HERAFitter Project
Open Source QCD Fit framework

Voica Radescu
on behalf of the HERAFitter team
Why do we still need to care about PDFs?

- Discovery of new exciting physics relies on precise knowledge of proton structure.
- **Factorisation theorem:**
  - Cross section can be calculated by convoluting short distance partonic reactions (calculable in pQCD) with Parton Distribution Functions (PDFs):

\[
\frac{d\sigma(h_1 h_2 \rightarrow cd)}{dx_1 dx_2} = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1, \mu_F^2) f_{b/h_2}(x_2, \mu_F^2) d\hat{\sigma}^{(ab \rightarrow cd)}(Q^2, \mu_F^2)
\]

- PDFs cannot be calculated in perturbative QCD, however they are process independent (universal) and their evolution with the scale is predicted by pQCD.

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**Higgs**

**PDFs**

**SEARCHES**

**MC**

**Standard Model**

**Top**

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- PDFs cannot be calculated in perturbative QCD, however they are process independent (universal) and their evolution with the scale is predicted by pQCD
  
  - PDFs are one of the main theory uncertainties in $M_W$ measurement
  - PDFs are one of main theory uncertainties in Higgs production.
Proton Structure Measurements

The cleanest way to probe Proton Structure is via Deep Inelastic Scattering [DIS]:

- Neutrinos, muons, electrons

Precision of PDFs can be complemented by the Drell Yan [DY] processes at the collider experiments - [Tevatron and LHC]

Different data constrain different parton combinations at different $x$, evolution with the scale is predicted by pQCD:
HERAFitter Project: www.herafitter.org

- HERAFitter Project was initiated in 2011 as a necessity to transfer the legacy and expertise on proton structure from HERA to LHC:
  - a unique open source QCD Fit Platform:

- HERAFitter:
  - provides a unique QCD framework to address theoretical differences
  - provides means to the experimentalists to optimise the measurement and assess impact/consistency of new data
HERAFitter Releases:

- https://www.herafitter.org/HERAFitter/HERAFitter/DownloadPage

List of releases:

<table>
<thead>
<tr>
<th>Date</th>
<th>Version</th>
<th>Files</th>
</tr>
</thead>
<tbody>
<tr>
<td>09/2014</td>
<td>1.1.0</td>
<td>herafitter-1.1.0.tgz</td>
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<tr>
<td>12/2013</td>
<td>1.0.0</td>
<td>herafitter-1.0.0.tgz</td>
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<tr>
<td>06/2013</td>
<td>0.3.1</td>
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<td>0.3.0</td>
<td>herafitter-0.3.0.tgz</td>
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<tr>
<td>07/2012</td>
<td>0.2.1</td>
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<tr>
<td>05/2012</td>
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<tr>
<td>09/2011</td>
<td>0.1.0</td>
<td>herafitter-0.1.0.tgz</td>
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</tbody>
</table>

- Versioning convention: i,j,k with
  - i - stable release
  - j - beta release
  - k - bug fixes.

HERAFitter: Releases and Updates
September, 2014

HERAFitter versions are labeled as herafitter-i.j.k where i is the stable release number, j is beta release number, and k is bug fixes.

<table>
<thead>
<tr>
<th>Release</th>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>herafitter-1.1.0</td>
<td>29.09.2014</td>
<td>- Removed dependence on CERNLIB and related libraries.</td>
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<tr>
<td></td>
<td></td>
<td>- Added interface to LHAPDFv6.</td>
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<td></td>
<td></td>
<td>- Added more and improved drawing options for visualisation of results.</td>
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<tr>
<td></td>
<td></td>
<td>- Added possibility to deal with multi-dimensional data (virtual grids).</td>
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<tr>
<td></td>
<td></td>
<td>- Additional options in parametrisation styles: added mixed forms between</td>
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<tr>
<td></td>
<td></td>
<td>HERA style for gluon and sea and CTEQ style for valence.</td>
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<tr>
<td></td>
<td></td>
<td>- Added new data from Tevatron, ATLAS and CMS.</td>
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<tr>
<td></td>
<td></td>
<td>- Added improvements and more flexibility in the $\chi^2$ and covariance</td>
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<tr>
<td></td>
<td></td>
<td>matrix code: possibility to transform into nuisance representation for</td>
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<tr>
<td></td>
<td></td>
<td>data with uncertainties given in the covariance form.</td>
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<td></td>
<td></td>
<td>- Included a new fastNLO version, which was generalised in order to</td>
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<tr>
<td></td>
<td></td>
<td>accommodate DiffTop grids.</td>
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<tr>
<td></td>
<td></td>
<td>- Added DiffTop grids via fastNLO.</td>
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</tbody>
</table>
HERAFitter Program at glance

- HERAFitter code is a combination of C++ and Fortran 77 libraries with minimal dependencies and modular structure with interface to external packages:
  - QCDNUM, APPLGRID, FASTNLO, ACOT, TR', OPENQCDRAD, TMD, HATHOR

<table>
<thead>
<tr>
<th>Experimental Data</th>
<th>Process</th>
<th>Reaction</th>
<th>Theory schemes calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA, Fixed Target</td>
<td>DIS NC</td>
<td>$e^+e^-$, $\mu^+\mu^-$</td>
<td>TR', ACOT, ZM (QCDNUM), FFN (OPENQCDRAD), QCDEM, TMD (uPDreco)</td>
</tr>
<tr>
<td>HERA</td>
<td>DIS CC</td>
<td>$ep \rightarrow v, X$</td>
<td>ACOT, ZM (QCDNUM), FFN (OPENQCDRAD)</td>
</tr>
<tr>
<td></td>
<td>DIS jets</td>
<td>$ep \rightarrow e, jetsX$</td>
<td>NLOJet++ (fastNLO)</td>
</tr>
<tr>
<td></td>
<td>DIS heavy quarks</td>
<td>$ep \rightarrow e, eX, e, eX$</td>
<td>TR', ACOT, ZM (QCDNUM), FFN (OPENQCDRAD), QCDEM</td>
</tr>
<tr>
<td>Tevatron, LHC</td>
<td>Drell-Yan</td>
<td>$pp(\bar{p}) \rightarrow lX, pp(\bar{p}) \rightarrow lX$</td>
<td>MC@NLO (APPLGRID)</td>
</tr>
<tr>
<td></td>
<td>top pair</td>
<td>$pp(\bar{p}) \rightarrow llX$</td>
<td>MC@NLO (APPLGRID), HATHOR, Difftop</td>
</tr>
<tr>
<td></td>
<td>single top</td>
<td>$pp(\bar{p}) \rightarrow llX, pp(\bar{p}) \rightarrow lX, pp(\bar{p}) \rightarrow lWX$</td>
<td>MC@NLO (APPLGRID)</td>
</tr>
<tr>
<td></td>
<td>jets</td>
<td>$pp(\bar{p}) \rightarrow jetsX$</td>
<td>NLOJet++ (APPLGRID), NLOJet++ (fastNLO)</td>
</tr>
<tr>
<td>LHC</td>
<td>DY heavy quarks</td>
<td>$pp \rightarrow VHX$</td>
<td>MC@NLO (APPLGRID)</td>
</tr>
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</table>

Initialisation

Data
- Collider, Fixed Target: $ep, \mu p$
- Collider: $pp, p\bar{p}$

QCD Analysis
- Treatment of the Uncertainties
- Fast $\chi^2$ Computation
- Minimisation (MINUIT)

Theories
- PDF Parametrisation
- QCD Evolution:
  - DGLAP (QCDNUM), non-DGLAP (CCFM, dipole)
- Cross Section Calculation

Results
- PDFs, LHAPDF, TMDlib Grids
- $\alpha_s, m_C, \ldots$
- Data vs. Predictions
- $\chi^2$, Pulls, Shifts
Latest Results from HERAFitter

- Research activities in HERAFitter are steered by demands of the users

**List of analyses by HERAFitter**

<table>
<thead>
<tr>
<th>Date</th>
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**List of analyses using HERAFitter**

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<td>10.2014</td>
<td>LHC/ATLAS</td>
<td>ATL-PHYS-PUB-2014-015</td>
<td>Studies of theoretical uncertainties on the measurement of the mass of the W boson at the LHC</td>
</tr>
<tr>
<td>10.2014</td>
<td>LHC/CMS</td>
<td>arXiv:1410.6765 (CMS-SMP-12-028)</td>
<td>Constraints on parton distribution functions and extraction of the strong coupling constant from the inclusive jet cross section in pp collisions at sqrt(s) = 7 TeV</td>
</tr>
<tr>
<td>09.2014</td>
<td>LHC/ATLAS</td>
<td>arXiv:1406.7844</td>
<td>Comprehensive measurements of t-channel single top-quark production cross sections at sqrt(s)=7 TeV with the ATLAS detector</td>
</tr>
<tr>
<td>08.2014</td>
<td>PROSA</td>
<td>preliminary</td>
<td>Impact of the LHCb measurements of forward charm and beauty production on PDFs</td>
</tr>
</tbody>
</table>

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

- New, herafitter-1.1.0, package was recently released
 Quantitative Assessment

- HERAFitter program can be used with external predictions (i.e. not built-in) to quantify the level of agreement when confronting theory with measurements, taking into account all sources of provided uncertainties (either exp. or th. like PDFs, scale).

- **Applied recent examples:**
  - Low Mass DY (ATLAS) data [arXiv:1404.1212]
  - t-channel single top-quark production cross sections (ATLAS) [arXiv:1406.7844]

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<table>
<thead>
<tr>
<th>Prediction</th>
<th>$\chi^2$ (8 points) Nominal</th>
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<tr>
<td>POWHEG NLO+LLPS</td>
<td>22.4 (19.8)</td>
</tr>
<tr>
<td>FEWZ NLO</td>
<td>48.7 (28.6)</td>
</tr>
<tr>
<td>FEWZ NNLO</td>
<td>13.9 (12.9)</td>
</tr>
</tbody>
</table>

$\rightarrow$ conclusion NNLO is needed to describe data.
HERA has finalised its separate measurements relevant to PDFs and there are ongoing efforts on combining final measurements to reach their ultimate precision:

- HERAFitter is used to extract PDFs, mc, mb, alphas …
Running beauty mass from F2b

The value of the running beauty mass is obtained using HERAFitter (via OPENQCDRAD):

- chi2 scan method from QCD fits in FFN scheme to the combined HERA I inclusive data + beauty measurements, beauty-quark mass is defined in the $\overline{\text{MS}}$ scheme.

The extracted $\overline{\text{MS}}$ beauty-quark mass is in agreement with PDG average and LEP results.
Transverse Momentum Distributions

- QCD applications to multiple-scale scattering problems and complex final-state observables require in general formulations of factorisation which involve transverse-momentum dependent (TMD) - or known also as unintegrated PDFs.

\[
\sigma_j(x, Q^2) = \int_x^1 dz \int d^2k_t \, \hat{\sigma}_j(x, Q^2, z, k_t) \, A(z, k_t, \mu)
\]

- Fits to combined measurements of proton's structure functions from HERA using transverse momentum dependent QCD factorisation and CCFM evolution is performed using HERAFitter platform.

The extracted gluon TMD with experimental and theory uncertainty [JH-2013-set1] is then used as prediction to vector boson+jet production process at the LHC [Phys. Rev. D 85 (2012) 092002.]

- This process is important both for SM physics and for new physics searches at the LHC.
- Results compare well with the measurements of jet multiplicities and transverse momentum spectra within the pdf uncertainties.
QCD interpretation of W production at CMS

- Impact on valence PDFs from W asymmetry is investigated within the HERA FITTER framework through a QCD fit analysis.

- In addition, W+charm data provides direct sensitivity to the strange quark.
DiffTop in HERAFitter [arXiv:1406.0386]

- Top-quark pair production at the LHC probes high-x gluon ($x \approx 0.1$):
  - $\rightarrow$ there is a strong correlation between $g(x)$, $\alpha_s$ and the top-quark mass $m_t$
- Precise measurements of the total and differential (normalised and absolute) cross section of $t\bar{t}$ pair production can constrain and de-correlate $\alpha_s$, gluon, $m_t$
- DiffTop and its interface to FastNLO have been implemented into Herafitter.

- First exploratory PDF fits at NNLO have been performed by using differential cross sections of top-quark pair production together with other data sets [HERA I, W asymm.] to study the impact on the gluon at large $x$.

$\rightarrow$ More data is needed: absolute differential cross section data will bring more information.

[arXiv:1406.0386]
The inclusive jet cross section measured by CMS at 7 TeV provide important input for the gluon density at high $x$ and for the strong coupling constant at large energy scales.

The impact of the CMS inclusive jet data on proton PDFs is investigated by including the jet cross section measurement in a combined fit with the HERA-I inclusive DIS cross sections.

Two prescriptions were used:

- a la HERAPDF style: HERAPDF method
- a la NNPDF style: MC method (data driven regularisation)

Combined fit of PDFs and the strong coupling constant:

- HERAPDF method: $\alpha_s(M_Z) = 0.1192^{+0.0023}_{-0.0019}$ (all except scale).
- MC method: $\alpha_s(M_Z) = 0.1188 \pm 0.0041$ (all except scale).
Studies of theoretical uncertainties of Mw mass at the LHC

ATL-PHYS-PUB-2014-015

- The measurement of the mass of the W boson provides a stringent test of the SM
- At the LHC, the best experimental precision on Mw boson might be achieved from the pT distribution of the charged electron/muon from leptonic decay of W:
- A quantitative study of the theoretical uncertainties due to the incomplete knowledge of the quark PDF, and to the uncertainties on the modelling of the low-pT region of W/Z bosons, performed using HERAFitter platform.
- Theoretical predictions is based on MCFM and CuTe (interfaced to APPLGRID)
- A PDF set is generated using simply HERA I data to study the model variations (mc, strange) and propagated via chi2 profiling method to study the effect of PDF uncertainties
HERAFitter Paper

- Ratios of cross sections are used to reduce common uncertainties, however the theoretical calculations sometimes are not available at the same order of accuracy in pQCD.

\[
\frac{\sigma_{X}^{NLO} \otimes PDF_{NLO}}{\sigma_{Y}^{NLO} \otimes PDF_{NLO}} \quad \text{PDF uncertainties cancel large scale uncertainty}
\]

\[
\frac{\sigma_{X}^{NLO} \otimes PDF_{NNLO}}{\sigma_{Y}^{NNLO} \otimes PDF_{NNLO}} \quad \text{improved scale uncertainty No cancellation of PDF uncertainty}
\]

- HERAFitter provides possibility to account for correlations between PDFs at different orders which can lead to reduction of overall theoretical uncertainties:

\[
\frac{\sigma_{X}^{NLO} \otimes PDF_{corr}}{\sigma_{Y}^{NNLO} \otimes PDF_{corr}} \quad \text{PDF uncertainties cancel improved scale uncertainty}
\]

- mixed-order calculations with correlated PDFs help to reduce PDF and scale uncertainties
  - total theoretical uncertainty is reduced by 30-40%
Summary and Outlook

❖ HERAFitter is an open source QCD software package which encodes results from a wide range of experimental data in ep, pp, ppbar complemented with a variety of theoretical options for calculating PDF-dependent cross section predictions.

www.herafitter.org
latest release: herafitter-1.1.0

❖ The further progress of HERAFitter is driven by the latest QCD advances in theoretical calculations and in the precision of experimental data:
   ❖ QED +QCD via QEDEvol (R. Sadykov)
   ❖ FONLL and low x resummation via **APFEL** (J.Rojo, V. Bertone, S. Carrazza)
   ❖ ACOT @ NNLO (P. Nadolsky)
HERAFitter Program at glance

- HERAFitter code is a combination of C++ and Fortran 77 libraries with minimal dependencies and modular structure with interface to external packages:
  - QCDNUM for evolution of PDFs
- DIS inclusive processes in ep and fixed target
  - Different schemes of heavy quark treatment
    - VFNS, FFNS:
      - OPENQCDRAD (ABM)
      - TR’ (MSTW)
      - ACOT (CT)
- Diffractive PDFs
- Dipole Models
- Unintegrated PDFs (TMDs)
- Jet production (ep, pp, ppbar)
  - FastNLO and APPLGRID techniques
- Drell-Yan processes (pp, ppbar)
  - LO calculation x NLO k-factors
  - APPLGRID technique
- Top pair production
  - total inclusive ttbar cross sections (HATHOR)
  - differential (DiffTop approx NNLO via fastNLO grids)
HERAFitter in the ggH benchmark studies

- Efforts in reducing the PDF uncertainties arising from discrepancy between PDF groups:
  - Benchmark comparisons of NNLO neutral current DIS cross sections (Exercise on HERA-I only data)

  ![Benchmark comparisons of NNLO neutral current DIS cross sections](image)

  - arxiv:1405.1067
  - Based on recently published NNLO PDFs.

  ![Based on recently published NNLO PDFs.](image)

  - Predictions from MSTW, CT, NNPDF and HERAPDF all consistent within PDF uncertainties
  - However the tendency among NNPDF, MSTW and CT is maintained

- Next step:
  - Continue this exercise by adding additional experimental data sets into the PDF fits sequentially:
  - Benchmarking the theoretical predictions used by each group for the different observables -
  - ==> HERAFitter will continue to participate in these studies.