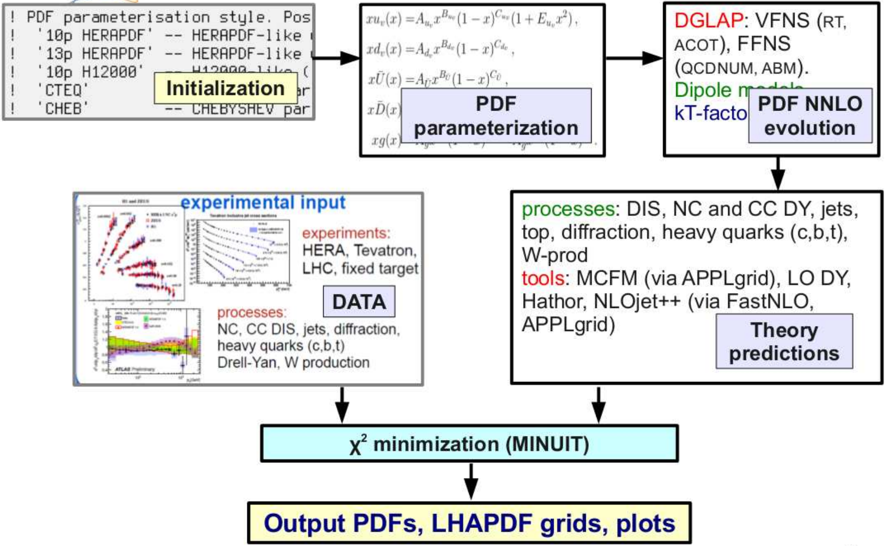
- Statistics of developers team

~100 downloads



- The releases are publicly accessed via https://www.herafitter.org

HERAFitter workflow



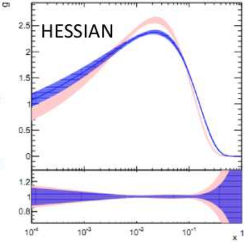
HERAFitter 0.3.1 Functioonalities: Uncertainties

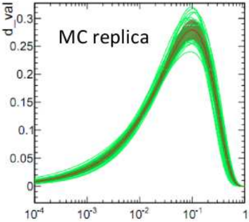
HERAFitter package allows for various types of data uncertainty treatment:

- Hessian and Monte Carlo replica method

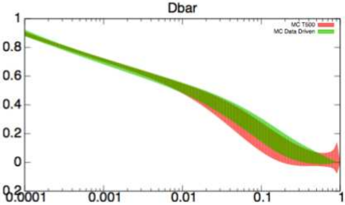
```
&MCErrors

  lRAND    = False
  lRANDDATA = True
  ISeedMC = 123456
  ! --- Choose what distribution for the rando
  ! STATYPE (SYS_TYPE)  =   1  gauss
  ! STATYPE (SYS_TYPE)  =   2  uniform
  ! STATYPE (SYS_TYPE)  =   3  lognormal
  ! STATYPE (SYS_TYPE)  =   4  poisson (only f
  STATYPE =   1
  SYSTYPE =   1
&End
```





- Regularisation methods: to constrain PDFs in a flexible parametrisation style:
  - Data Driven Regularisation (as used by NNPDF): fit and control samples
  - External Regularisation based on a penalty term in χ2 [was shown at QCD@LHC 2012]



HERAFitter usage example

DY data analysis: combining APPLgrid and K-factor methods:

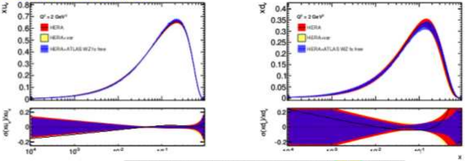
- Generate grids with APPLgrid and calculate corresponding HO QCD and/or EW K-factors in the data-optimized phase space region

y_{min}	y_{max}	$K_{QCD}(NNLO/NLO)$	$K_{EW}(NLO$
0.0	0.4	0.99943	0.99313
0.4	0.8	0.99423	0.99307
0.8	1.2	1.00320	0.99306
1.2	1.6	0.99889	0.99299
1.6	2.0	0.99846	0.99286
2.0	2.4	0.99750	0.99271
2.4	2.8	0.98983	0.9925
2.8	3.6	0.97726	0.99242

- Configure HERAFitter steering files and datafiles

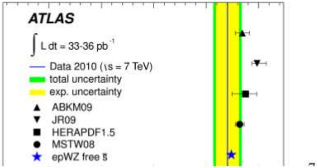
```
Reaction = 'NC pp'
TheoryType      = 'applgrid','kfactor'
NKfactor      = 2
TheoryInfoFile = 'theoryfiles/atlas/WZ2010/Z0-applgrid.root

PERCENT = F, 32*T
&END
  0.00      0.40      129.27        1.88    0.59  0.291
19  0.069  -0.101  -0.526  0.066  -0.164  0.343  -0.145
  0.40      0.80      129.44        1.90    0.58  0.291
```



- Perform QCD fit to extract PDF information

- Cross check and validate



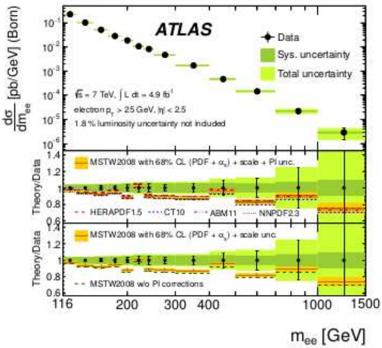
Results using HERAFitter

https://www.herafitter.org/HERAFitter/HERAFitter/results

- ATLAS results obtained using HERAFitter:
  - Determination of the strange quark density from ATLAS WZ measurements [Phys.Rev.Lett. 109 (2012) 012001]
  - Measurement of the inclusive jet cross section in pp collisions at 2.76 and 7 TeV [arXiv:1304.4739]
  - Measurement of the high-mass Drell-Yan differential cross-section in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector [arXiv:1305.4192]
- CMS several analyses are using HERAFitter for PDF constraints
  - inclusive jets, s-quark density determination
  - planned for DY and W+charm data
- HERA publications:
  - QCD Analysis to final H1 HERA data [JHEP 09 (2012) 061]
  - QCD Analysis of Charm Production Cross Section Measurements [Eur. Phys. J. C73 (2013) 2311]
- LHeC impact studies [J.Phys. G39 (2012)]
- Theory:
  - updates of ACOT scheme module (with CTEQ group)
  - inclusion of photon PDF in QCDNUM (publication is planned)

QED-modified evolution

- Recent studies on high mass Drell-Yan production in ATLAS [arXiv:1305.4192] has shown that the size of the γ-induced contribution ($\gamma\gamma \to e^+e^-$) is as large as the uncertainties arising from the different choice of PDF set



- Therefore it become important to address the impact of QED corrections to PDFs
- Currently only two PDF sets are available which incorporate photon contribution. These are MRST2004qed [arXiv:0411040] (which are based on old data) and most recent NNPDF2.3 [arXiv:1305.4179]

QED-modified evolution

- For the next stable release of HERAFitter in October 2013 we are going to include the possibility of data fits based on QED-modified DGLAP evolution
- New beta version of `QCDNUM` released by Michiel Botje on 26.07.2013 allows to solve $n \times n$ coupled evolution equations in FFNS and VFNS (see M. Botje slides at HERA Fitter User's meeting https://indico.cern.ch/conferenceDisplay.py?confId=257700)
- For $n_f = 5$ we have to solve 4 coupled equations for $\Delta, \Sigma, g, \gamma$ and 5 uncoupled equations for $d_v, u_v, \Delta_{ds}, \Delta_{uc}, \Delta_{sb}$ (assuming $s = \bar{s}$, $c = \bar{c}$, $b = \bar{b}$)
- It takes $\sim$ 5 s of CPU time (Intel Core i7-3630QM, 2.4 GHz) to fill weight tables of splitting functions and $\sim$ 0.5 s to evolve this distributions on 100×50 grid in x and μ^2

QED-modified evolution

QED-modified DGLAP evolution equations for Parton Distribution Functions of quarks $q_i(x, \mu_F^2)$, anti-quarks $q_i(x, \mu_F^2)$, gluon $g(x, \mu_F^2)$ and photon $\gamma(x, \mu_F^2)$ can be written as:

$$\frac{\partial q_i}{\partial \ln \mu^2} = \sum_{j=1}^{n_f} P_{q_i q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{q_i \bar{q}_j} \otimes \bar{q}_j + P_{q_i g} \otimes g + P_{q_i \gamma} \otimes \gamma,$$

$$\frac{\partial \bar{q}_i}{\partial \ln \mu^2} = \sum_{j=1}^{n_f} P_{\bar{q}_i q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{\bar{q}_i \bar{q}_j} \otimes \bar{q}_j + P_{\bar{q}_i g} \otimes g + P_{\bar{q}_i \gamma} \otimes \gamma,$$

$$\frac{\partial g}{\partial \ln \mu^2} = \sum_{j=1}^{n_f} P_{g q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{g \bar{q}_j} \otimes \bar{q}_j + P_{gg} \otimes g,$$

$$\frac{\partial \gamma}{\partial \ln \mu^2} = \sum_{j=1}^{n_f} P_{\gamma q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{\gamma \bar{q}_j} \otimes \bar{q}_j + P_{\gamma\gamma} \otimes \gamma.$$

QED-modified evolution

The expressions for splitting functions at NLO QCD and LO QED

$$P_{q_i q_j} = P_{\bar{q}_i \bar{q}_j} = a_s \delta_{ij} P_{qq}^{(0)} + a_s^2 \left(\delta_{ij} \frac{P_+^{(1)} + P_-^{(1)}}{2} + \frac{P_{qq}^{(1)} - P_+^{(1)}}{2n_f} \right) + a \delta_{ij} e_i e_j \tilde{P}_{qq}^{(0)},$$

$$P_{q_i \bar{q}_j} = P_{\bar{q}_i q_j} = a_s^2 \left(\delta_{ij} \frac{P_+^{(1)} - P_-^{(1)}}{2} + \frac{P_{qq}^{(1)} - P_+^{(1)}}{2n_f} \right),$$

$$P_{q_i g} = P_{\bar{q}_i g} = a_s \frac{P_{qg}^{(0)}}{2n_f} + a_s^2 \frac{P_{qg}^{(1)}}{2n_f},$$

$$P_{q_i \gamma} = P_{\bar{q}_i \gamma} = a e_i^2 \frac{P_{q\gamma}^{(0)}}{2n_f},$$

$$P_{g q_i} = P_{g \bar{q}_i} = a_s P_{gq}^{(0)} + a_s^2 P_{gq}^{(1)},$$

$$P_{gg} = a_s P_{gg}^{(0)} + a_s^2 P_{gg}^{(1)},$$

$$P_{\gamma q_i} = P_{\gamma \bar{q}_i} = a e_i^2 P_{\gamma q}^{(0)},$$

$$P_{\gamma\gamma} = a P_{\gamma\gamma}^{(0)}.$$

QED-modified evolution

In the case of QCD evolution equations can be simplified using singlet and non-singlet combinations of quark densities. Then the singlet quark density obeys the evolution equation coupled to gluon density and non-singlet combinations evolve independently. But this decomposition is not suitable for QED-modified evolution since up- and down-quarks have different electric charges.

For QED-modified DGLAP evolution it is convenient to use the following basis of distribution functions

$$
\begin{aligned}
f_1 &= \Delta = u + \bar{u} + c + \bar{c} - d - \bar{d} - s - \bar{s} - b - \bar{b},\\
f_2 &= \Sigma = u + \bar{u} + c + \bar{c} + d + \bar{d} + s + \bar{s} + b + \bar{b},\\
f_3 &= g,\\
f_4 &= \gamma,\\
f_5 &= d_v = d - \bar{d},\\
f_6 &= u_v = u - \bar{u},\\
f_7 &= \Delta_{ds} = d + \bar{d} - s - \bar{s},\\
f_8 &= \Delta_{uc} = u + \bar{u} - c - \bar{c},\\
f_9 &= \Delta_{sb} = s + \bar{s} - b - \bar{b}.
\end{aligned}
$$

QED-modified evolution

In this basis we have 4 coupled and 5 uncoupled evolution equations:

$$\frac{\partial}{\partial \ln \mu^2} \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix} = \begin{pmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{pmatrix} \otimes \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix},$$

$$\frac{\partial f_i}{\partial \ln \mu^2} = P_{ii} \otimes f_i, \quad i = 5, \ldots, 9.$$

The expressions for splitting kernels P_{ii} at NLO QCD and LO are given by

$$\begin{aligned}
P_{11} &= a_s P_{qq}^{(0)} + a_s^2 P_{+}^{(1)} + \frac{e_u^2+e_d^2}{2} a\tilde{P}_{qq}^{(0)}, \\
P_{12} &= \frac{n_u-n_d}{n_f} a_s^2 (P_{qq}^{(1)} - P_{+}^{(1)}) + \frac{e_u^2-e_d^2}{2} a\tilde{P}_{qq}^{(0)}, \\
P_{13} &= \frac{n_u-n_d}{n_f} (a_s P_{qg}^{(0)} + a_s^2 P_{qg}^{(1)}), \\
P_{14} &= \frac{n_u e_u^2 - n_d e_d^2}{n_f} a P_{q\gamma}^{(0)}, \\
P_{21} &= \frac{e_u^2-e_d^2}{2} a\tilde{P}_{qq}^{(0)}, \\
P_{22} &= a_s P_{qq}^{(0)} + a_s^2 P_{qq}^{(1)} + \frac{e_u^2+e_d^2}{2} a\tilde{P}_{qq}^{(0)}, \\
P_{23} &= a_s P_{qg}^{(0)} + a_s^2 P_{qg}^{(1)}, \\
P_{24} &= \frac{n_u e_u^2 + n_d e_d^2}{n_f} a P_{q\gamma}^{(0)}, \\
P_{31} &= 0, \\
P_{32} &= a_s P_{gq}^{(0)} + a_s^2 P_{gq}^{(1)},
\end{aligned}$$

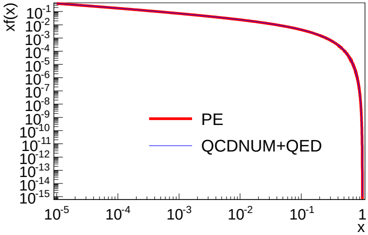
$$\begin{aligned}
P_{33} &= a_s P_{gg}^{(0)} + a_s^2 P_{gg}^{(1)}, \\
P_{34} &= 0, \\
P_{41} &= \frac{e_u^2-e_d^2}{2} a P_{\gamma q}^{(0)}, \\
P_{42} &= \frac{e_u^2+e_d^2}{2} a P_{\gamma q}^{(0)}, \\
P_{43} &= 0, \\
P_{44} &= a P_{\gamma\gamma}^{(0)}, \\
P_{55} &= a_s P_{qq}^{(0)} + a_s^2 P_{-}^{(1)} + a e_d^2 \tilde{P}_{qq}^{(0)}, \\
P_{66} &= a_s P_{qq}^{(0)} + a_s^2 P_{-}^{(1)} + a e_u^2 \tilde{P}_{qq}^{(0)}, \\
P_{77} &= P_{99} = a_s P_{qq}^{(0)} + a_s^2 P_{+}^{(1)} + a e_d^2 \tilde{P}_{qq}^{(0)}, \\
P_{88} &= a_s P_{qq}^{(0)} + a_s^2 P_{+}^{(1)} + a e_u^2 \tilde{P}_{qq}^{(0)}.
\end{aligned}$$

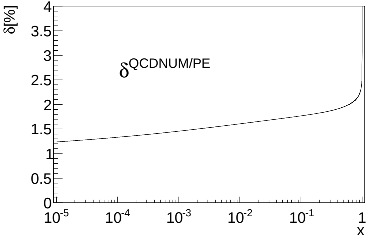
QED-modified evolution

- Numerical comparison was performed between `QCDNUM` with QED and `partonevolution-1.1.3` (PE) program of S. Weinzierl in FFNS
- In VFNS the results of `QCDNUM` with QED were compared with MRST2004qed PDF set
- The distributions are evolved from initial scale $\mu_0^2 = 2\ \mathrm{GeV}^2$ to $\mu^2 = 10^4\ \mathrm{GeV}^2$ on 1000×1000 grid in x and μ^2

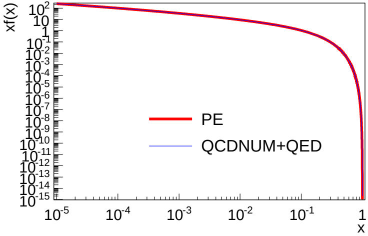
QED-modified evolution

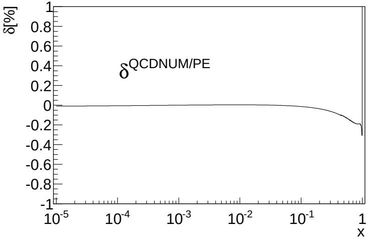
photon distribution at $\mu = 100$ GeV: $\delta = \frac{xf(QCDNUM+QED) - xf(PE)}{xf(PE)}$





gluon distribution at $\mu = 100$ GeV:

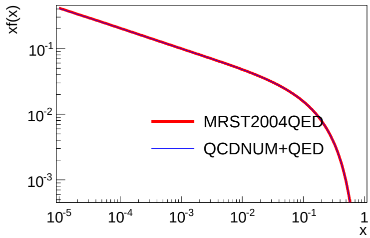


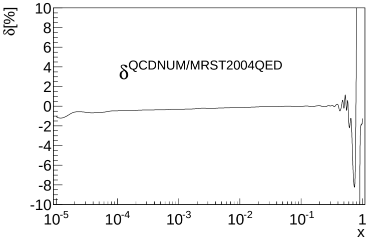


QED-modified evolution

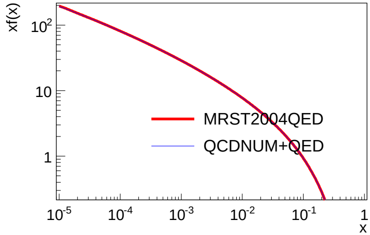
photon distribution at $\mu = 100$ GeV:

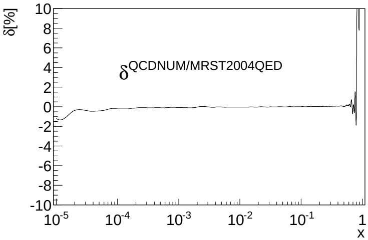
$$\delta = \frac{xf(QCDNUM+QED) - xf(MRST2004qed)}{xf(MRST2004qed)}$$





gluon distribution at $\mu = 100$ GeV:





Summary

- Successfull releases of HERAFitter package, latest in March 2013
- Monthly users' meetings, weekly developers' meetings
- HERAFitter tool has grown into multifunctional QCD platform
  - Different treatments for heavy flavours
  - Robust data input
  - Various parameterization techniques
  - Various physics cases
- Ready for tests within experimental data analysis as well as theoretical studies. User-friendly interface, documentation and technical support
- QED-modified evolution equations is realized with help of new beta version of `QCDNUM` program and cross-cheked in FFNS and VFNS. It is planned to be implemented into next release of `HERAFitter`
- Next release scheduled for October 2013