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# xFitter

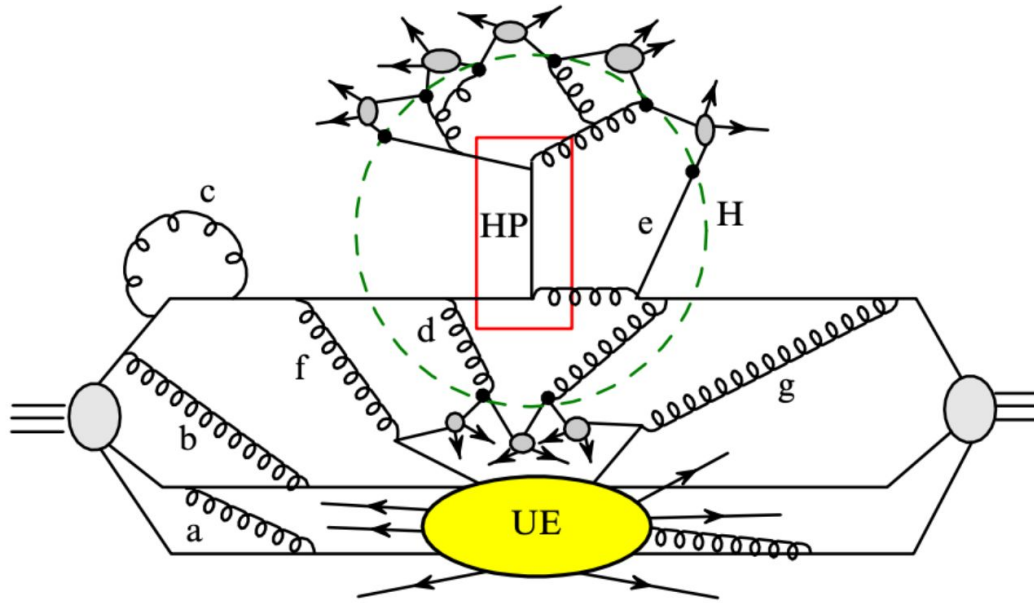
— S. Glazov, CTEQ school,  
29 August 2024 —

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# Proton-proton interactions and factorization



Soft part, from  
data

Hard part, from  
theory

$$\sigma = \text{PDFs}(\mu_F) \otimes C(\mu_F)$$

Factorisation scale

- Accurate theoretical predictions are challenging
- High-momentum transfer processes, or “**hard processes**”, can be **factorized** into interaction of a pair of partons.
- Cross section is a convolution of universal parton distribution functions and coefficient functions specific for the process.

# PDFs in a nutshell

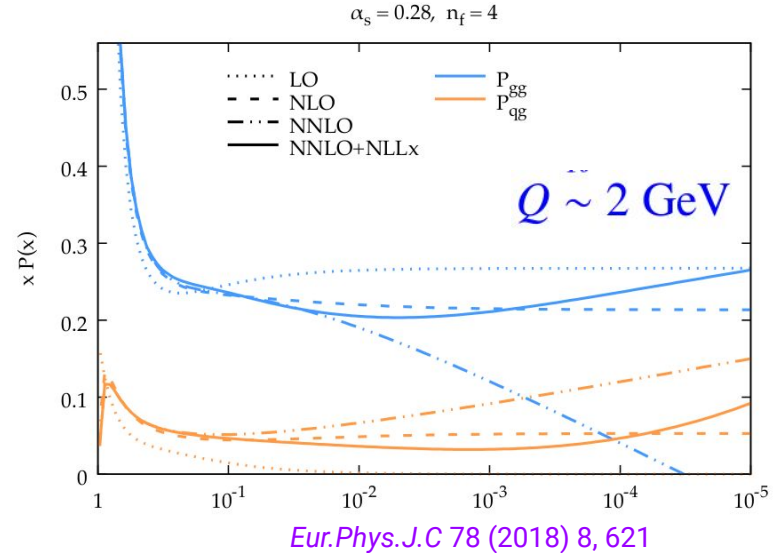
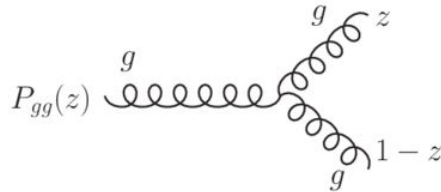
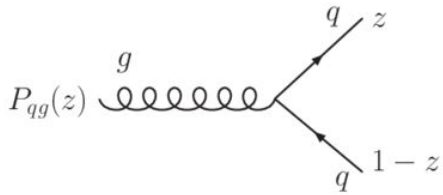
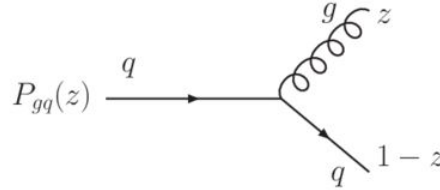
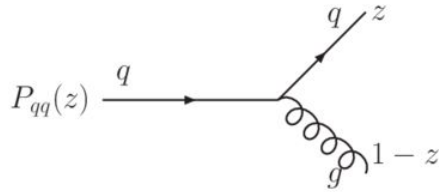
# PDFs: decomposition and evolution

- At LO, PDFs can be interpreted as a probability to find a parton inside the proton with  $x$ -momentum fraction of the proton at the momentum transfer squared  $q^2$
- Standard **11** partons are (anti-)quarks  $(u,d,s,c,b)(x,q^2)$ , and the gluon  $g$ . Photons,  $W,Z$  bosons, and leptons may be considered as partons to include electroweak effects
- $c$ - and  $b$ -quarks can be determined perturbatively from the gluon; for high  $q^2$  treating them as light quarks is better. Top is never considered as a parton.
- PDFs at higher scales  $q^2$  and larger  $x$  are computed from lower scales using **DGLAP** evolution. It is decoupled for the **valence** quarks  $(u_v, d_v)$ , and coupled for **singlet/gluon** combination

$$\frac{d}{d \log Q^2} \begin{pmatrix} \Sigma \\ g \end{pmatrix} = \frac{\alpha_S}{2\pi} \int_x^1 \frac{dz}{z} \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \begin{pmatrix} \Sigma \\ g \end{pmatrix} \quad \Sigma = \sum q + \bar{q}$$

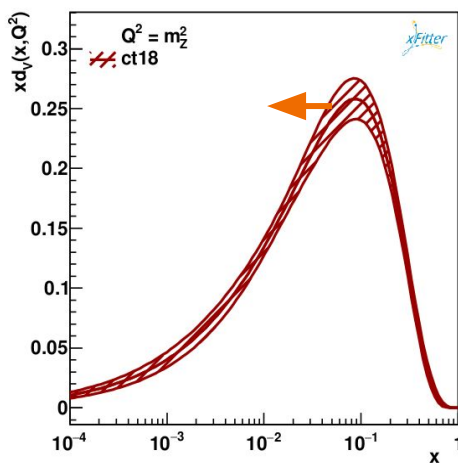
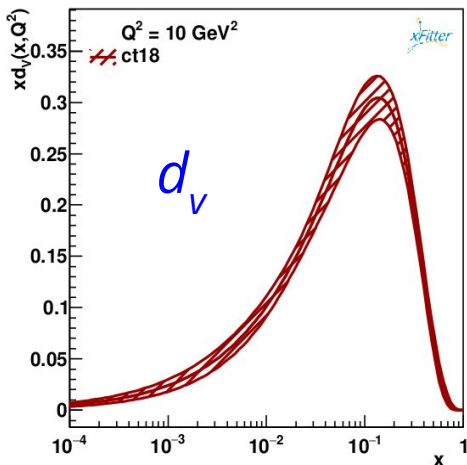
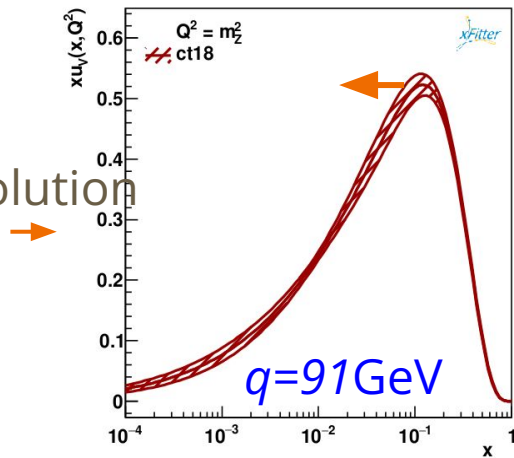
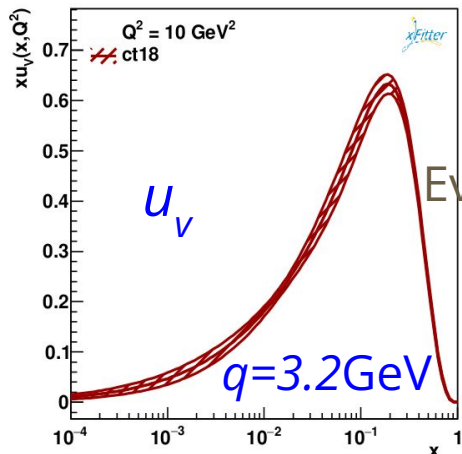
# QCD Evolution

$$\frac{d}{d \ln Q^2} q^{NS}(x, Q^2) = \frac{\alpha_S(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} P_{qq} \left( \frac{x}{z}, \alpha_S(Q^2) \right) q^{NS}(z, Q^2)$$



- QCD splitting functions  $P_{qq}, P_{gq}, P_{qg}, P_{gg}$ : at LO, probability to find a parton  $a$  inside parton  $b$  with momentum fraction  $x$
- Known at LO, NLO, NNLO, NNLO+NLLx and recently approximate N3LO
- Numerical solutions of DGLAP evolution by HOPPET, QCDNUM APFEL(++)

# PDFs: valence quarks



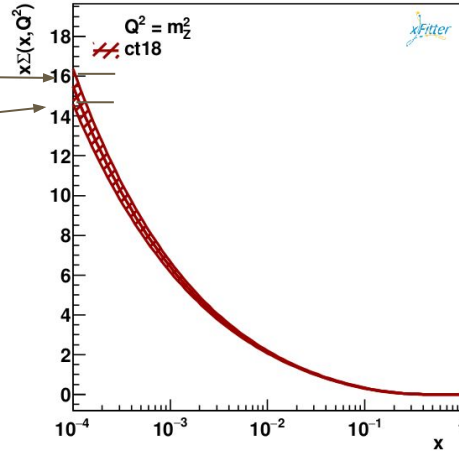
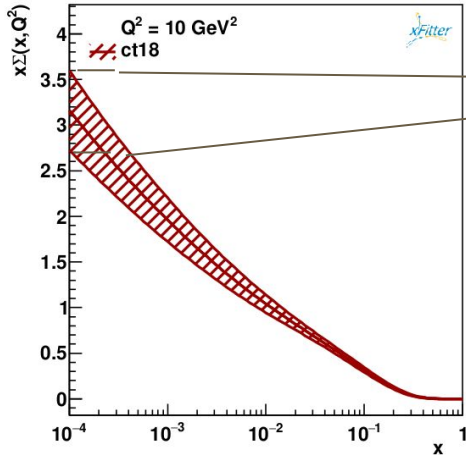
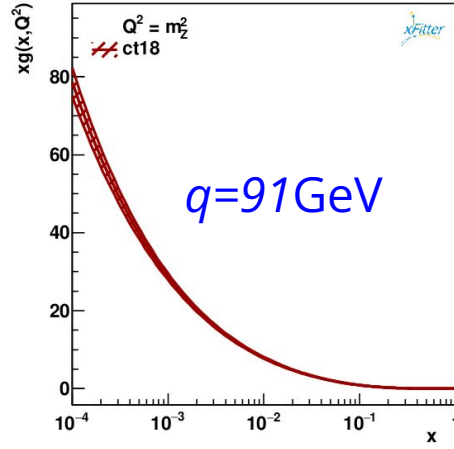
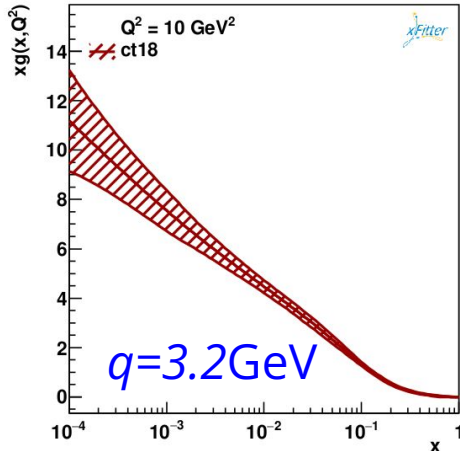
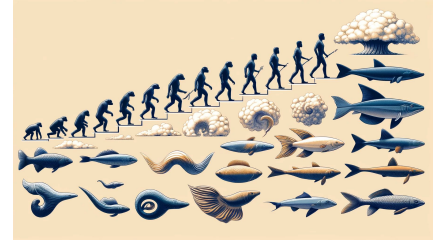
Valence quarks  $u_v = u - u_{bar}$ , and  $d_v = d - d_{bar}$  obey quark-counting sum rules:

$$\int u_v(x) dx = 2, \int d_v(x) dx = 1,$$

which states that total amount of  $u_v$  and  $d_v$  is preserved under evolution.

Shapes of the distributions changes mildly from low to high  $q^2$ , with peak moving to lower  $x$  due to gluon emission.

# PDFs: gluon and sea



The gluon and sea quarks evolve very rapidly, especially at low  $x$ .

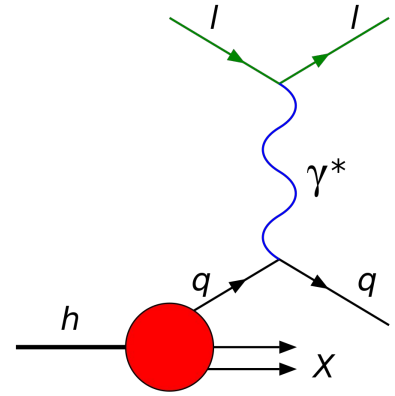
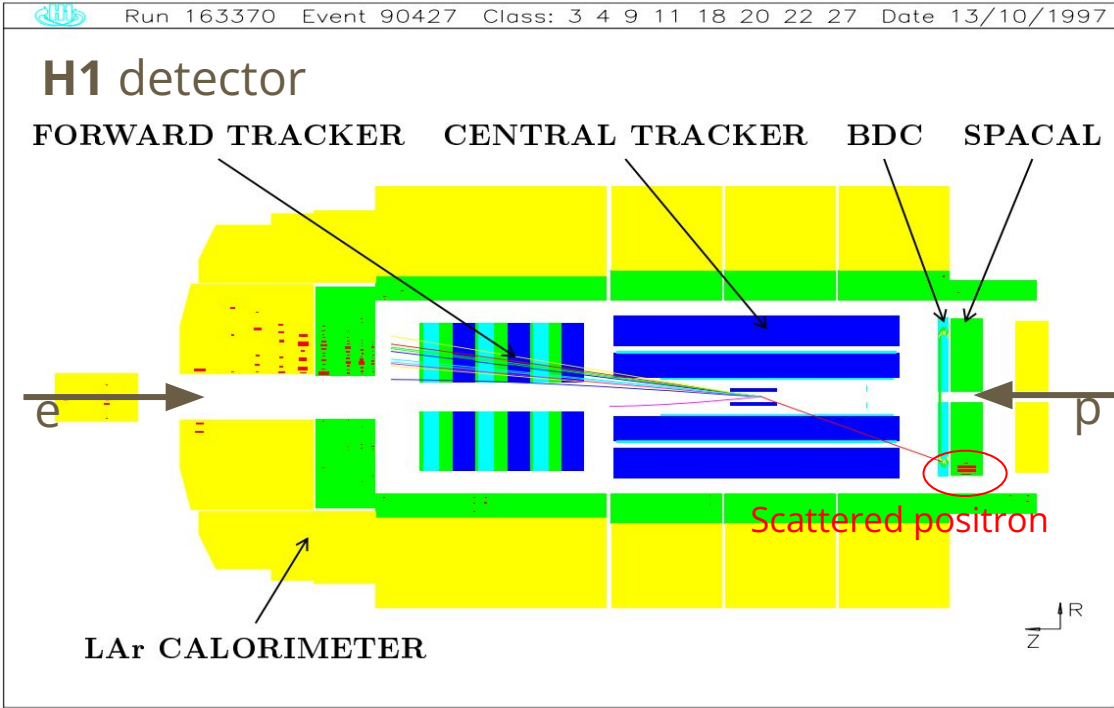
Linear DGLAP evolution preserves approximately absolute uncertainties on PDFs; relative uncertainties shrink / increase where PDFs become larger / smaller with evolution.

→ relative PDF uncertainties at **high  $x$**  and **high  $q^2$**  are in general **very large**.

# Determination of PDFs



# Deep inelastic ep scattering and PDFs



Probing proton structure with elementary leptons

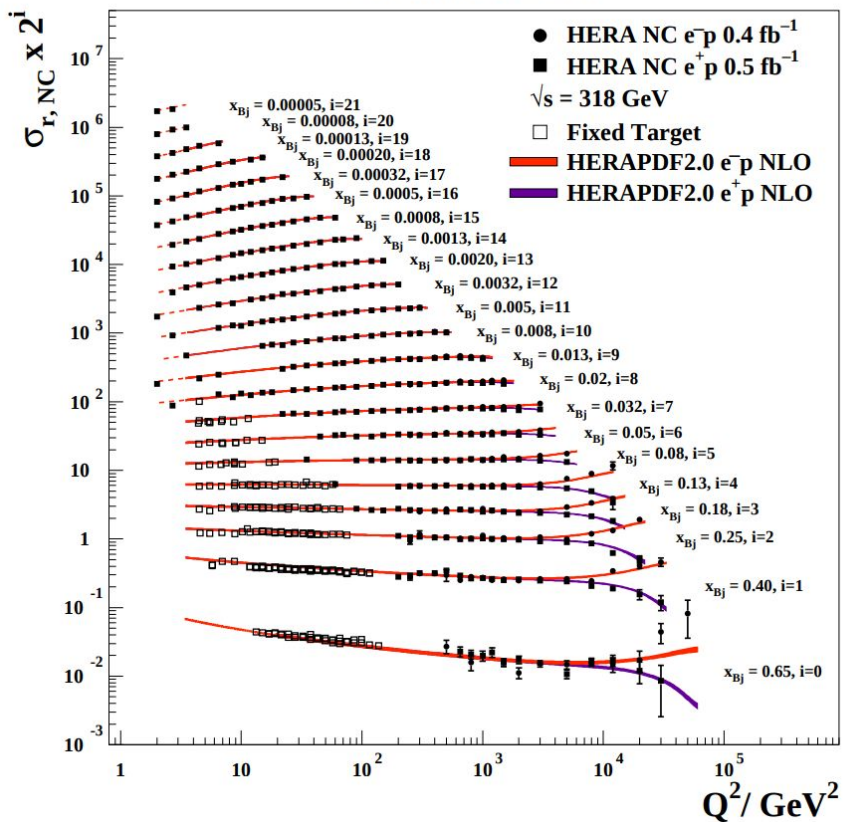
Kinematics based on scattered leptons (and hadrons, for low inelasticity  $y$ )

accurate results for  $0.01 < y < 0.8$

$$y_e = 1 - \frac{E'_e(1 - \cos \theta_e)}{2E_e}, \quad Q_e^2 = \frac{P_{T,e}^2}{1 - y_e}, \quad x = \frac{Q^2}{S y}$$

# Determination of the PDFs using electron-proton data

## H1 and ZEUS



$$\frac{d^2\sigma_{e^+p}^{NC}}{dx dQ^2} = \frac{2\pi\alpha^2 Y_{\pm}}{xQ^4} \left( F_2 - \frac{y^2}{Y_{\pm}} F_L \pm \frac{Y_{\mp}}{Y_{\pm}} xF_3 \right)$$

$$Y_{\pm} = 1 \pm (1-y)^2$$

$$F_2 = x \sum e_q^2 (q(x) + \bar{q}(x))$$

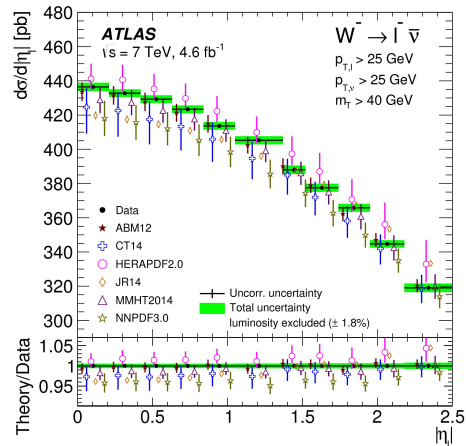
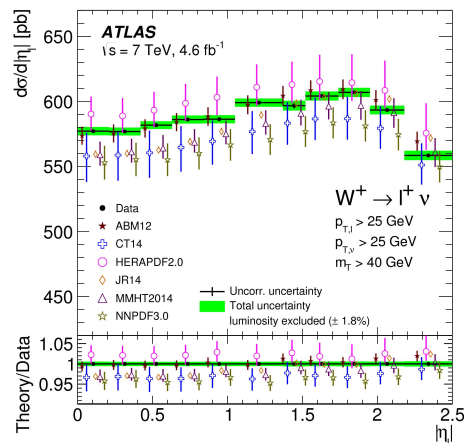
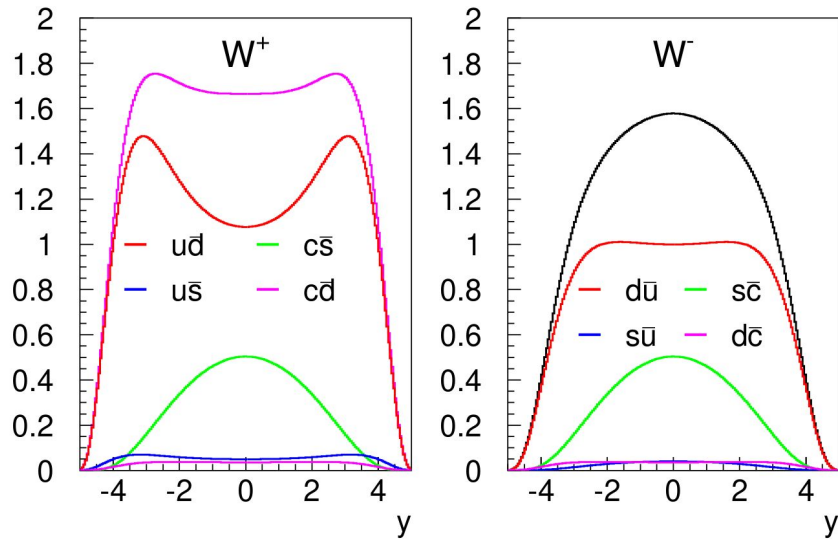
$$xF_3 = x \sum 2e_q a_q (q(x) - \bar{q}(x))$$

Measurement of inclusive  $ep$  cross section provides a clean to determine **linear combinations** of PDFs. At HERA photon exchange dominates, the best PDF determined is  $u(x)$ .

Gluon is measured from  $q^2$  dependence of the structure function  $F_2$

Lower accuracy at high  $x$

# Example of PDF input from LHC: $W$ boson production

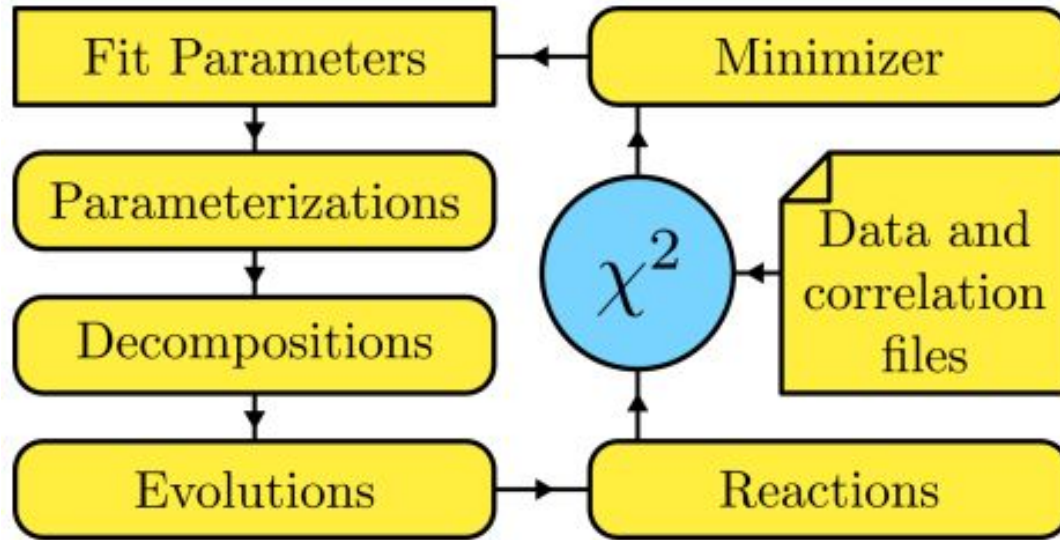


*Eur.Phys.J.C* 77 (2017) 6, 367

$W^\pm$  boson production is sensitive to CKM matrix element weighted bilinear form of  $u, d, s, c$  PDFs.

The difference of  $W^+$  vs  $W^-$  production provides important constraints on  $u_v - d_v$  at  $x$  around 0.01

# What is xFitter



Quantitative comparison of the data and QCD predictions aimed to determine theory parameters involves a number of steps. **xFitter** binds them together.

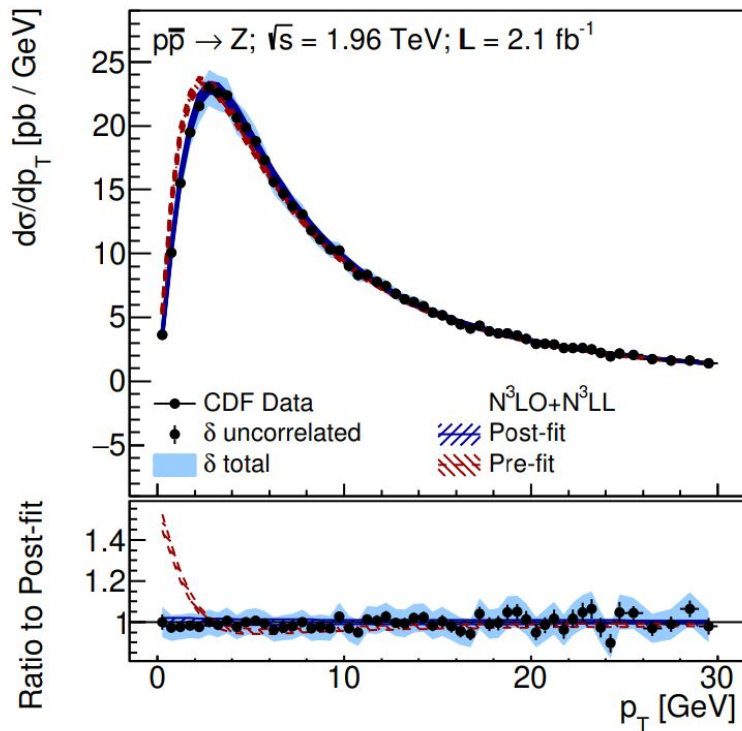
# xFitter motivation

- Enable phenomenological interpretation of data, for both experimental and theory analyses.
- Data interpretations should be fully reproducible: publish tools to obtain them.
- Reference fits to the data are important for validation of the data correlation model
- Reduce threshold for quantitative comparison between data and a new theory model: easy interface for new developments.

# xFitter analysis flow

- Parameterise PDFs at the starting scale
  - Several parameterisations and decompositions available
  - Sum-rules to constrain some parameters
- Evolve to all scales relevant for the data
  - QCDNUM, APFEL, APFEL++ (in development: HOPPET)
  - Alternatives to collinear DGLAP evolution
- Compute predictions to the data
  - Several schemes for inclusive DIS (TR, FONLL, ACOT)
  - Grid-based methods for
  - Explicit computation for some processes (HATHOR, DYTURBO)
- Compare data and predictions, compute likelihood
  - Detailed modeling of data systematic uncertainties and correlations
- Repeat within a minimizer
  - Minuit, CERES

# Example analysis: CDF Z-pt

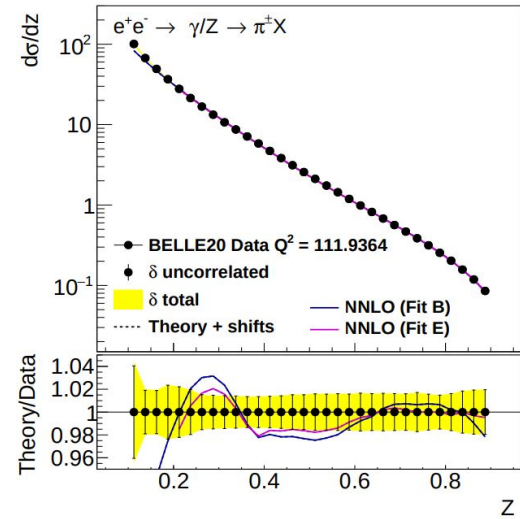
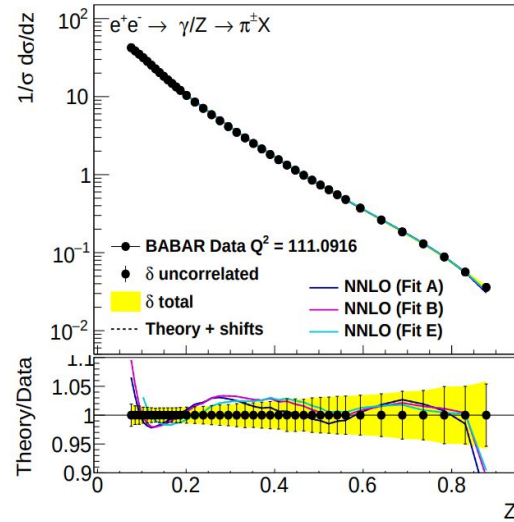
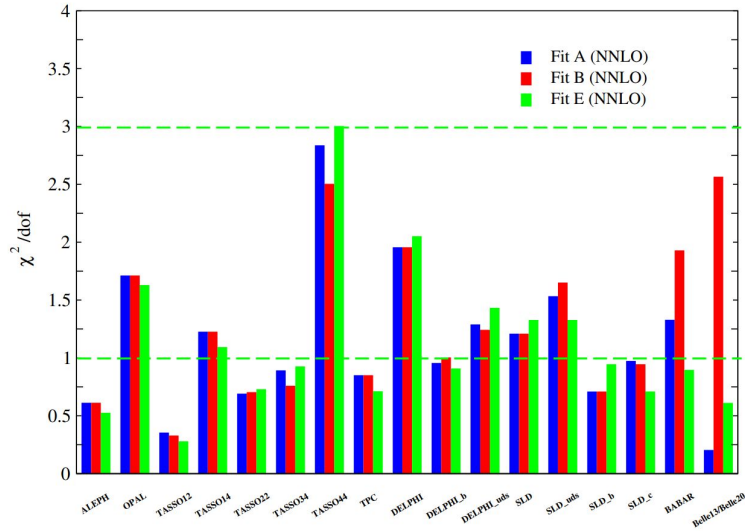


- Determination of  $\alpha_S$  using CDF full phase-space  $P_t$  data and  $N^3\text{LO} + N^3\text{LL}$  prediction from DYTURBO <https://arxiv.org/abs/2203.05394>
- Data, predictions are included in xFitter
- **`./tools/test.sh ZPT`**

$$\alpha_S(m_Z) = 0.1185^{+0.0014}_{-0.0015}$$

Reproduces one iteration of the fit to HERA + CDC data.

# Example analysis: pion fragmentation



- NNLO fit using APFEL to single-inclusive annihilation (SIA) data from  $e^+e^-$  colliders to determine pion fragmentation function. Tensions between Belle and Babar data at low  $z$ .
- Reproduce on iteration in xFitter by running `./tools/test.sh Pion_FF`



# xFitter capabilities

The strength of xFitter is that it contains many ways to compute theory predictions and that it is flexible to include new models.

- Collinear PDFs
  - Evolution codes from QCDNUM and APFEL
  - Deep Inelastic Scattering predictions from ABM, NNPDF (FONLL), RT, ACOT
  - pp predictions via APPLGRID and FastNLO, up to NNLO
  - Interface to DYTURBO for DY production.
- TMDs
  - Parton branching evolution
- Fragmentation functions
  - e+e- SIA via APFEL
- Alternative phenomenological models
  - Tensor pomeron

# xFitter code access

xFitter

Welcome to xFitter (former HERAFitter)

Proton parton distribution functions (PDFs) are essential for precision physics at the LHC and other hadron colliders. The determination of the PDFs is a complex endeavor involving several physics process. The main process is the lepton proton deep-inelastic scattering (DIS), with data collected by the HERA ep collider covering a large kinematic phase space needed to extract PDFs. Further processes (fixed target DIS, ppbar collisions etc.) provide additional constraining powers for flavour separation. In particular, the precise measurements obtained or to come from LHC will continue to improve the knowledge of the PDF.

The xFitter project is an open source QCD fit framework ready to extract PDFs and assess the impact of new data. The framework includes modules allowing for a various theoretical and methodological options, capable to fit a large number of relevant data sets from HERA, Tevatron and LHC. This framework is already used in many analyses at the LHC.

Downloads of xFitter software package



All the xFitter releases can be accessed [HERE](#) including **2.2.0 FutureFreeze** release  
All the former (HERAFitter) releases can be accessed [HERE](#).  
Description: <http://arxiv.org/abs/1410.4412>

xFitter Meetings

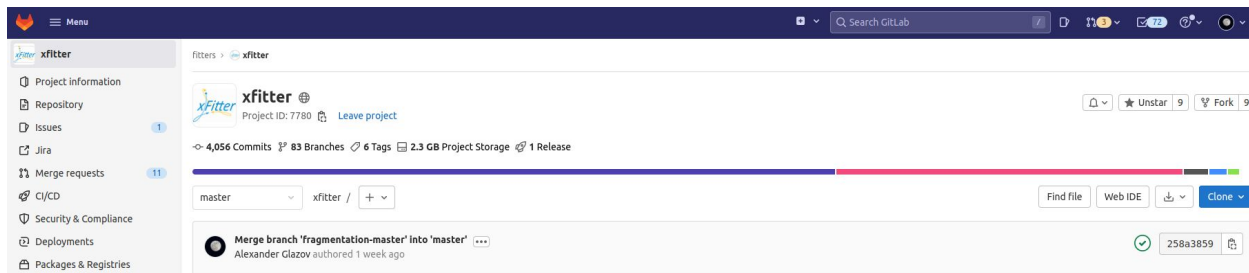
- xFitter Workshop at Orsay 9-11 March 2022
- User's Meetings: meetings to enhance communication between users and developers (open access)
- Developer's Meeting: technical weekly meetings to ensure communication among developers (restricted access)
- Steering Group's Meeting (restricted access)

xFitter representation

- Snowmass contribution
- List of results
- List of collected talks







- xFitter [frontpage](#) contains all relevant links
- Going directly to the [gitlab](#) repository is another possibility



The screenshot shows the GitLab interface for the xFitter repository. The repository name is 'xfitter' and its ID is 7780. It has 4,056 commits, 83 branches, 6 tags, 2.3 GB of project storage, and 1 release. The current branch is 'master'. A recent commit by Alexander Glazov is visible, titled 'Merge branch 'fragmentation-master' into 'master''.

# xFitter releases

Date	Version	Files	Remarks
 03/2022	<b>2.2.0 FutureFreeze</b>	<a href="#">📄 xfitter-2.2.0.tgz</a>	Major update of evolution and reaction interfaces
 05/2019	<b>2.0.1 OldFashioned</b>	<a href="#">📄 xfitter-2.0.1.tgz</a>	update/bug fix to 2.0.0 FrozenFrog
 03/2017	<b>2.0.0 FrozenFrog</b>	<a href="#">📄 xfitter-2.0.0.tgz</a>	stable release with decoupled data and theory files
 02/2020	<b>2.0.1N Nuclear Daiquiri</b>	<a href="#">📄 xfitter-2.0.1N.tgz</a>	Nuclear xFitter based on OldFashioned 2.0.1

- Couple of “stable” releases used by many analyses in the past (plus dedicated release for nuclear PDFs)
- Major changes with the [Future Freeze](#) release 2.2.0, a few additions in the master branch (which is fairly stable).

# Getting information

xfitter

Project information

Repository

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Jira

Merge requests 11

CI/CD

Security & Compliance

Deployments

Packages & Registries

Infrastructure

Monitor

Analytics

Wiki

Snippets

Settings

filters > xfitter > Wiki > Home

Last edited by Alexander Glazov 1 week ago

## Home

### Version 2.2

#### User

IF YOU HAVE A PROBLEM

Installation script

Installing all datafiles

Installing with cmake

#### Program steering

Basic program usage

YAML steering

Data file format

Chi2 definition

Cuts

xfitter-draw

xfitter-process

Minimisers

Parameters

Parameterisations

Decompositions

Evolutions

Reactions

Reaction parameters

LHAPDF6 output

Profiler and PDF sensitivity study

PDF rotation

Chi2 scan

#### Developer

Code and commit style

Reaction interface

cmake

Tests

Running the CI locally

## parameters.yaml



Since version 2.2, parameters.yaml is the main steering file for xfitter. Some options that control the old fortran code are still in steering.txt, but we are planning to slowly migrate to the YAML steering and get rid of steering.txt completely.

The fitted parameters, the used parameterizations, decompositions and evolutions are defined in parameters.yaml. See [defining parameters](#), [defining parameterisations](#), [defining evolutions](#)

### Including files

Other YAML files can be included in the main file like this:

```
? !include PATH_TO_FILE
```

For example, if constants.yaml contains:

```
Mz : 91.1876
Order: NNLO
mch: 1.2
Map:
  A: 12
  B: "On"
```

- The main documentation of the project is moved to [gitlab wiki](#) which was significantly improved for release 2.2.0
- Directory [examples/](#) contains a number of sample analyses to try.

# Installing xFitter

```
6501 Testing chi2scanMTOp ... PASS [details in temp/chi2scanMTOp/test.log]
6502 Testing defaultNLO ... PASS [details in temp/defaultNLO/test.log]
6503 Testing defaultNNLO ... PASS [details in temp/defaultNNLO/test.log]
6504 Testing evolutionAPFELxx ... PASS [details in temp/evolutionAPFELxx/test.log]
6505 Testing fractalFit ... PASS [details in temp/fractalFit/test.log]
6506 Testing modifyDataSetParameter ... PASS [details in temp/modifyDataSetParameter/test.log]
6507 Testing paramABMP16 ... PASS [details in temp/paramABMP16/test.log]
6508 Testing paramBG ... PASS [details in temp/paramBG/test.log]
6509 Testing profilerAs ... PASS [details in temp/profilerAs/test.log]
6510 Testing profilerLHAPDF ... PASS [details in temp/profilerLHAPDF/test.log]
6511 Testing profilerLHAPDF-HERAPDF20 ... PASS [details in temp/profilerLHAPDF-HERAPDF20/test.log]
6512 Testing ttbar3D ... PASS [details in temp/ttbar3D/test.log]
6513 -> 39 test(s) PASS
6514 Cleaning up project directory and file based variables
6516 Job succeeded
```

- It is recommended to use the latest release 2.2.0 or the **master** branch
- The master branch is tested nightly; all dependencies should be satisfied at any time for a number of tested platforms (EL7, Ubuntu 20.04)
- Exotic platforms such as apple M. raspi ( $\geq 4\text{GB}$ ), RISC-V work too.

# Data samples

```
datafiles/lhc/alice/charmProduction/:  
1702.00766 1901.07979  
  
datafiles/lhc/atlas/drellYan/:  
1305.4192 1404.1212  
  
datafiles/lhc/atlas/jets/:  
1112.6297 1304.4739  
  
datafiles/lhc/atlas/singleTopProduction/:  
1406.7844  
  
datafiles/lhc/atlas/topProduction/:  
1406.5375 1407.0371  
  
datafiles/lhc/atlas/wzProduction/:  
1203.4051 1612.03016  
  
datafiles/lhc/cms/jets/:  
1212.6660 1609.05331 2111.10431  
  
datafiles/lhc/cms/singleTopProduction/:  
1403.7366  
  
datafiles/lhc/cms/topProduction/:  
1208.2671 1211.2220 1703.01630 1904.05237 cms-pas-top-11-024  
  
datafiles/lhc/cms/wzProduction/:  
1110.4973 1206.2598 1310.1138 1312.6283 1603.01803  
  
datafiles/lhc/lhcb/beautyProduction/:  
1306.3663  
  
datafiles/lhc/lhcb/charmProduction/:  
1302.2864 1510.01707 1610.02230
```

- A number of data files are stored in <https://gitlab.cern.ch/fitters/xfitter-datafiles> repository
- The data format allows for complex correlation model including correlations across data samples
- Used as de-facto reference for PDF groups

# xFitter team



- xFitter is not a collaboration, but self governed developers' team
- Developers from different areas, experiment and phenomenology
- Developments by O(10) persons, during their free time
- Open publication policy, papers can be published within or outside the team
- Biweekly meetings to share the news

# Contributing to xFitter development



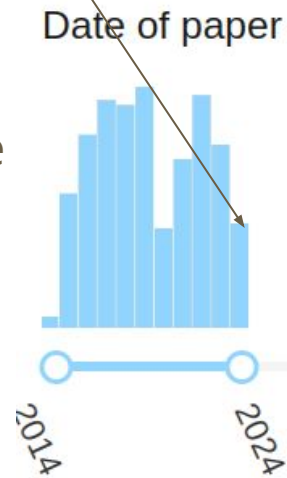
- xFitter code is open for new contributions
- For developers with CERN account, use [gitlab.cern.ch](https://gitlab.cern.ch), otherwise use [gitlab.org](https://gitlab.org) mirror
- The code should follow light coding recommendations, described in the wiki
- Updates are normally to be presented at a developers meeting
- A merge request is subject to CI tests, that ensure stability of the xFitter main functionality and a (light) review by another developer



# Summary

- xFitter is a handy tool for the HEP community that is in active use
- A couple of new developments recently, with the [Future Freeze 2.2.0](#) release and beyond
- xFitter received many contributions from experimental and theory groups, and more participation is always welcome

21 citations in 2024



# Docker image-based tutorial

[https://docs.google.com/document/d/1Lbitf1XLxFzjanbNFqXhIGh2GIR0R\\_fQEe\\_hkMY1XYY8/edit](https://docs.google.com/document/d/1Lbitf1XLxFzjanbNFqXhIGh2GIR0R_fQEe_hkMY1XYY8/edit)

Slides describing the tutorial:

<https://indico.cfnssbu.physics.sunysb.edu/event/111/contributions/988/attachments/317/491/fra2023.pdf>

# xFitter tutorial addendum for docker image

**Exercise #2:** start with **installing dyturbo** (it is not installed by default)

- Make sure that we are at the current master branch:
  - git checkout master
  - git pull
- Check the configuration
  - ./make.sh reconfigure
- Install dyturbo (from the top directory):
  - ./tools/install-dyturbo
  - ./make.sh reconfigure
  - ./make.sh install

```
-- Found Hathor 2.0: /home/xfitter/deps/Hathor-2.0
-- DYTurbo not found
-- Found yaml 0.2.5: /usr/lib64/libyaml.so
```

```
-- Found Hathor 2.0: /home/xfitter/deps/Hathor-2.0
-- Found DYTurbo 1.3.3: /home/xfitter/deps/dyturbo-1.3.3
-- Found yaml 0.2.5: /usr/lib64/libyaml.so
```

# Running exercise #2 faster

- Try to use CERES instead of MINUIT:
  - Minimizer: CERES
- Compute partial derivatives in a parallel manner:
  - threads: 20 in CERES: block (where 20 is number of cores in your laptop)

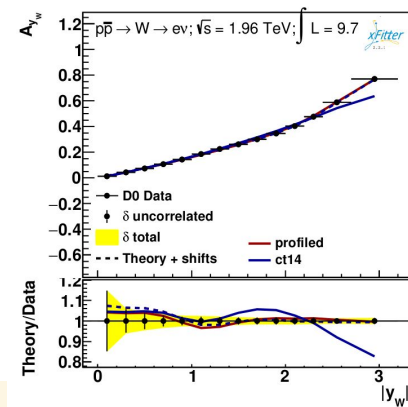
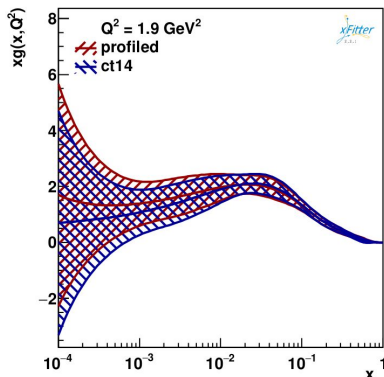
```
CERES:  
  offset: 2  
  tolerance: 1e-5  
  strategy: 0  
  covariance: 1  
  threads: 20
```

# Fixes for exercise #3

- Instead of HERAPDF, we shall profile CT14nnlo:

```
Profiler:  
Evolutions:  
  proton-LHAPDF:  
    sets: [CT14nnlo]  
    members: [[0,1,end]]  
Status: "On" # "Off" to turn off profiler  
WriteTheo: "Asymmetric" # Can be "Off", "On" or "Asymmetric" (to store asymmetric variations)  
getChi2: "On" # determine and report chi2 for each variation  
enableExternalProfiler: "On"
```

- CT14nnlo can be uploaded as xFitter suggests:
  - `./tools/download-lhapdf.sh CT14nnlo` (from top container directory)
- Profiled results can be drawn using `xfitter-draw`:
  - `xfitter-draw --bands profile:output:profiled output:ct14`



# xFitter plans and wish list

- Complete re-structuring of the code which started with the [Future Freeze 2.2.0](#) release: chi2 evaluation, data handling.
- Update to follow modern QCD developments (N3LO, N4LL,...)
- Extend beyond PDF and FF fits: combined PDF+FF fits at least at NNLO, starting from SIA + SIDIS data fits.
- More TMD developments
- Further developments of PDF+EWK fits, SM+BSM.
- Complete development of ultra-fast fits using “APFELgrid” technology, analytic derivatives and modern minimizers → global fit in seconds.

# VirtualBox Notes

pw:  
vboxuser:       xfit2024  
cfns:            EIC2024!

## **Suggestions:**

General: Advanced: Bidirectional Clipboard & Drag'n'Drop  
Base Memory: 8Gb+  
CPU: 2+  
Display: 48Mb+  
Shared Folders (optional)  
/home/MyArea/ SHARE SHARE (auto mount)