Future (possible) studies with the xFitter fitting framework

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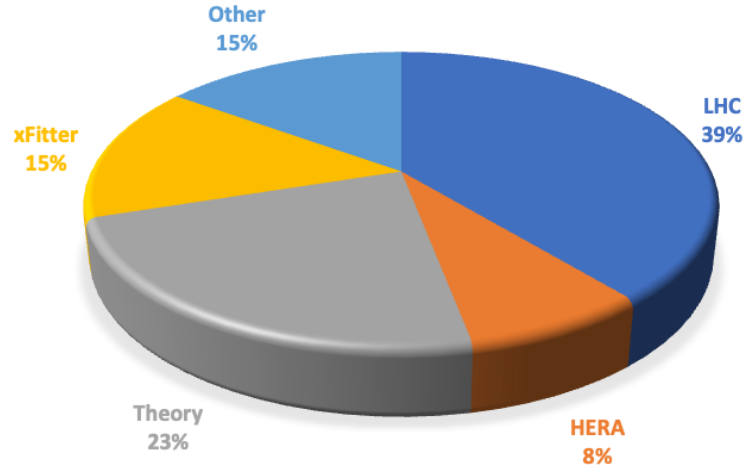
30th International Workshop on Deep Inelastic Scattering and Related Topics (MSU, USA)

28/03/2023

The xFitter Project

- The xFitter project (former HERAFitter) is a **unique open-source QCD fit framework**
- GitLab repository (open access)
- This code allows users to:
  - **extract PDFs** from a large variety of data
  - assess the **impact** of **new data on PDFs**
  - check the **consistency** of experimental data
  - test different **theoretical assumptions**



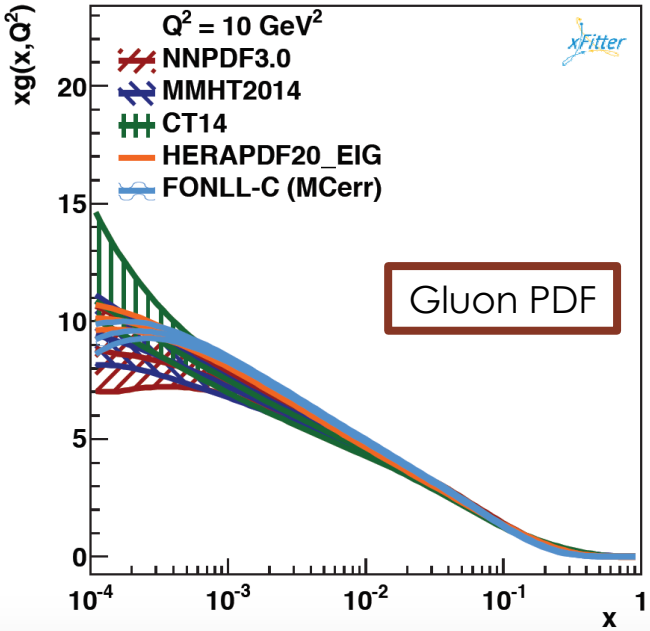
- Several active developers between experimentalists and theorists
- More than 100 publications obtained using xFitter since the beginning of the project
- List of recent analyses by the xFitter Developers' Team:

MORE IN PREPARATION!

Phys.Rev.D 104 (2021) 5, 056019, arXiv:2105.11306	QCD analysis of pion fragmentation functions in the xFitter framework
Phys.Rev.D 102 (2020) 1, 014040, arXiv:2002.02902	Parton Distribution Functions of the Charged Pion Within The xFitter Framework

xFitter in a nutshell

- **Parametrise** PDFs at the initial scale:
  - several functional forms available
  - define PDF parameters to be minimised
- **Evolve** PDFs to the scales of the fitted data points:
  - DGLAP evolution up to NNLO in QCD and NLO QED (QCDNUM, APFEL, MELA)
  - non-DGLAP evolutions (dipole, CCFM)
- **Compute** predictions for the data points:
  - several mass schemes available in DIS (ZM-VFNS, ACOT, FONLL, TR, FFNS)
  - predictions for hadron-collider data through fast interfaces (APPLgrid, FastNLO)
- **Comparison data-predictions** via χ^2:
  - multiple definitions available
  - consistent treatment of the systematic uncertainties
- **Minimise** the χ^2 w.r.t. the fitted parameters
  - using MINUIT or by Bayesian reweighting
- **Useful drawing tools** – nice and colorful plots
- Last xFitter workshop in Orsay (9-11 March 2022)



xFitter release 2.2.0

xFitter

Sample data files:
LHC: ATLAS, CMS, LHCb
Tevatron: CDF, D0
HERA: H1, ZEUS, Combined
Fixed Target: …
User Supplied: …

GitLab

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Releases of the xFitter QCD analysis package

- The release notes can be found in this attachment: xFitter_release_notes.pdf .
- Installation script for xFitter together with QCDNUM, APFEL, APPLGRID, LHAPDF install-xFitter-2.0.1
  - New installation script from master branch install-xfitter-master
- Data and theory files can be downloaded from gitlab gitlab data repository

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

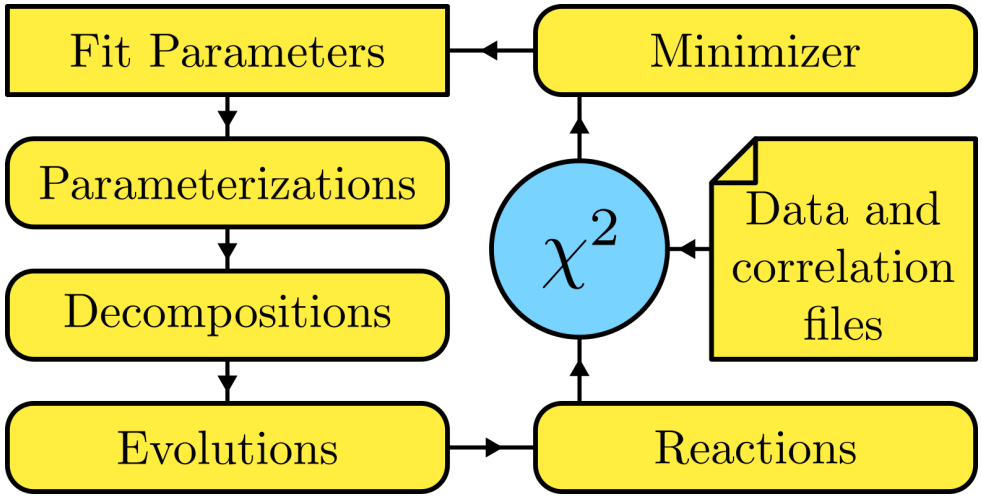
2.2.0
Future Freeze

https://www.xfitter.org/xFitter/xFitter/DownloadPage

- Release 2.2.0 released! (major update of evolution and reaction interfaces)
- Script to install xFitter and all its dependencies: **install-xFitter**

Talking about the new release…

- **Significant changes** in the internal structure
- **Re-written interfaces** to minimizers, PDF parameterisation, decomposition, evolution and theory reactions
- **Large changes in the user interface**
- Data handling, format and chi2 calculation remain largely the same (but there are changes)
- Nicely summarized in this talk by S. Glazov
- Picture taken from Ivan Novikov's talk



Pion Fragmentation Functions

PRD 104 (2021) 5 056019

- To perform the extraction of **pion fragmentation functions** (FFs) from single inclusive electron-positron annihilation (SIA) + BELLE13/20 data

- SIA $e^+e^- \xrightarrow{\gamma^*,Z} \pi^\pm X$ data allow to separate Δq and $\Delta\bar{q}$

- **Parametrization form**: $$D_i^{\pi^\pm}(z,Q_0) = \frac{\mathcal{N}_i z^{\alpha_i}(1-z)^{\beta_i}[1+\gamma_i(1-z)^{\delta_i}]}{B[2+\alpha_i,\beta_i+1]+\gamma_i B[2+\alpha_i,\beta_i+\delta_i+1]}$$

- We assume isospin symmetry $D_u^{\pi^+} = D_{\bar{d}}^{\pi^-}$ and $D_{\bar{u}}^{\pi^+} = D_d^{\pi^-}$

- We assume the charge conjugate $D_i^{\pi^+} = D_i^{\pi^-}$ for all the flavour component

- We fit the flavour combinations $i = u^+, d^+, s^+, c^+, b^+$ and g

- We parametrise FFs at a starting scale of Q_0^2 = 5 GeV^2

- **19 free parameters in total**

- Fitted distributions: $\frac{d\sigma^h}{dz}$, $\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dp_h}$, $\frac{s}{\beta}\frac{d\sigma^h}{dz}$, $\frac{1}{\beta\sigma_{\rm tot}}\frac{d\sigma^h}{dz}$, ... ($z = 2E_h/\sqrt{s}$)

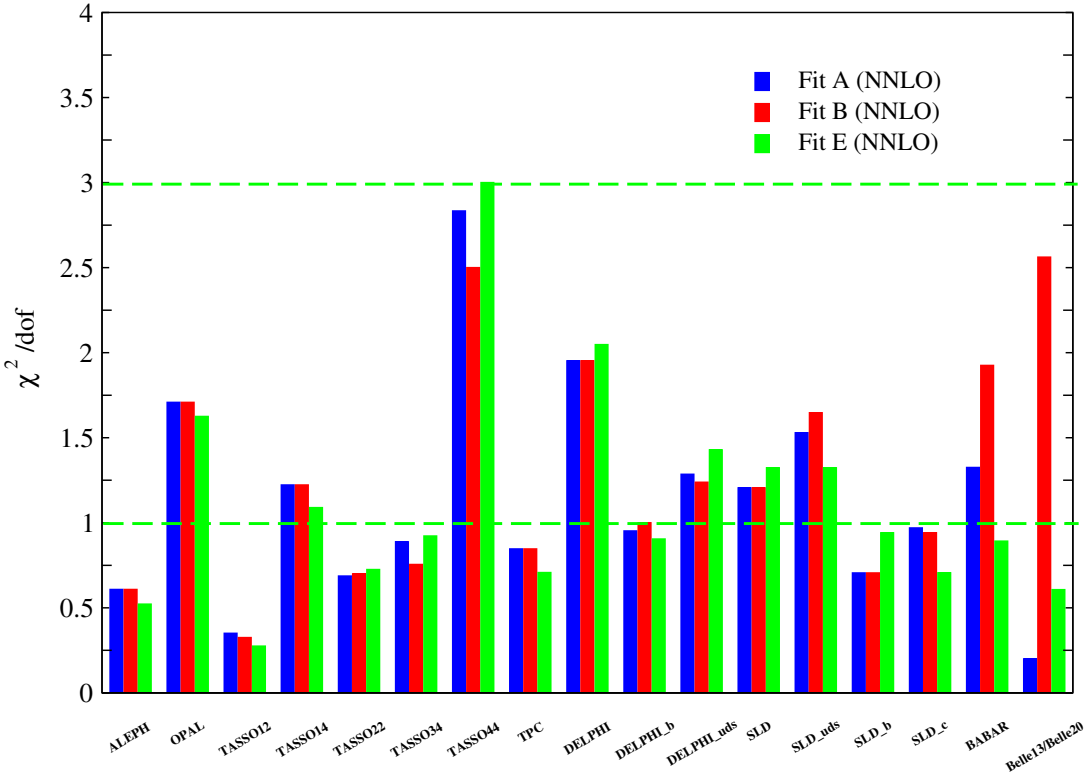
Pion Fragmentation Functions

- Several fits ran:
  - **Fit A** focuses on the impact of BELLE13 data (no BELLE20 data)
  - **Fit B** focuses on the impact of BELLE20 data (no BELLE13 data)
  - **Fit C** focuses on the impact of BELLE20 data without BaBar set (no BELLE13 data)
  - **Fit D** focuses on the impact of low-z BELLE20 data (No BELLE13 and BaBar data) – z > 0.2
  - **Fit E** focuses on the impact of low-z BELLE20 and BaBar data (no BELLE 13 data) – z > 0.2 (BELLE20) and z > 0.1 (BaBar)

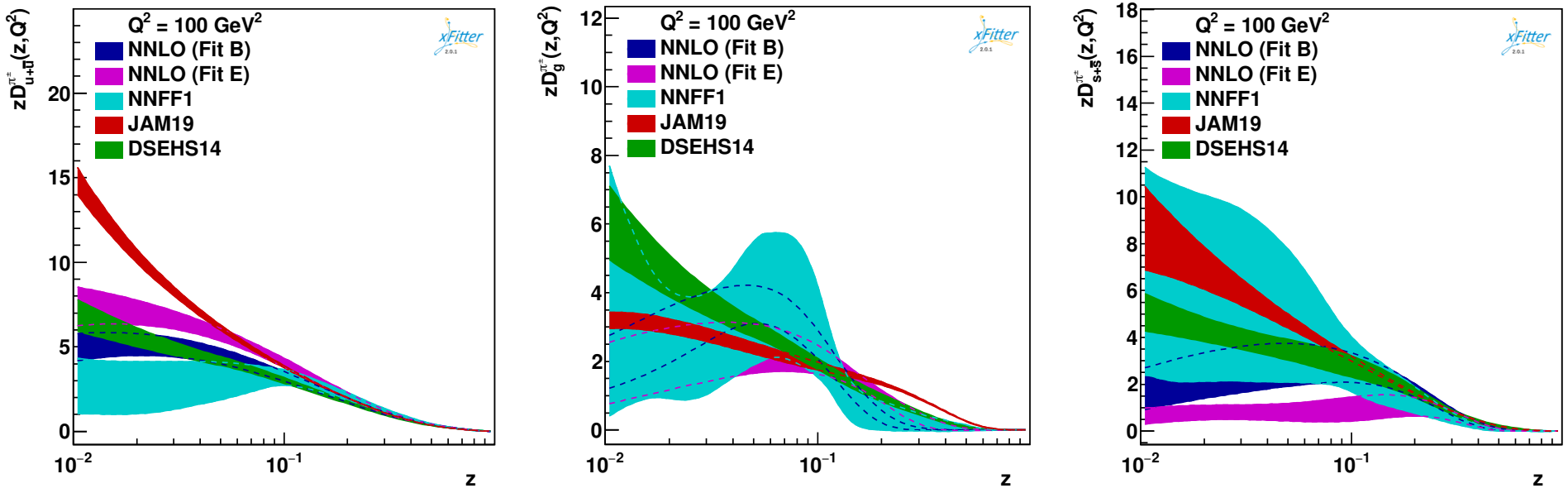
- The inclusion of higher-order QCD corrections noticeably improves the quality of our fits

- Fits performed with enhanced tolerance T = $\sqrt{\Delta\chi^2}$= 20

- FFS NLO and NNLO uncertainty bands overlap → perturbative uncertainties are under control (and reasonable choice of T)



Pion Fragmentation Functions



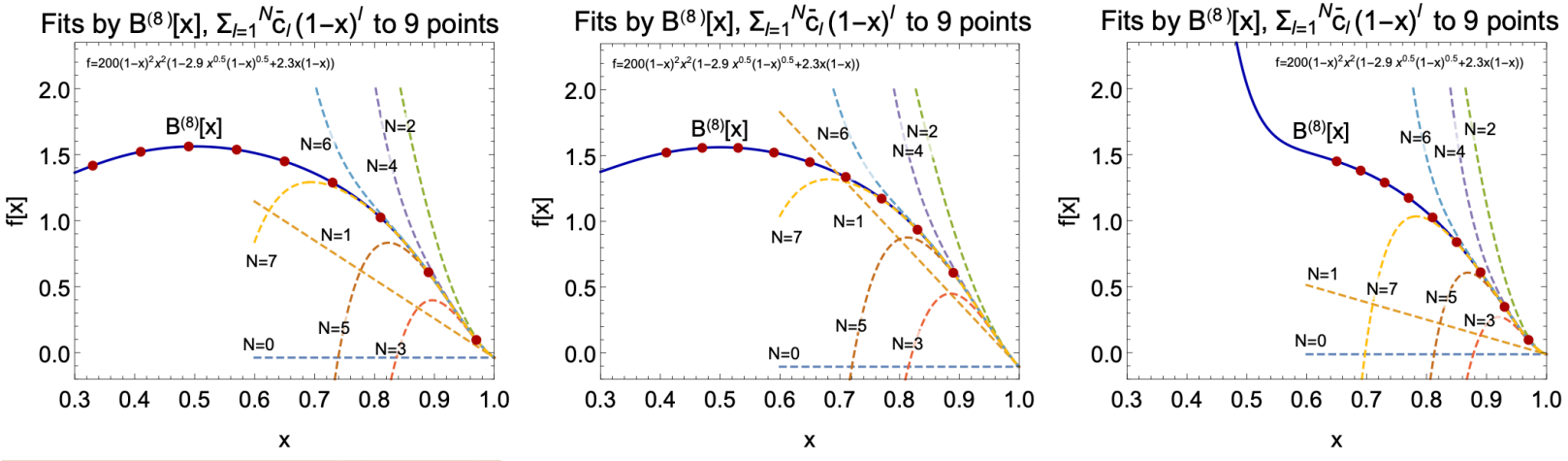
- Comparison with NNLO NNFF1 and NLO JAM19 and DSEHS14
- **Generally compatible with NNFF1 and DSEHS14 at larger z**, but they differ at low-z (more pronounced for Fit E)
- The **gluon** is generally **compatible with NNFF1** (larger uncertainties)
- FFs generally have a different behaviour as compared to JAM19 – they have much steeper slope at low-z for quarks, with the gluon lying above our curves for intermediate- to larger-z

More on mesons PDF

- Charged pion PDF studied in PRD 102 (2020) 014040

$$xv(x) = A_v x^{B_v}(1-x)^{C_v}(1+D_v x^{\frac{5}{2}}),$$ **$C_V \sim 1$** (but some theories predict $C_V \sim 2$)

- It is not possible to uniquely determine the exact (1 − x)-exponent given the present data – A. Courtoy, P. Nadolsky



Main idea: **New parameterization methods for mesons PDF fits**

The new modular xFitter 2.2 version was a HUGE help for this project

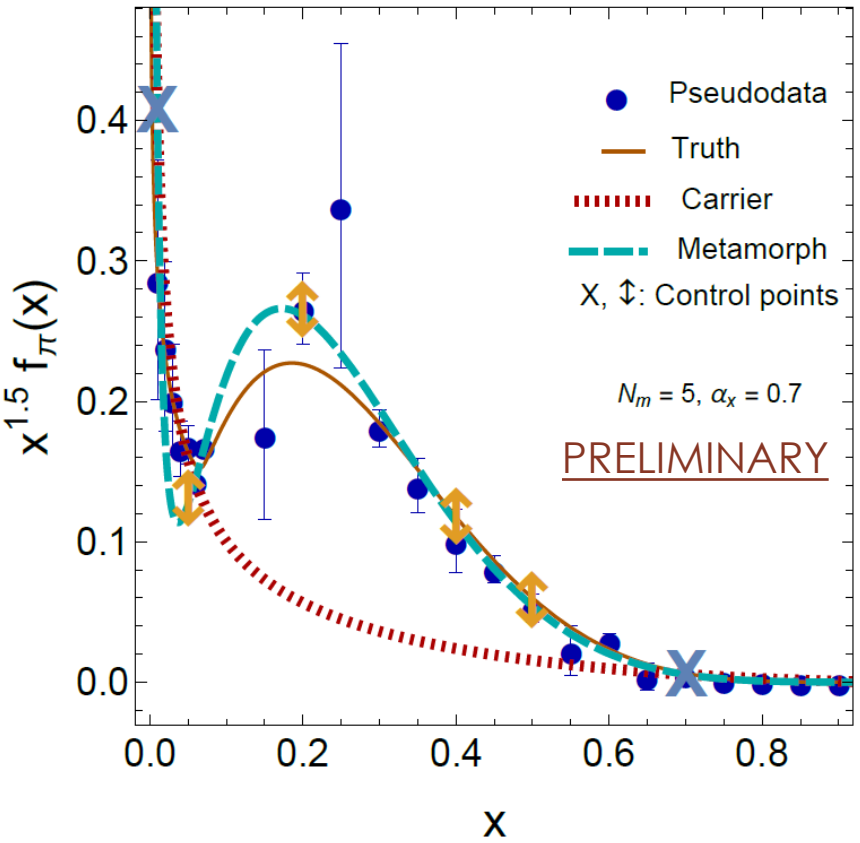
Fantômas4QCD: advanced polynomial parametrisations

L. Kotz, M. Chavez, A. Courtoy, P. Nadolsky, F. Olness, V. Purohit, 2023

Parametrize PDFs using **Bézier curves** $B^{(n)}(x;a) = \sum_{k=0}^{n} a_{k+2} \binom{n}{k} x^k (1-x)^{n-k}$

A metamorph $f(x) \equiv a_0 \underbrace{x^{a_1}(1-x)^{a_2}}_{\text{carrier}} B^{(n)}(x^{\alpha_x};a)$

- Metamorphs can mimic a variety of behaviors of PDFs and their uncertainties. A versatile alternative to neural networks!
- The shape of a metamorph is computed from function values at user-specified **control points**
- The carrier component controls asymptotic limits at $x \to 0$ and $x \to 1$
- L. Kotz's talk for more details (WG1)

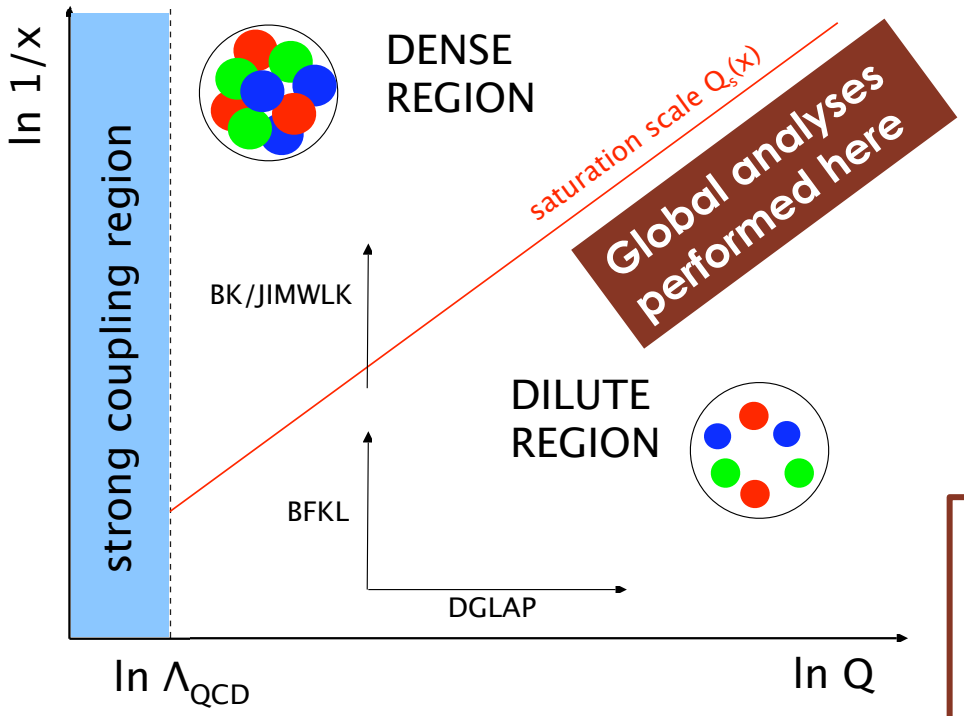


xFitter usage in the HEP comunity

- xFitter is the **tool of choice for PDF/QCD analyses by the LHC Collaborations**
- **ATLAS**:
  - PDF fit from diverse ATLAS data at $\sqrt{s}$ = 7, 8 and 13 TeV - EPJC 82 (2022) 5 438
- **Drell-Yan phenomenology:**
  - PDF impact of A_{FB} in NC Drell-Yan events - JHEP 10 (2019) 176
  - PDF sensitivity of the longitudinal Z-boson polarisation - Phys.Lett.B 821 (2021) 136613
  - PDF sensitivity to A_{FB} and A_W in Drell-Yan for Precision EW Measurements and New Physics Searches - Nucl.Phys.B 968 (2021) 115444
  - Enhancing the LHC sensitivity to broad W'/Z' resonances of new gauge sectors - JHEP 02 (2022) 179, 2211.06188
- Important contribution in **several ongoing activities of the LHC EW WG**:
  - **Correlations between different PDFs** trough pseudo-data fits
  - ATLAS/CMS/LHCb $\sin^2\theta^l_{eff}$ **pseudo data** and combination exercise
  - Tevatron/ATLAS (and in future LHCb and CMS) m_W **combination**
- α_S **extraction** from Z boson transverse momentum distribution - 2203.05394, ATLAS-CONF-2023-015

xFitter and EIC

- **Exploring QCD in extreme limits**
- SURGE collaboration

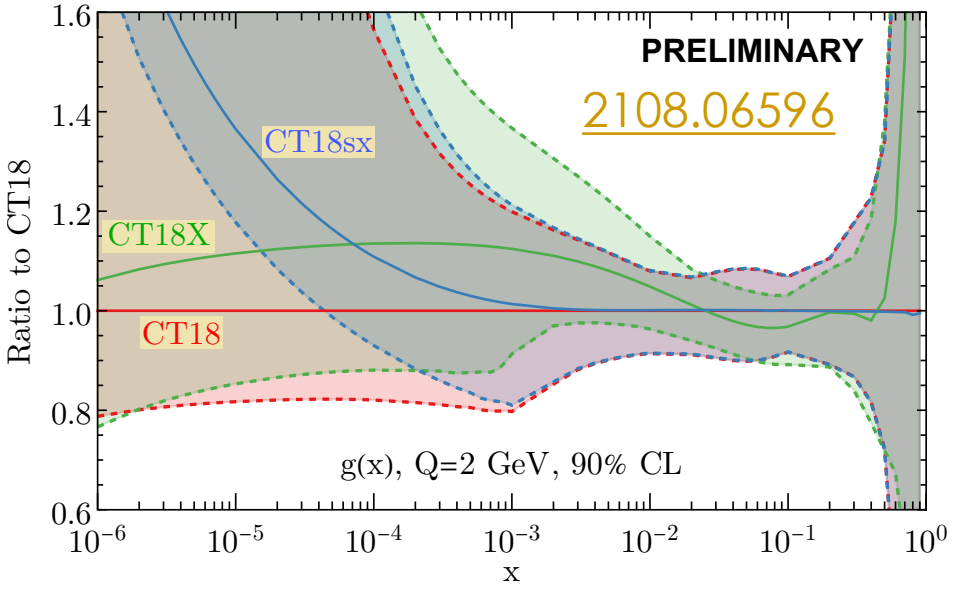


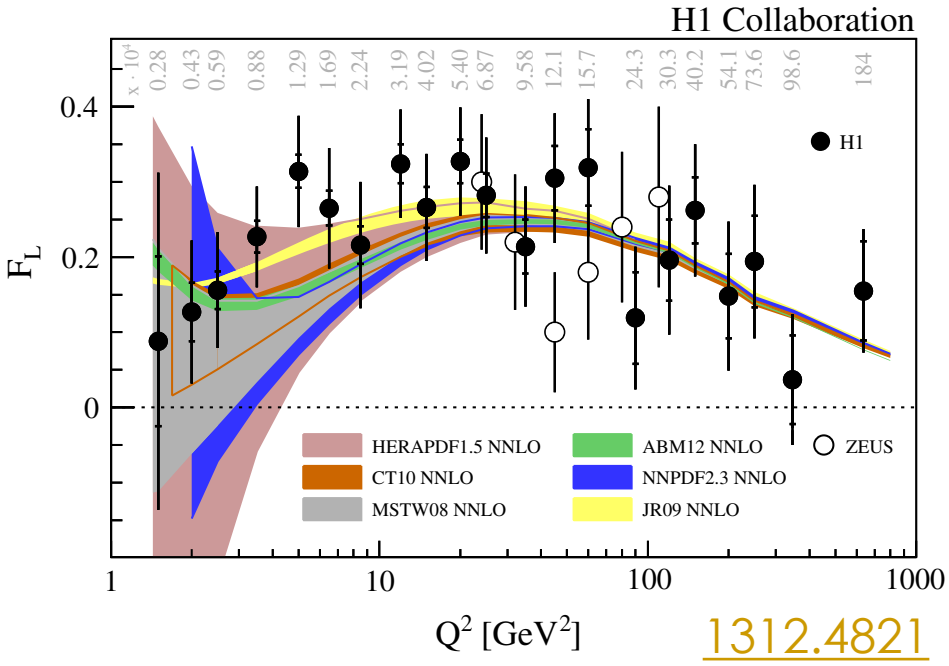
- Current PDF analyses use "standard" DGLAP
- Extend analyses into extreme limits of QCD
- Include additional effects into PDF fits
- This can all be done with xFitter! Thanks to its modular framework

To unequivocally:

- establish **saturation**
- perform **comprehensive global analysis** minimizing uncertainties
- extracting universal building blocks of **high energy factorization**

xFitter and EIC





Gluon PDF:

- Differences: DGLAP, BFKL, saturation
- Diferent {x, Q^2, A} dependence
- Large uncertainties: EIC can improve

Longitudinal Structure Function F_L:

- Current theory is challenged
- Gluon strongly influences F_L
- Older xFitter-based analyses: small-x resummation, dipole and tensor pomeron models
- Large uncertainties: EIC can improve

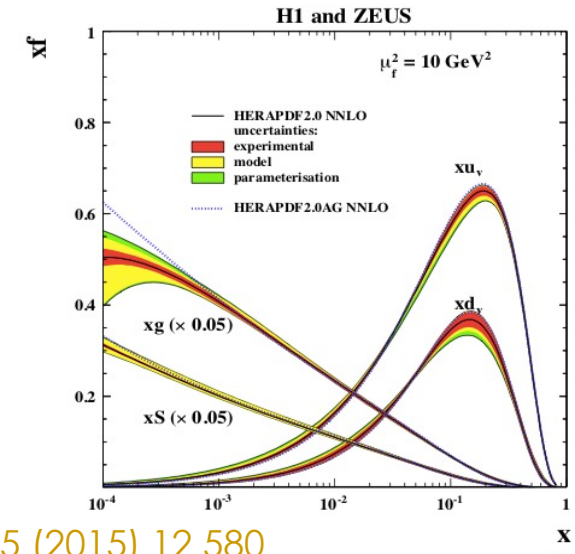
Conclusion & outlook

- The xFitter project (former HERAFitter) is a **unique open-source QCD fit framework**
- With its flexibility and modular structure, easy to use – **Future Freeze 2.2.0** out!
- **Improved user interface** for more flexible PDF parametrisation and adding new processes, QCD + EW fits, (SM)EFT interpretation, etc.
- Interfaced with APFEL/APFEL++ → TMD phenomenology and FO predictions matched to small-q_T resummed calculations (SIDIS)
- NNLO grids can be used in xFitter → consistent set of predictions - APPLfast
- **Foreseen future physics** (low-x phenomenology, nuclear PDF, FFs, etc.)
- Fits of PDFs with resummation scale variations - 2202.03380
- Heavy flavour and quarkonia production (HEFTY Collaboration)
- Nice summary of xFitter capabilities submitted to Snowmass

Backup Slides

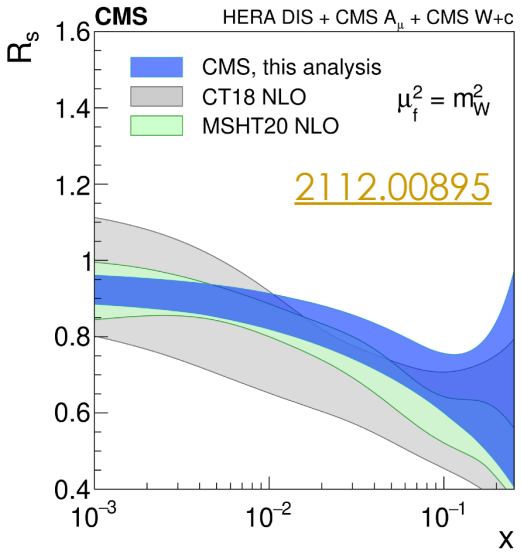
Results obtained with xFitter

DIS inclusive processes (ep)

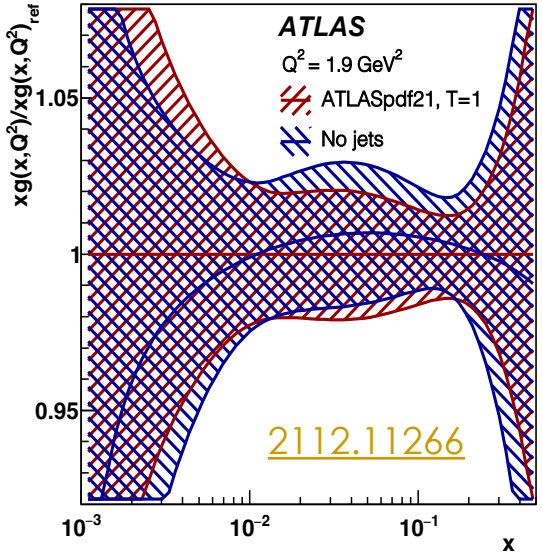


EPJC 75 (2015) 12 580

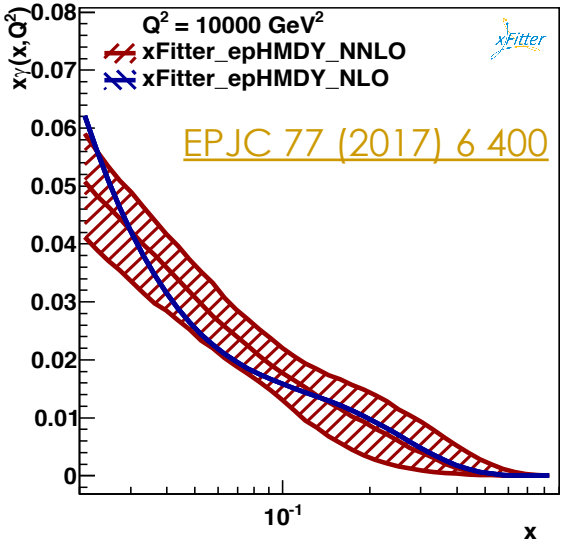
Drell-Yan processes ($pp, p\bar{p}$)



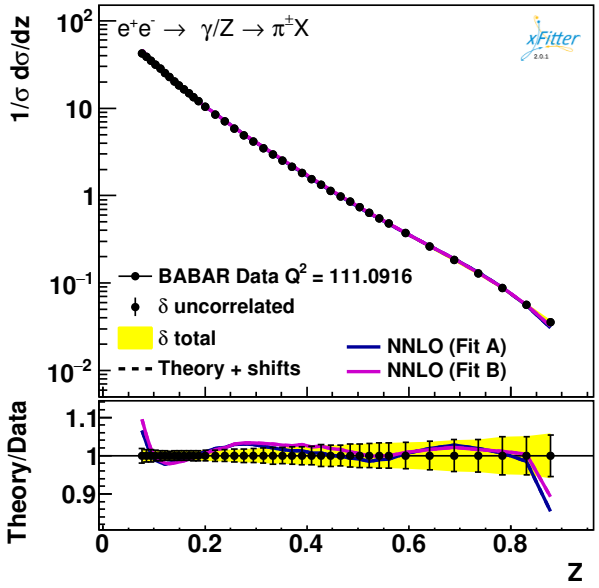
Jet production ($ep, pp, p\bar{p}$)

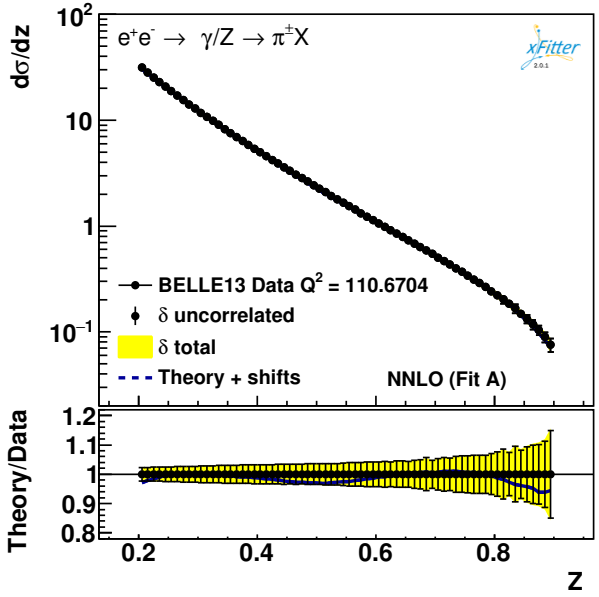


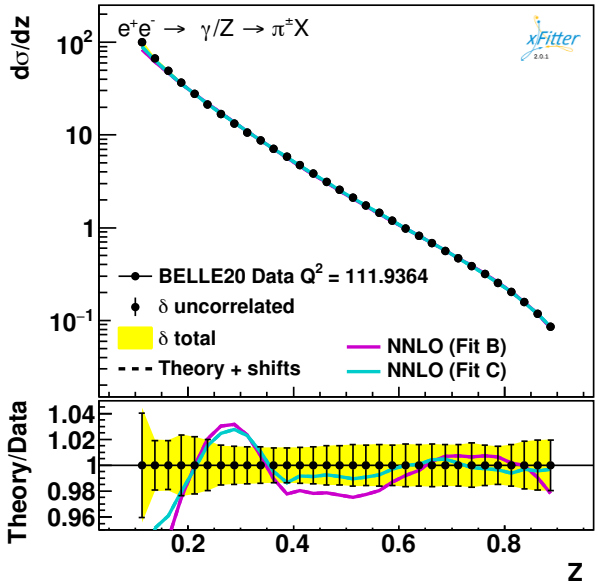
DY data sensitivity to photon PDF



Pion Fragmentation Functions



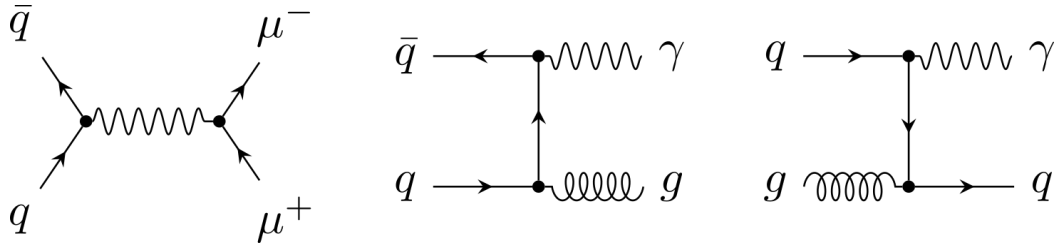




- Theoretical predictions entirely consistent with the experimental data – partly due to larger uncertainties (BELLE13)
- Fits yield a **good description of the data** **with the exception of the low-z region** (BELLE20 and BaBar)
- **BELLE and BaBar** data sets appear to pull the fit in **opposite directions** - χ^2(Fit B) for BELLE20 is 82/32 vs χ^2(Fit C) for BELLE20 is 32/32
- The effect of excluding low-z data is dramatic - χ^2/dof ~ 1.2 (similar cuts applied in JAM19)

Charged Pion PDF

- Pion structure is poorly studied experimentally PRD 102 (2020) 014040
- Currently available pion PDF sets in LHAPDF6 are provided without error bands
- Data from **E615**, **NA10** and **WA70** experiments (di-muon and direct photon production)



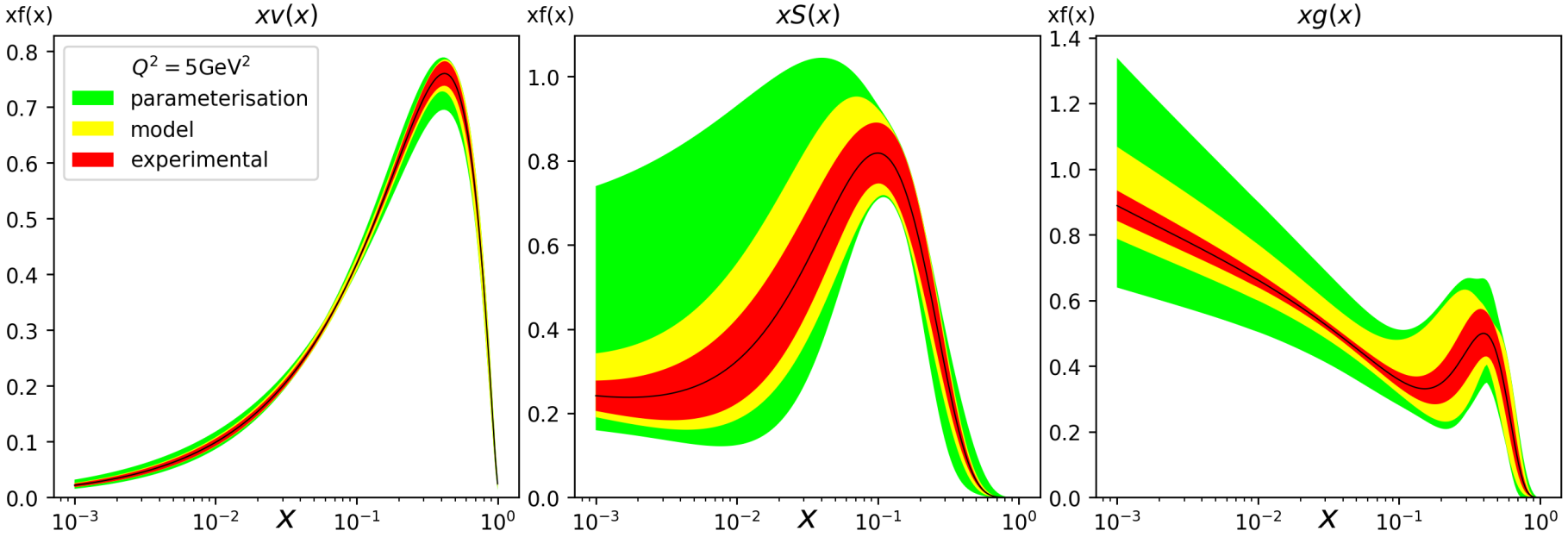
- Charge symmetry $d = \bar{u}$ and SU(3)-symmetric sea $u = \bar{d} = s = \bar{s}$ at the initial scale $Q_0^2 = 1.9$ GeV^2

$$v := (d - \bar{d}) - (u - \bar{u}), \qquad xv(x) = A_v x^{B_v}(1-x)^{C_v}(1 + D_v x^{\frac{5}{2}}),$$
$$S := 2u + 2\bar{d} + s + \bar{s} = 6u, \qquad xs(x) = A_S x^{B_S}(1-x)^{C_S},$$
$$g := g, \qquad xg(x) = A_g x^{B_g}(1-x)^{C_g}.$$

- The A_v and A_g parameters are determined by the sum rules:

$$\int_0^1 v(x)\mathrm{d}x = 2, \qquad \int_0^1 x(v(x) + S(x) + g(x))\mathrm{d}x = 1$$

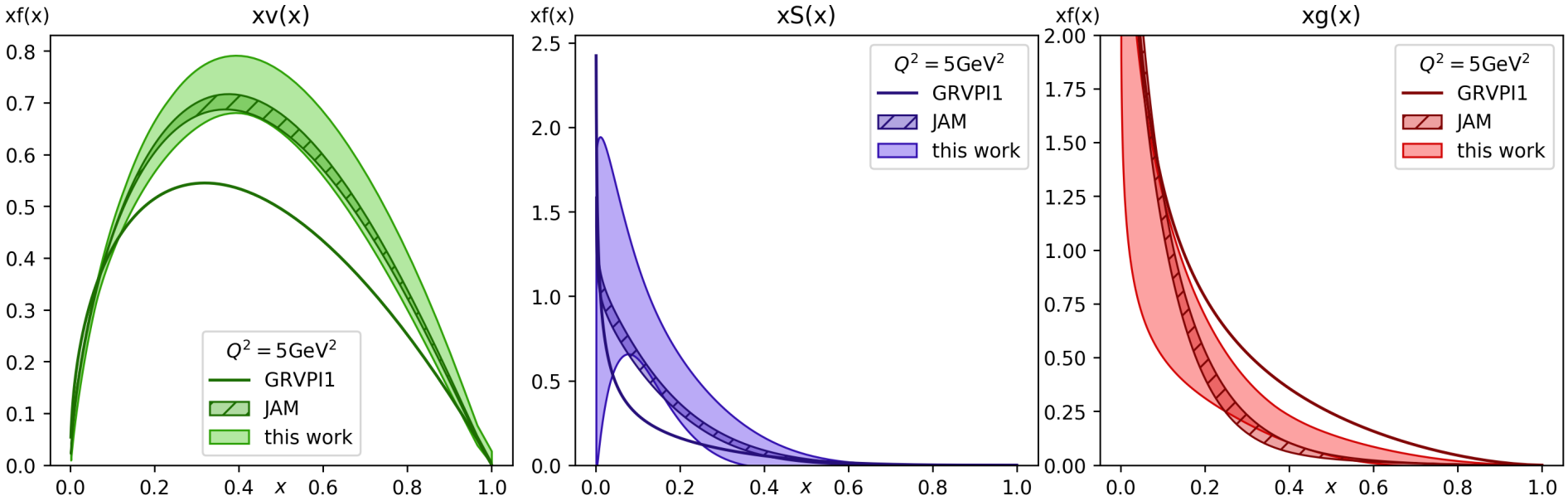
Charged Pion PDF



- PDFs with full uncertainties (e.g. α_S, Q_0^2, μ_R variations)
- Parametrisation uncertainties considered as well (e.g. fixing C_g or C_s)
- μ_R variation has the strongest impact
- Valence distribution is well-constrained
- Hard to determine sea and gluon distributions

Experiment	χ^2/N_{points}
E615	194/140
NA10 (194 GeV)	98/67
NA10 (286 GeV)	92/73
WA70	74/99

Charged Pion PDF



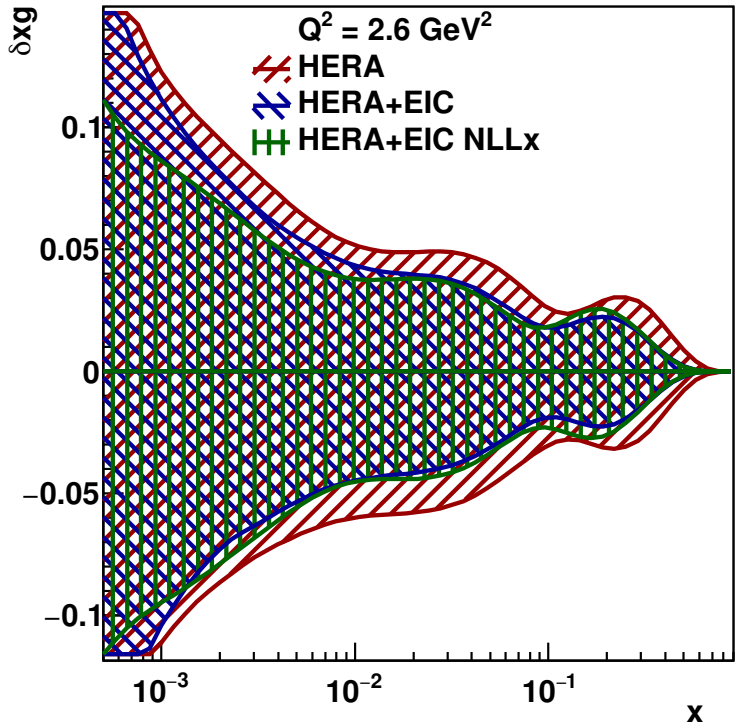
- Comparison with recent pion PDF determinations:
  - JAM collaboration
  - GRVPI1 pion PDF set
- Valence distribution in good agreement with JAM and both disagree with the early GRV analysis
- The relatively hard-to-determine sea and gluon distributions are different in all the three PDF sets

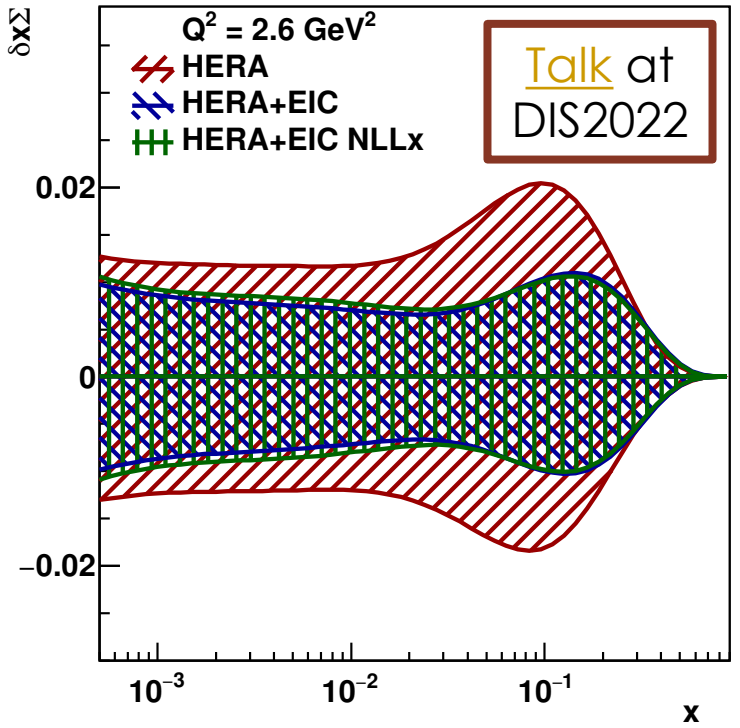
xFitter usage in the HEP comunity

- **CMS**:
  - Multi-differential $t\bar{t}$ cross sections at 13 TeV - EPJC 80 (2020) 7 658
  - Extraction of PDFs, α_S and contact-interactions from new inclusive jet cross section measurement at 13 TeV - JHEP 02 (2022) 142 (more in this talk)
  - W+charm analysis at 8 TeV - 2112.00895
- Strange quark PDF analysis with DIS HERA2 data, ATLAS W,Z cross-sections and ATLAS, CMS W+charm cross-sections - PRD 104 (2021) 7 076004
- NLO analysis of heavy-quark production cross-sections using **different mass renormalisation schemes** - JHEP 04 (2021) 043
- **TMD parton densities** and corresponding parton showers: the advantage of four- and five-flavour schemes - 2106.09791
- Implementation of **target mass corrections and higher-twist effects** in the xFitter framework - PRD 101 (2020) 7 074015
- NNLO PDFs with EW boson data from the LHC (**nuclear PDFs**) - 2112.11904

Small-x resummation and EIC data

- Study with the pseudo-data properly generated with the low-x resummation
- Small-x resummation corrections available through HELLx+APFEL (starting from $Q^2 = 2.5\ GeV^2$)





- When including NLLx corrections, uncertainties mildly affected – just the gluon at low-x
- Adding NLLx resummation doe not impact valence distributions – neither in shape nor in the size of the PDF uncertainties

New determination of $\alpha_S(m_Z)$

- ATLAS measurement of $\alpha_S(m_Z)$ **from Z p_T distribution** – full lepton phase space
- Exquisite per-mille level precision in the central region - enables precise and unambiguous PDF interpretation

ATLAS-CONF-2023-015

- **Most precise experimental determination of $\alpha_S(m_Z)$**
- Measurement dominated by theory uncertainties, but most of them can be constrained with more precise cross-section measurements