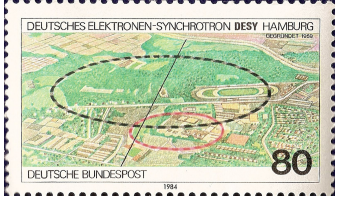
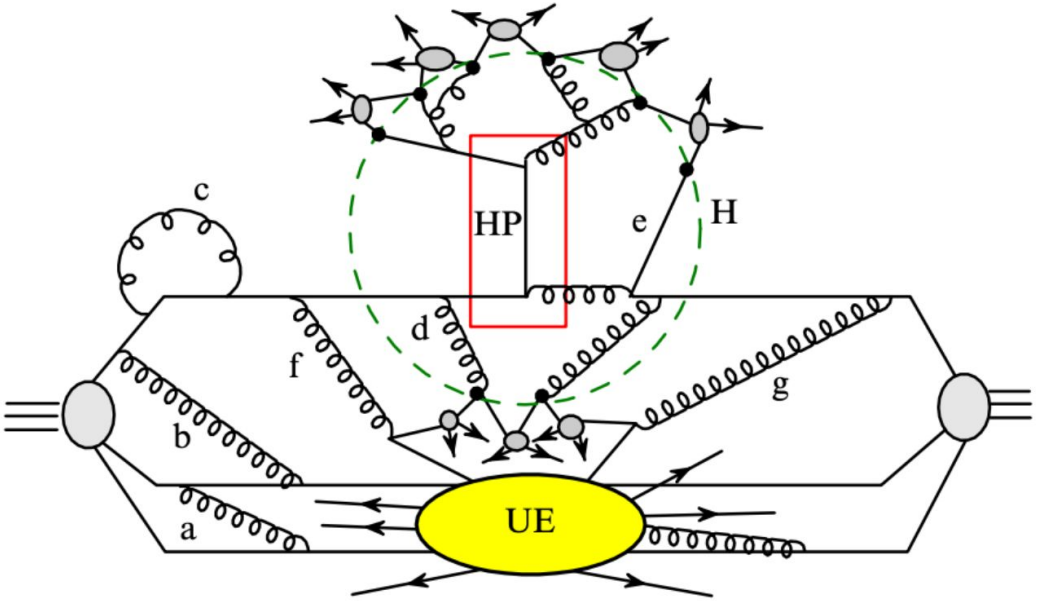


xFitter

S. Glazov, CTEQ school,
29 August 2024

Proton-proton interactions and factorization



- 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.

Soft part, from data

Hard part, from theory

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

Factorisation scale

PDFs in a nutshell

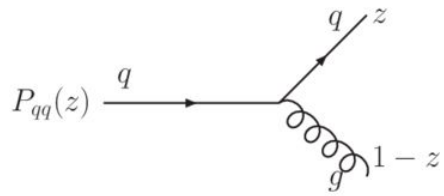
PDFs: decomposition and evolution

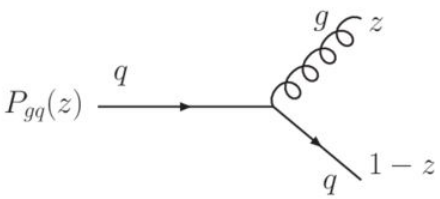
- At LO, PDFs can be interpreted as a probability to find a parton inside the proton with ***x***-momentum fraction of the proton at the momentum transfer squared q^2
- Standard **11** partons are (anti-)quarks $(u,d,s,c,b)(x,q^2)$, and the gluon g. Photons, W,Z bosons, and leptons may be considered 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

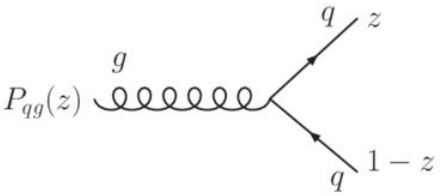
$$\frac{d}{d\log Q^2}\begin{pmatrix}\Sigma\\ g\end{pmatrix} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dz}{z}\begin{pmatrix}P_{qq} & P_{qg}\\ P_{gq} & P_{gg}\end{pmatrix}\begin{pmatrix}\Sigma\\ g\end{pmatrix} \qquad \Sigma = \sum q + \bar{q}$$

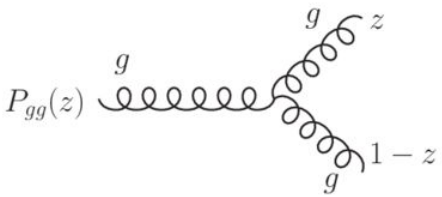
QCD Evolution

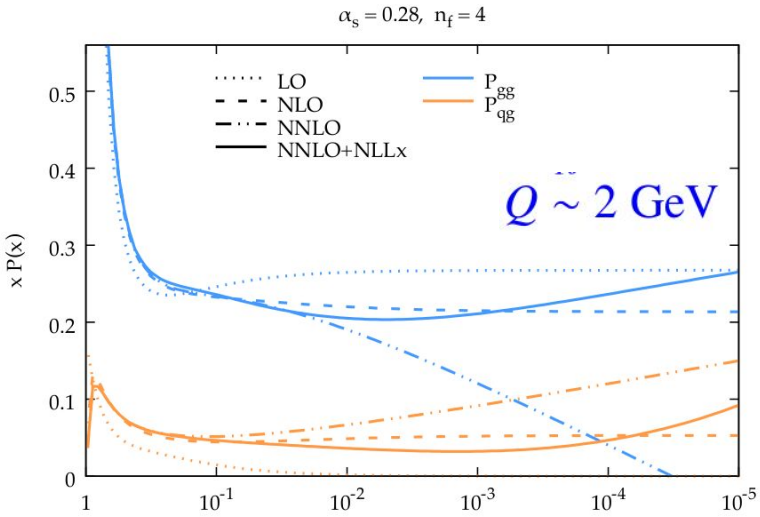
$$\frac{d}{d\ln Q^2} q^{NS}(x,Q^2) = \frac{\alpha_S(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} P_{qq}\left(\frac{x}{z}, \alpha_S(Q^2)\right) q^{NS}(z,Q^2)$$











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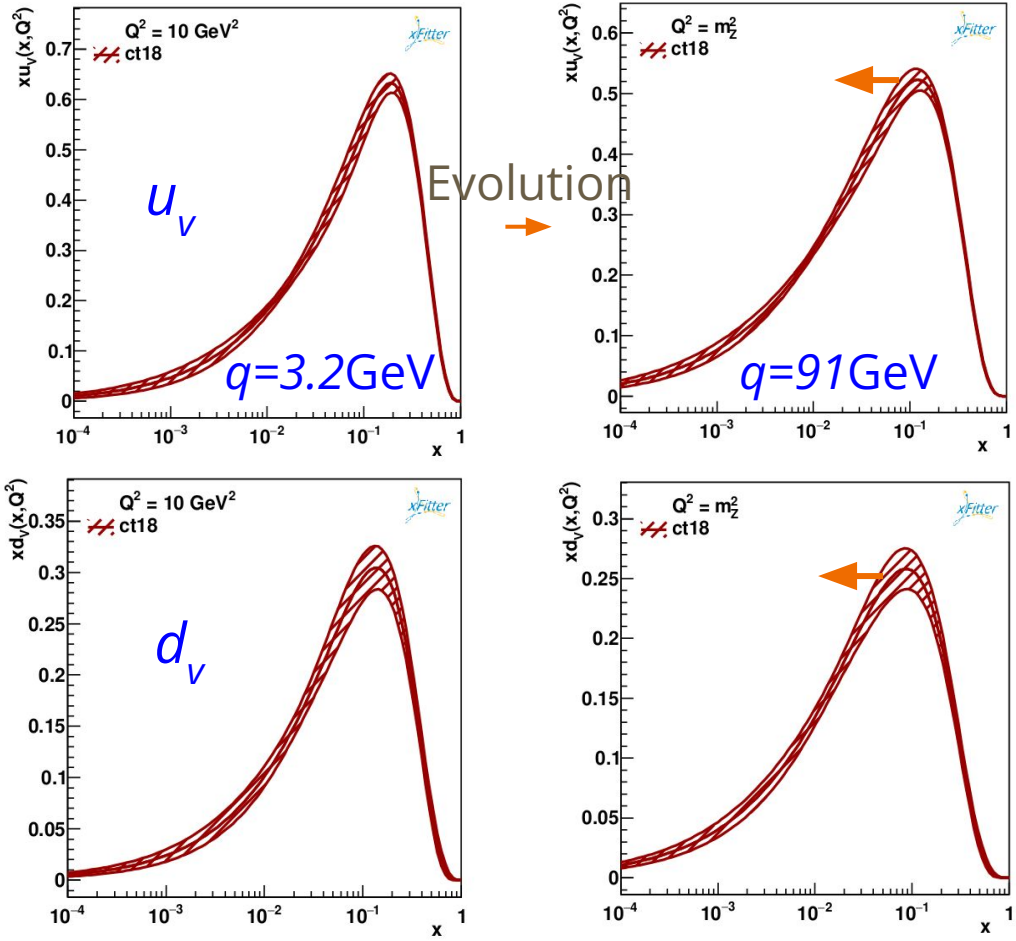
- QCD splitting functions P_{qq}, P_{gq}, P_{qg}, P_{gg}: at LO, probability to find a parton *a* inside parton *b* with momentum fraction x
- Known at LO, NLO, NNLO, NNLO+NLLx and recently approximate N3LO
- Numerical solutions of DGLAP evolution by HOPPET, QCDNUM APFEL(++)

PDFs: valence quarks



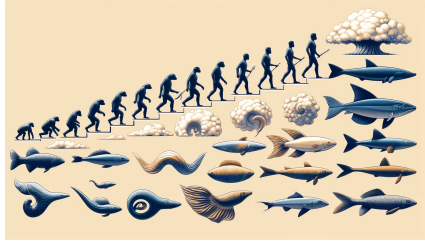
Valence quarks $u_v = u - ubar$, and $d_v = d - dbar$ obey quark-counting sum rules:

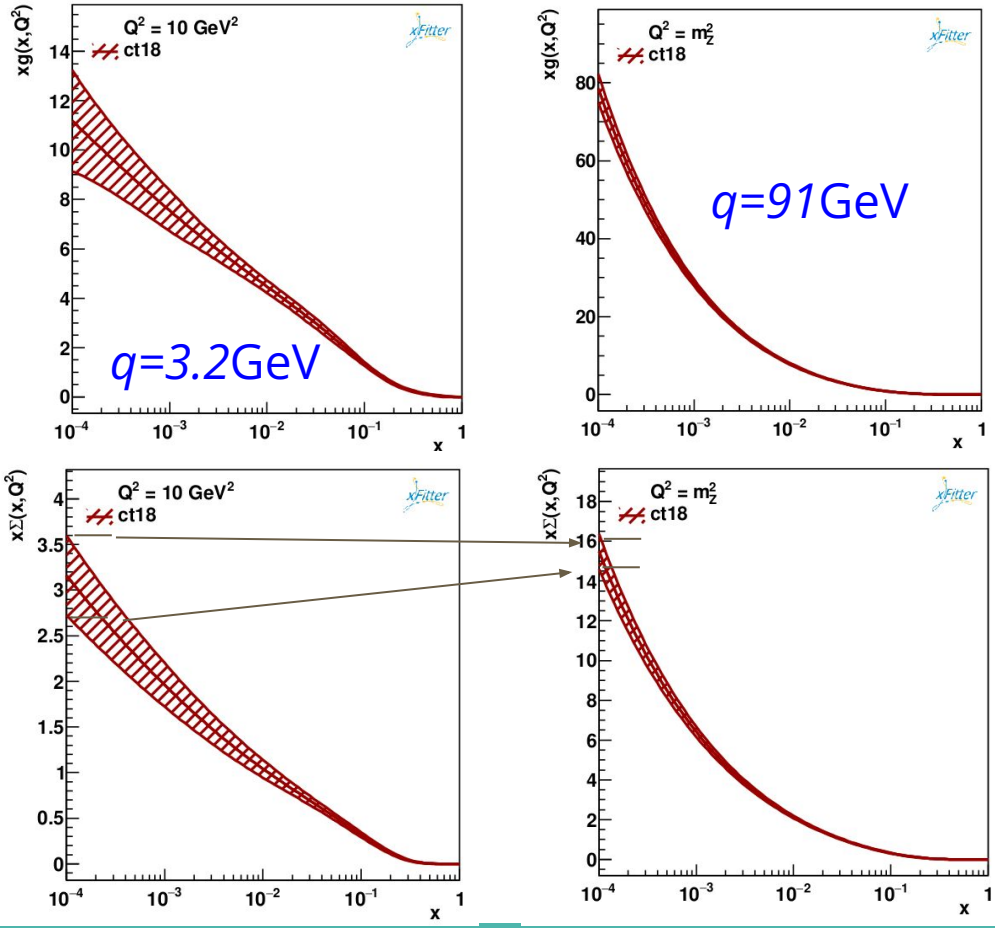
$$\int u_v(x)\,dx = 2,\ \int d_v(x)\,dx = 1,$$

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





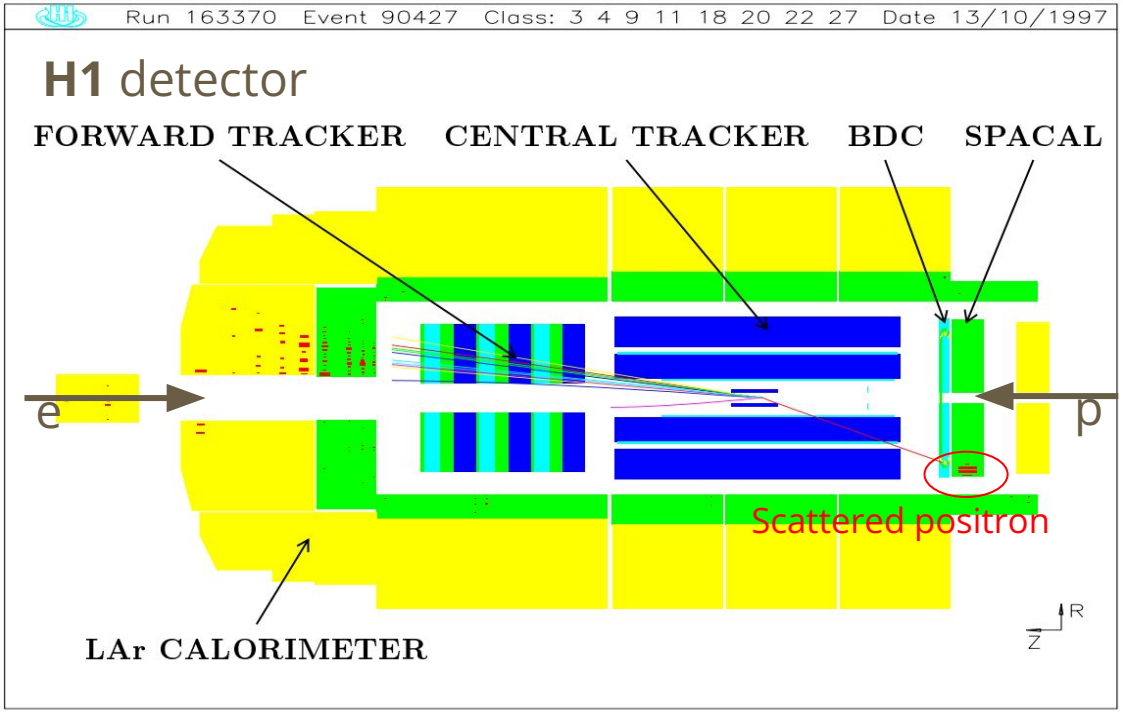
The gluon and sea quarks evolve very rapidly, especially at low *x*.

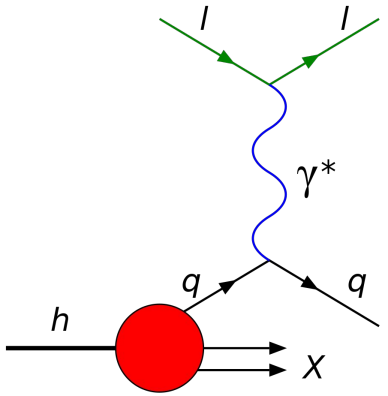
Linear DGLAP evolution preserves approximately absolute uncertainties on PDFs; relative uncertainties shrink / increase where PDFs become larger / smaller with evolution.

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

Determination of PDFs

Deep inelastic ep scattering and PDFs





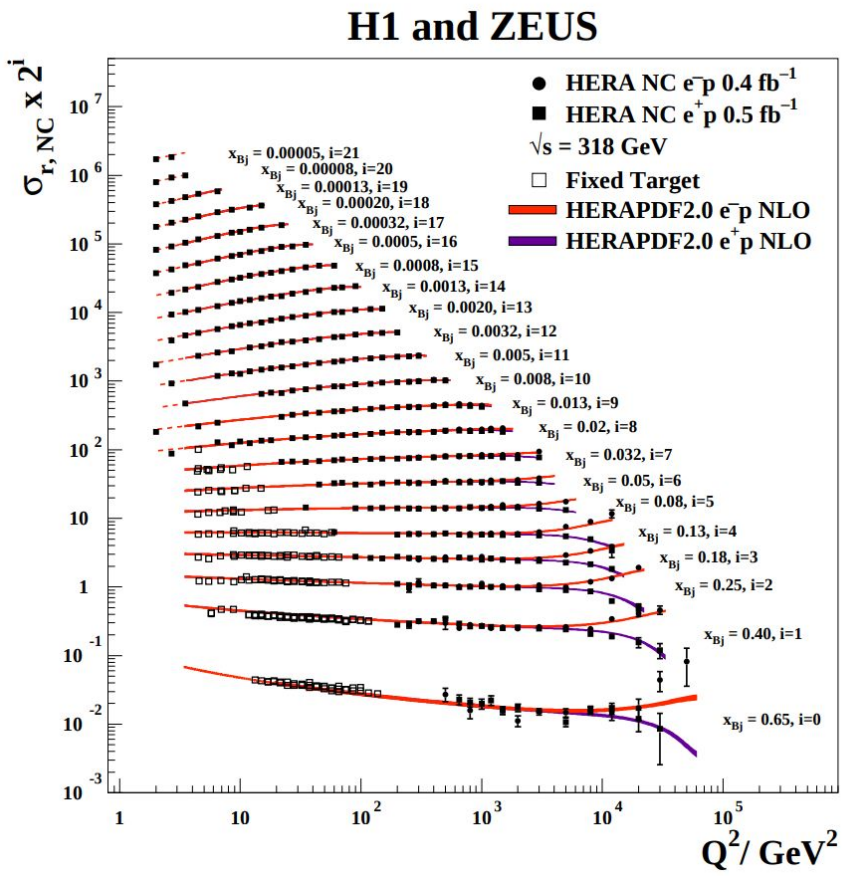
Probing proton structure with elementary leptons

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

accurate results for $0.01 < y < 0.8$

$$y_e = 1 - \frac{E'_e(1-\cos\theta_e)}{2E_e}, \quad Q^2_e = \frac{P^2_{T,e}}{1-y_e}, \quad x = \frac{Q^2}{Sy}$$

Determination of the PDFs using electron-proton data



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

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

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

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

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*

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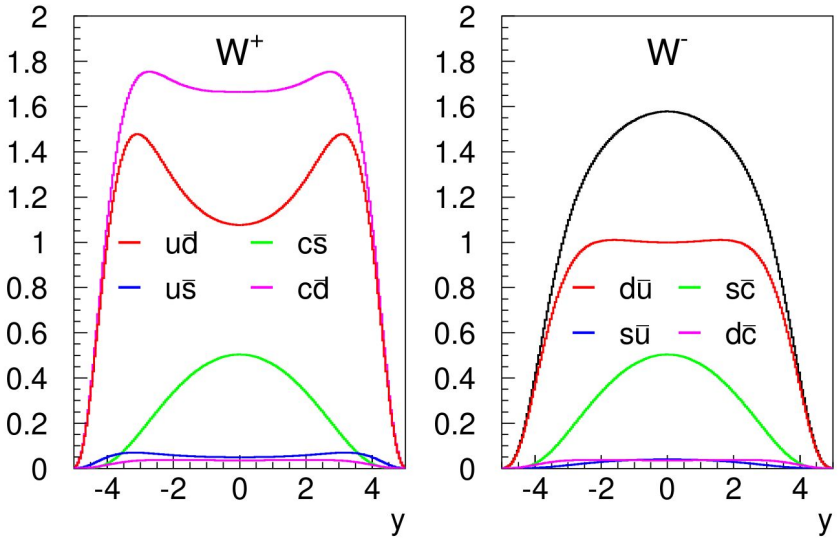
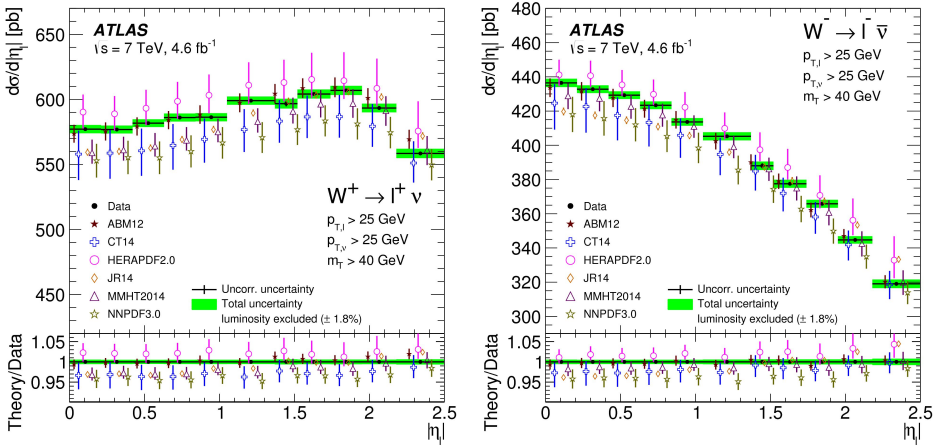
Example of PDF input from LHC: *W* boson production





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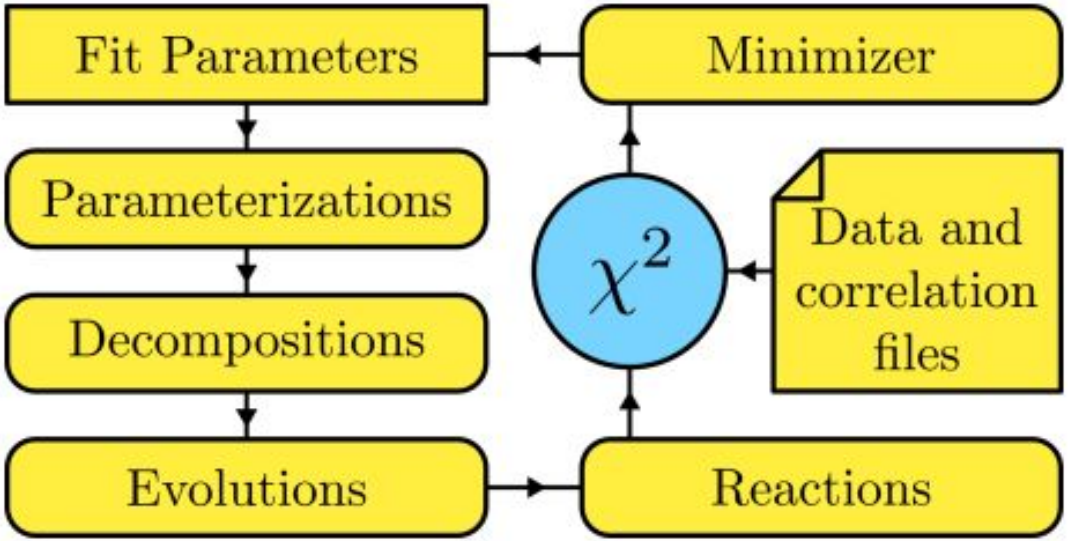
$W^{\pm}$ boson production is sensitive to CKM matrix element weighted **bilinear form** of *u,d,s,c* PDFs.

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.

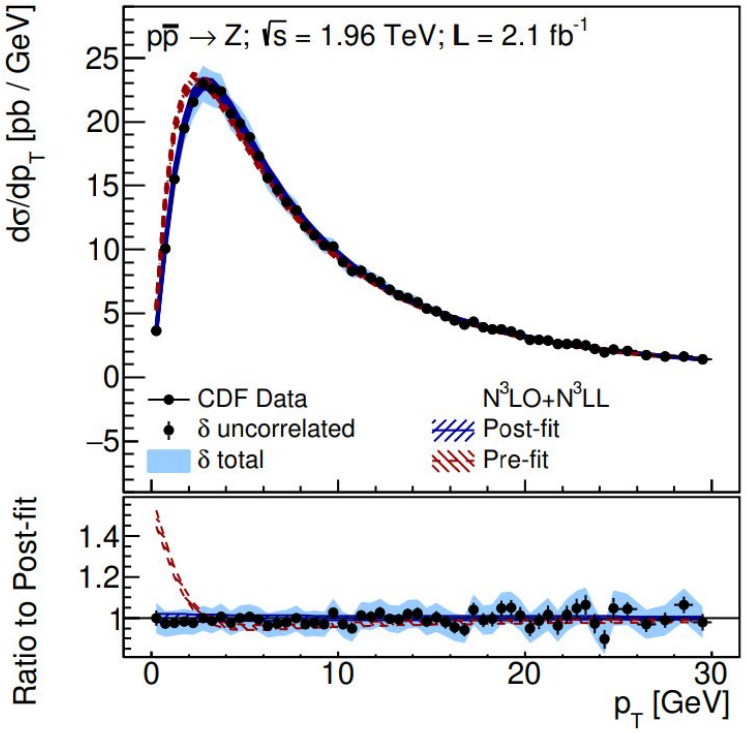
xFitter motivation

- 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 colinear 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



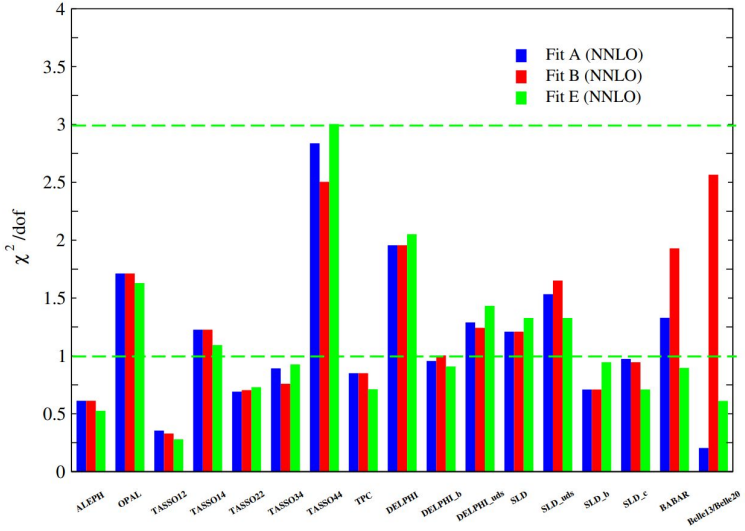
- Determination of α_S using CDF full phase-space P_t data and N^3LO + N^3LL prediction from DYTURBO https://arxiv.org/abs/2203.05394
- Data, predictions are included in xFitter
- **./tools/test.sh ZPT**

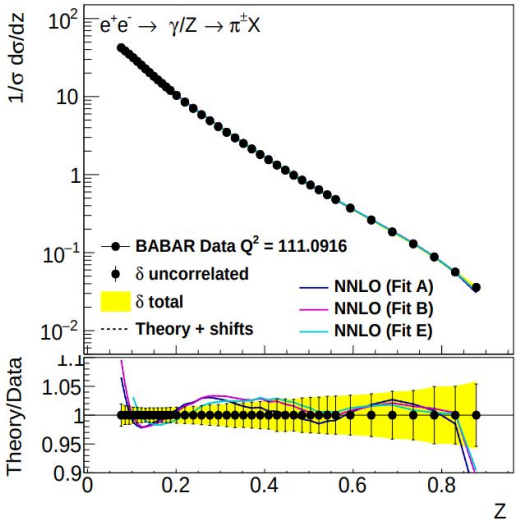
$$\alpha_S(m_Z) = 0.1185^{+0.0014}_{-0.0015}$$

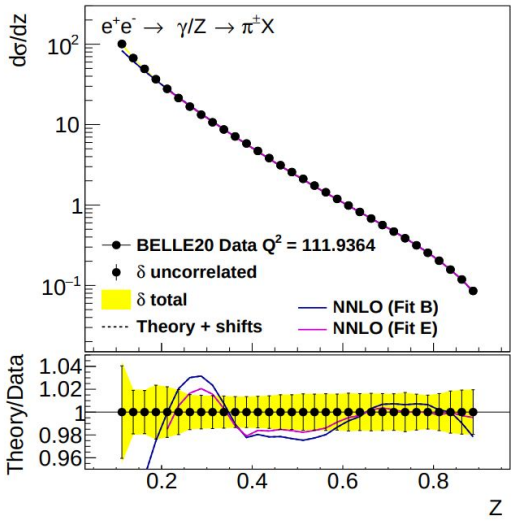
Reproduces one iteration of the fit to HERA + CDC data.

https://arxiv.org/pdf/2105.11306.pdf

Example analysis: pion fragmentation







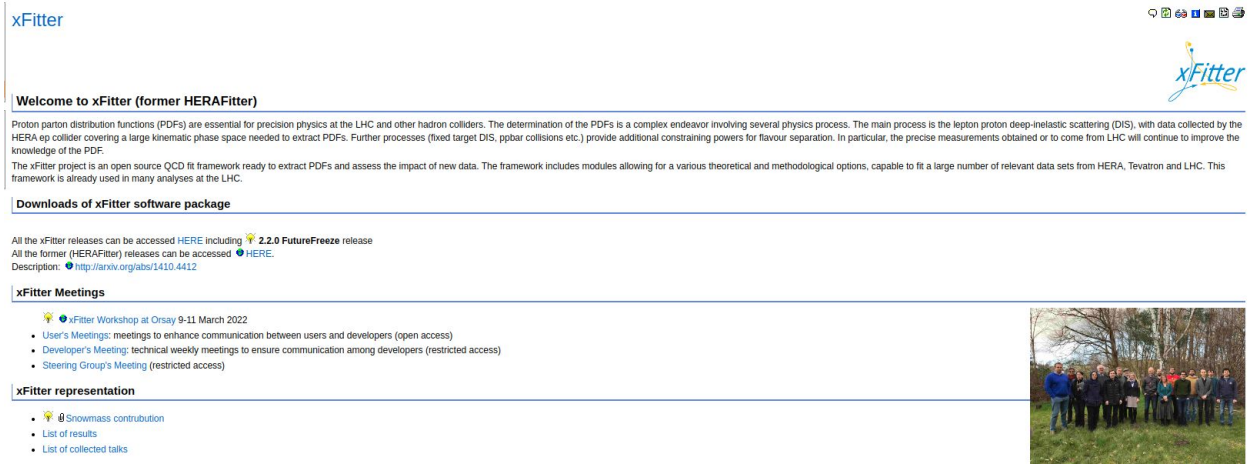
- NNLO fit using APFEL to single-inclusive annihilation (SIA) data from e^+e^- colliders to determine pion fragmentation function. Tensions between Belle and Babar data at low z.
- Reproduce on iteration in xFitter by running **./tools/test.sh Pion_FF**

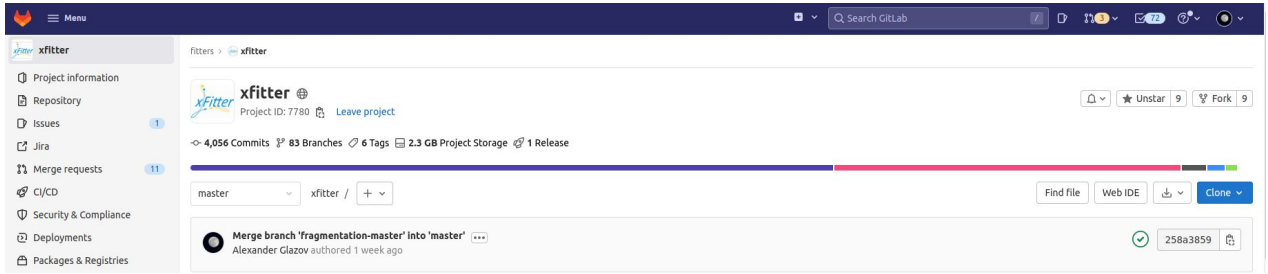
xFitter capabilities

The strength of xFitter in 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





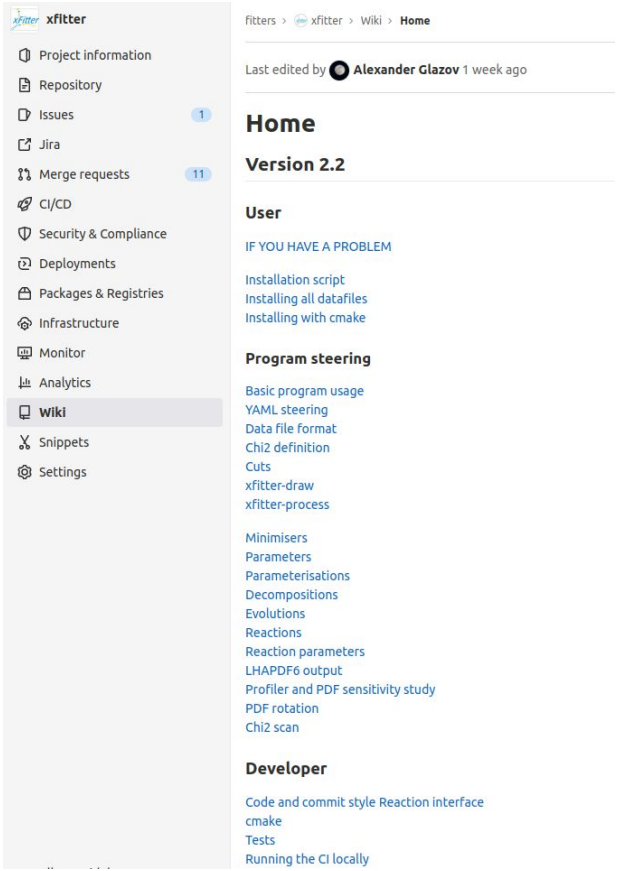
- xFitter frontpage contains all relevant links
- Going directly to the gitlab repository is another possibility

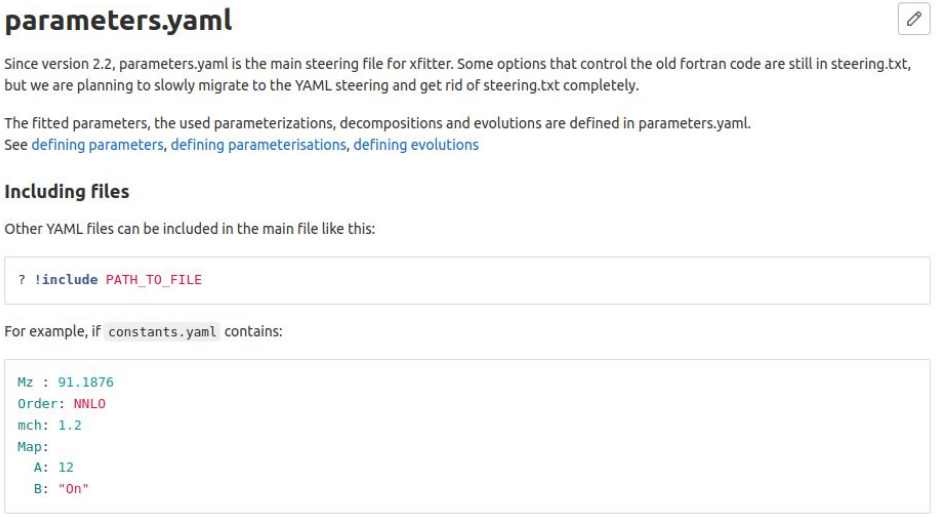
xFitter releases

Date	Version	Files	Remarks
 03/2022	2.2.0 FutureFreeze	xfitter-2.2.0.tgz	Major update of evolution and reaction interfaces
 05/2019	**2.0.1 OldFashioned**	xfitter-2.0.1.tgz	update/bug fix to 2.0.0 FrozenFrog
 03/2017	**2.0.0 FrozenFrog**	xfitter-2.0.0.tgz	stable release with decoupled data and theory files
 02/2020	**2.0.1N Nuclear Daiquiri**	xfitter-2.0.1N.tgz	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





- 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
```

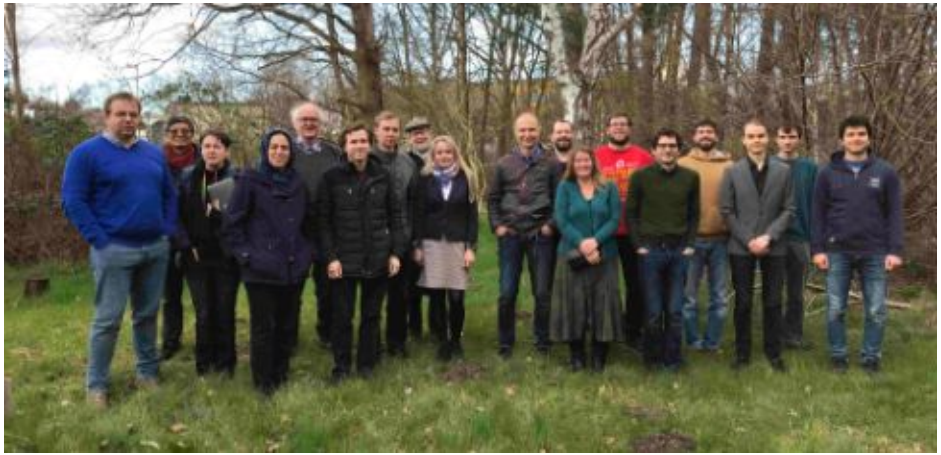
- It is recommended to use the latest release 2.2.0 or the **master** branch
- The master branch is tested nightly; all dependencies should be satisfied at any time for a number of tested platforms (EL7 ,Ubuntu 20.04)
- Exotic platforms such as apple M. raspi (>= 4GB), RISC-V work too.

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



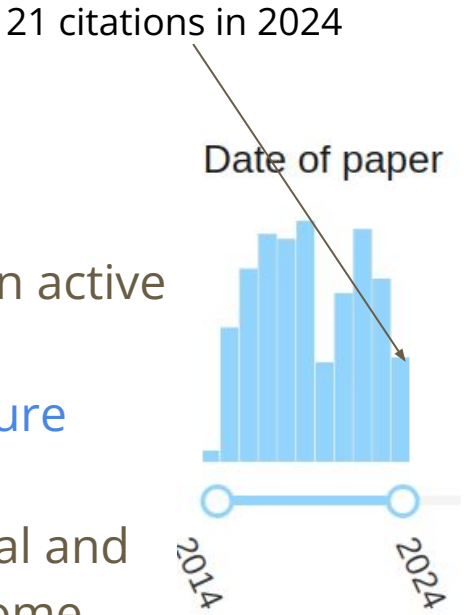
- xFitter is not a collaboration, but self governed developers' team
- Developers from different areas, experiment and phenomenology
- Developments by O(10) persons, during their free time
- Open publication policy, papers can be published within or outside the team
- Biweekly meetings to share the news

Contributing to xFitter development

- xFitter code is open for new contributions
- For developers with CERN account, use gitlab.cern.ch, otherwise use 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



Docker image-based tutorial

https://docs.google.com/document/d/1Lbitf1XLxFzjanbNFqXhIGh2GlR0R_fQEehkMY1XYY8/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

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

- Install dyturbo (from the top directory):
  - ./tools/install-dyturbo
  - ./make.sh reconfigure
  - ./make.sh install

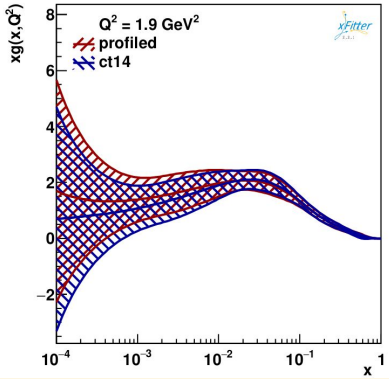
```
-- Found Hathor 2.0: /home/xfitter/deps/Hathor-2.0
-- Found DYTurbo 1.3.3: /home/xfitter/deps/dyturbo-1.3.3
-- Found yaml 0.2.5: /usr/lib64/libyaml.so
```

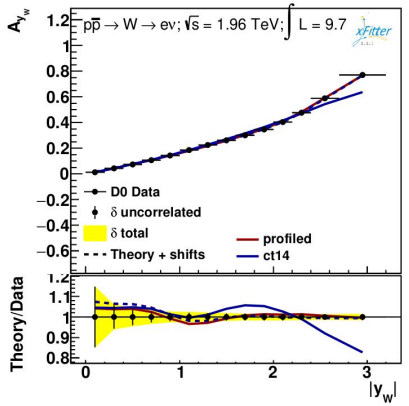
Running exercise #2 faster

- 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)