NNPDFs for pion and kaon structure

Juan Rojo

VU Amsterdam & Theory group, Nikhef

Perceiving the Emergence of Hadron Mass through AMBER@CERN

Zoom, 29/04/2021

Third, by focusing pions on nuclear targets, AMBER will measure the momentum distributions of the quarks and gluons that form the pion. These measurements will cast light on the particle dynamics that holds the pion together and ultimately on the origin of the masses of hadrons, which is known technically as the emergence of hadron mass.

Further insights into the emergence of hadron mass are anticipated from studies of the internal structure of kaons in the second phase ("phase-2") of AMBER. These studies require the beamline that feeds COMPASS to be upgraded to deliver a charged-kaon beam of high energy and intensity.

Combining AMBER's pion and kaon results will lead to a better understanding of the interplay between nature's two mass-generating mechanisms: the mechanism that gives hadrons their masses and the Higgs mechanism, which endows massive elementary particles with mass.

https://home.cern/news/news/physics/meet-amber

QCD and Proton Structure

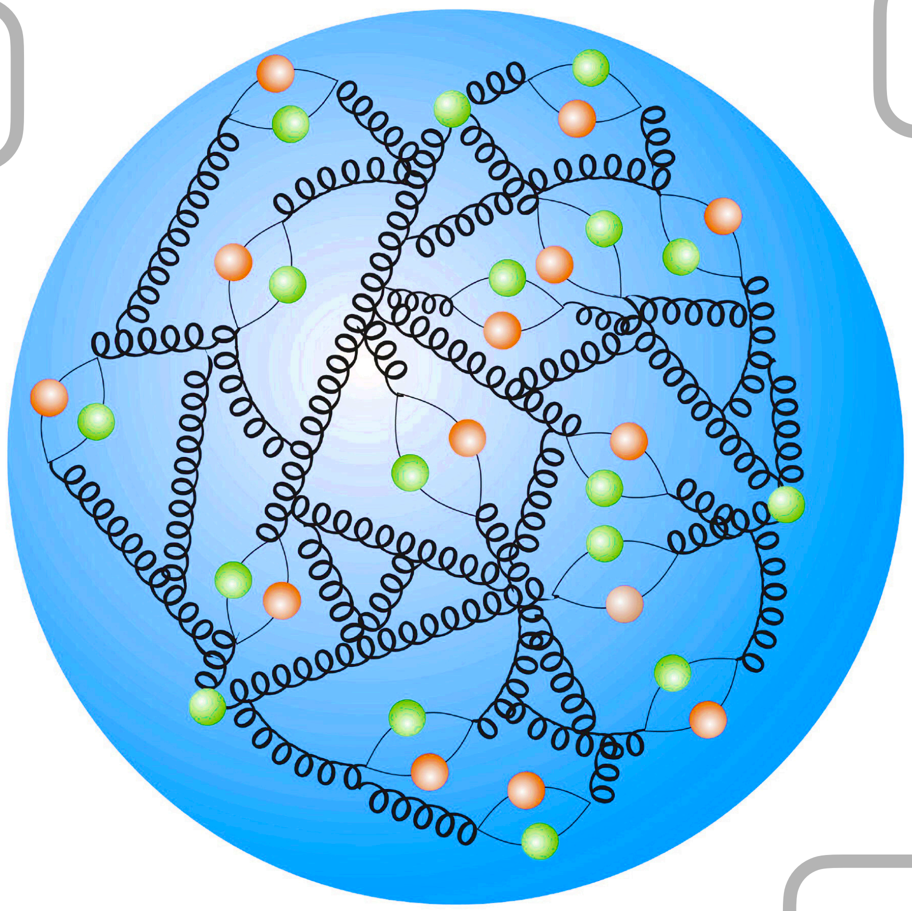
The many faces of the proton

QCD bound state of **quarks** and **gluons**

Origin of mass?

Origin of spin?

Gluon-dominated matter?



3D imaging?

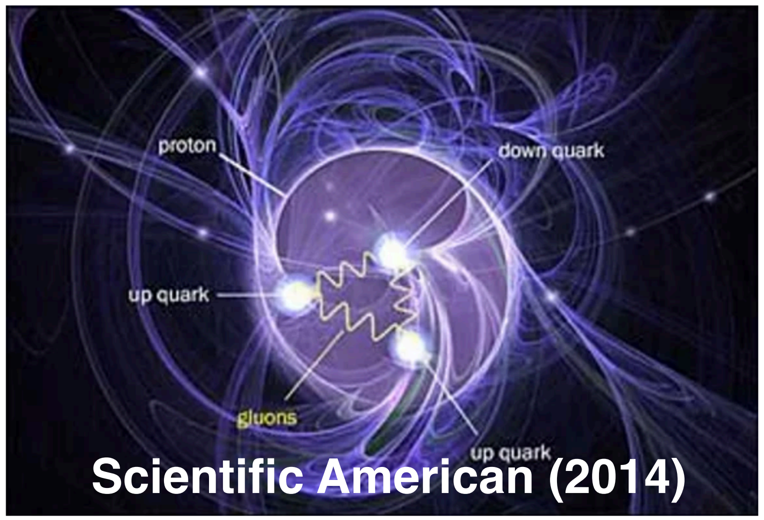
Heavy quark content?

Nuclear modifications?

The proton in the spotlight

THE SCIENCES

Proton Spin Mystery Gains a New Clue



Non-zero gluon polarisation

NEWS PARTICLE PHYSICS

The inside of a proton endures more pressure than anything else we've seen

For the first time, scientists used experimental data to estimate the pressure inside a proton

BY EMILY CONOVER 1:18PM, MAY 16, 2018

Nucleon pressure

The proton keeps surprising us as an endless source of **fundamental discoveries**

QUANTUM PHYSICS

Decades-Long Quest Reveals Details of the Proton's Inner Antimatter

27

Twenty years ago, physicists set out to investigate a mysterious asymmetry in the proton's interior. Their results, published today, show how antimatter helps stabilize every atom's core.

Antimatter asymmetry @ SeaQuest

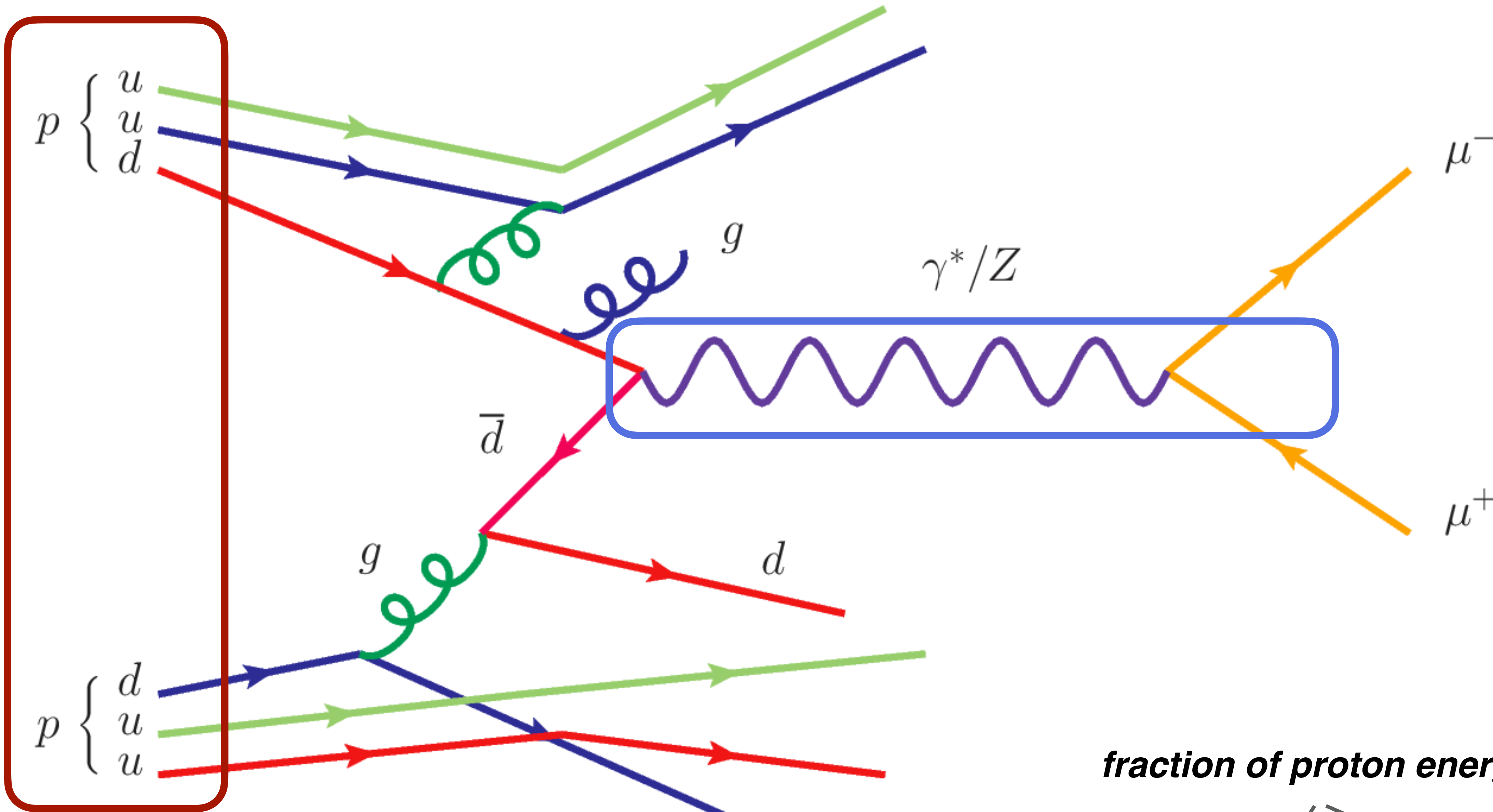
After 40 years of studying the strong nuclear force, a revelation

BFKL dynamics

This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force

Parton Distributions

In high-energy **hadron colliders**, such as the LHC, the collisions involve **composite particles** (protons) with **internal structure** (quarks and gluons)



fraction of proton energy

$$\frac{d\sigma(pp \to l^+l^-)}{dm_{ll}} = \frac{d\sigma(q_i\bar{q}_j \to l^+l^-)}{dm_{ll}} \otimes \mathrm{Prob}(q_i, x_1) \otimes \mathrm{Prob}(\bar{q}_j, x_2)$$

Parton Distributions

$$g(x, Q)$$

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Energy of hard-scattering reaction**:** inverse of resolution length

Dependence on *x* fixed by **non-perturbative QCD dynamics**: extract from experimental data

- **Energy conservation**: momentum sum rule

$$\int_0^1 dx\, x \left(\sum_{i=1}^{n_f} \left[q_i((x, Q^2) + \bar{q}_i(x, Q^2) \right] + g(x, Q^2) \right) = 1$$

- **Quark number conservation**: valence sum rules

$$\int_0^1 dx\, \left(u(x, Q^2) + \bar{u}(x, Q^2) \right) = 2$$

Parton Distributions

$$g(x, Q)$$

Energy of hard-scattering reaction**:** inverse of resolution length

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Dependence on ***Q*** fixed by **perturbative QCD dynamics**: computed up to $\mathcal{O}\left(\alpha_s^4\right)$

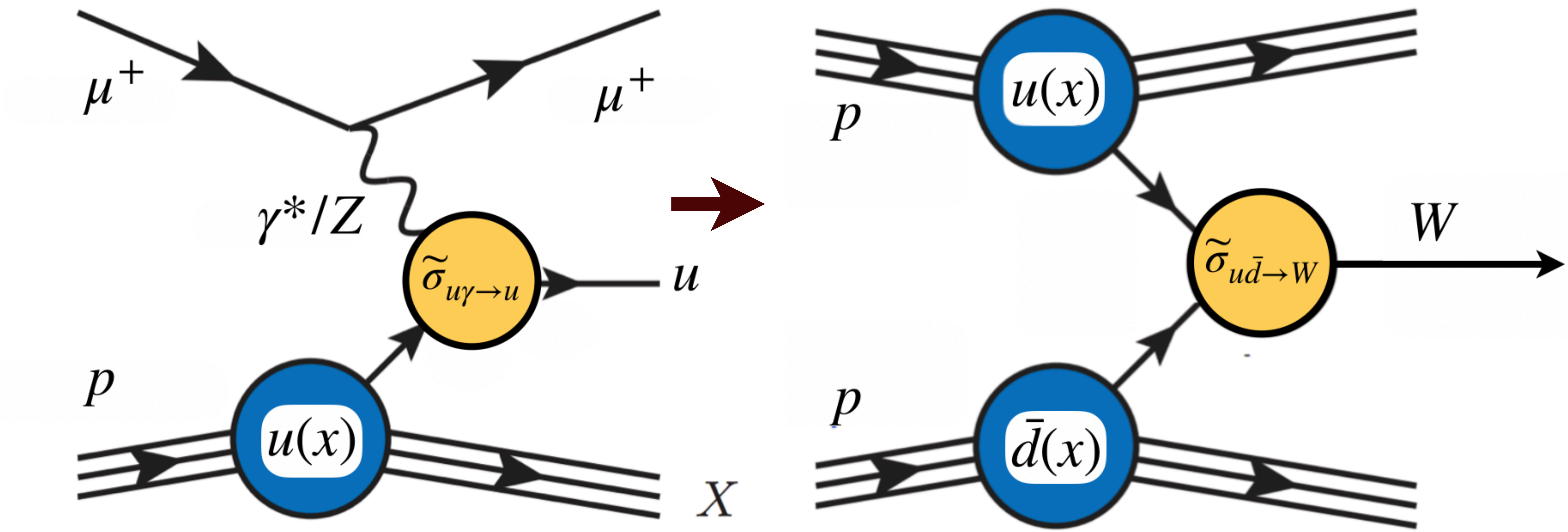
$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) q_j(z, Q^2)$$

***DGLAP** parton evolution equations*

The Global QCD analysis paradigm

QCD factorisation theorems**: PDF universality**

$$\sigma_{l\,p\to\mu\,X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x) \quad \rightarrow \quad \sigma_{p\,p\to W} = \widetilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$

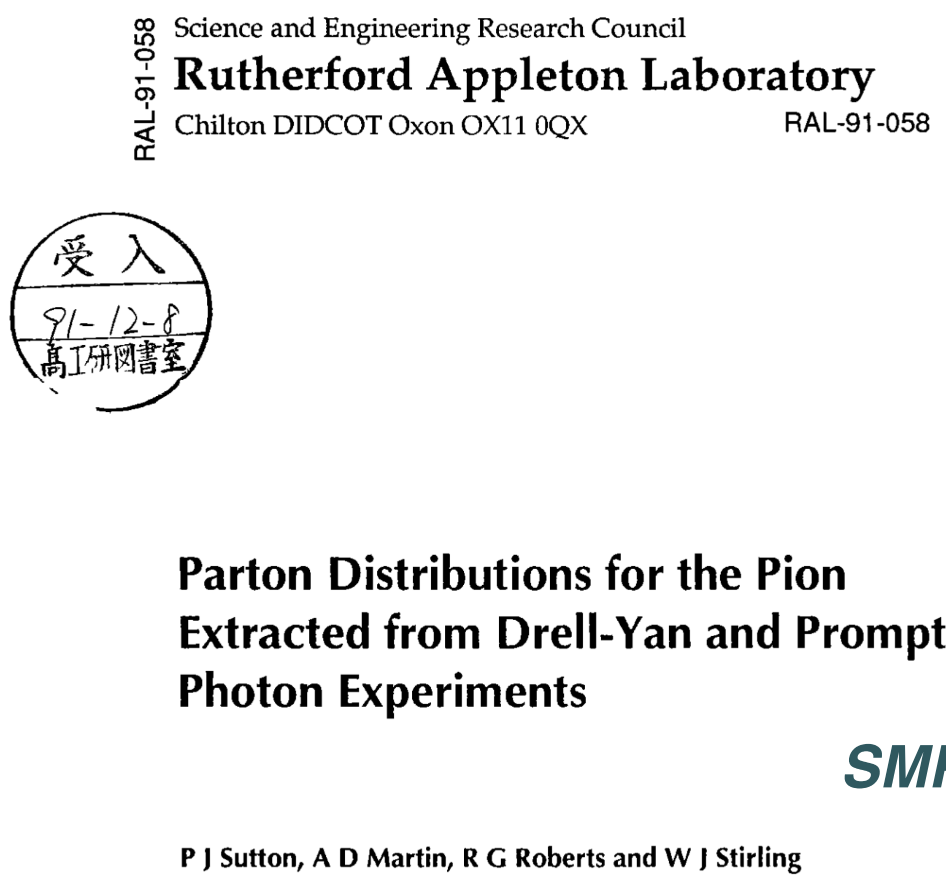


Determine PDFs from ***deep-inelastic scattering****…*

… and use them to compute predictions for ***proton-proton collisions***

what about pion and kaon structure?

The very same considerations that apply to the proton PDFs also hold for **pion and kaon PDFs**: perturbative hard-scattering cross-sections and DGLAP evolution are the same or very similar, only the non-perturbative matrix elements (PDFs) depend on the target/projectile!


RAL-91-058

Science and Engineering Research Council

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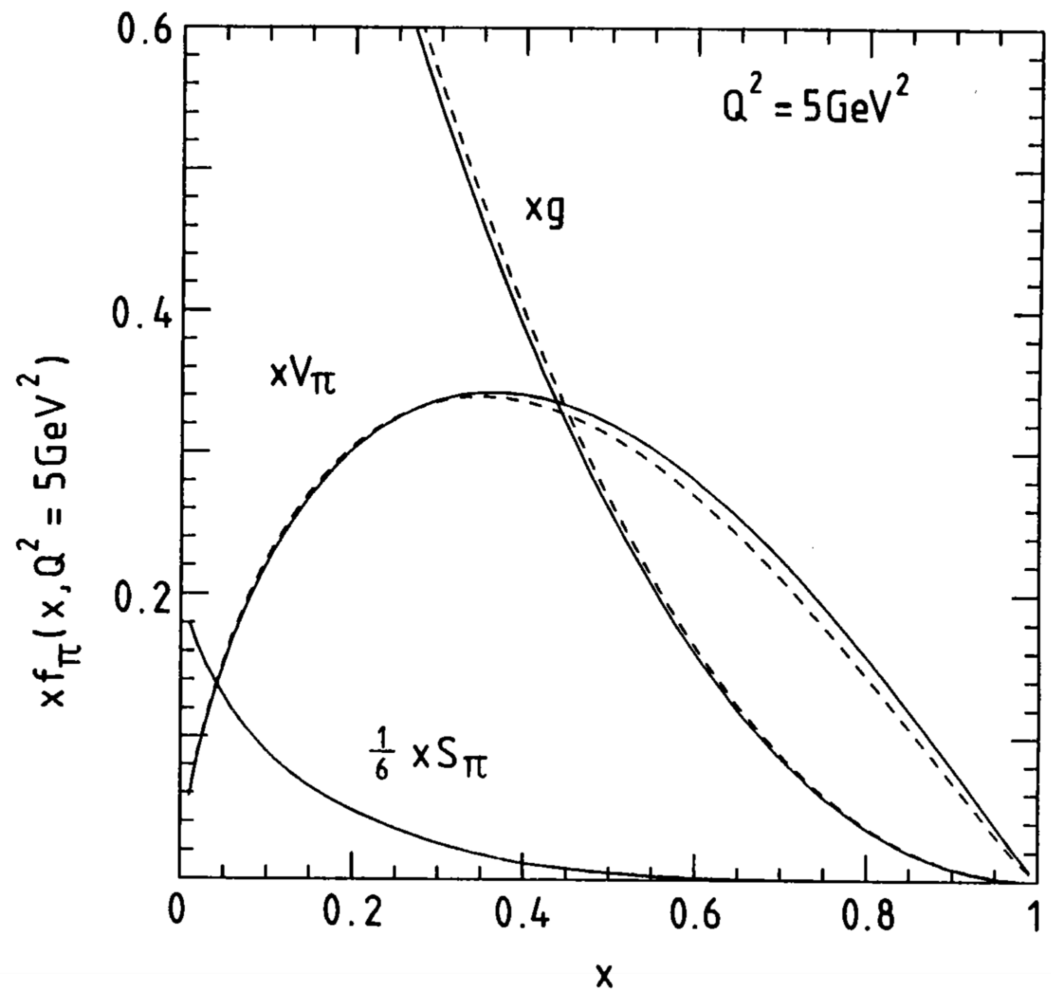
Chilton DIDCOT Oxon OX11 0QX RAL-91-058

Parton Distributions for the Pion Extracted from Drell-Yan and Prompt Photon Experiments

P J Sutton, A D Martin, R G Roberts and W J Stirling

SMRS91



Challenge: hard-scattering data with **pion and kaon targets/projectiles** is very scarce!

hence the crucial role to be played by AMBER

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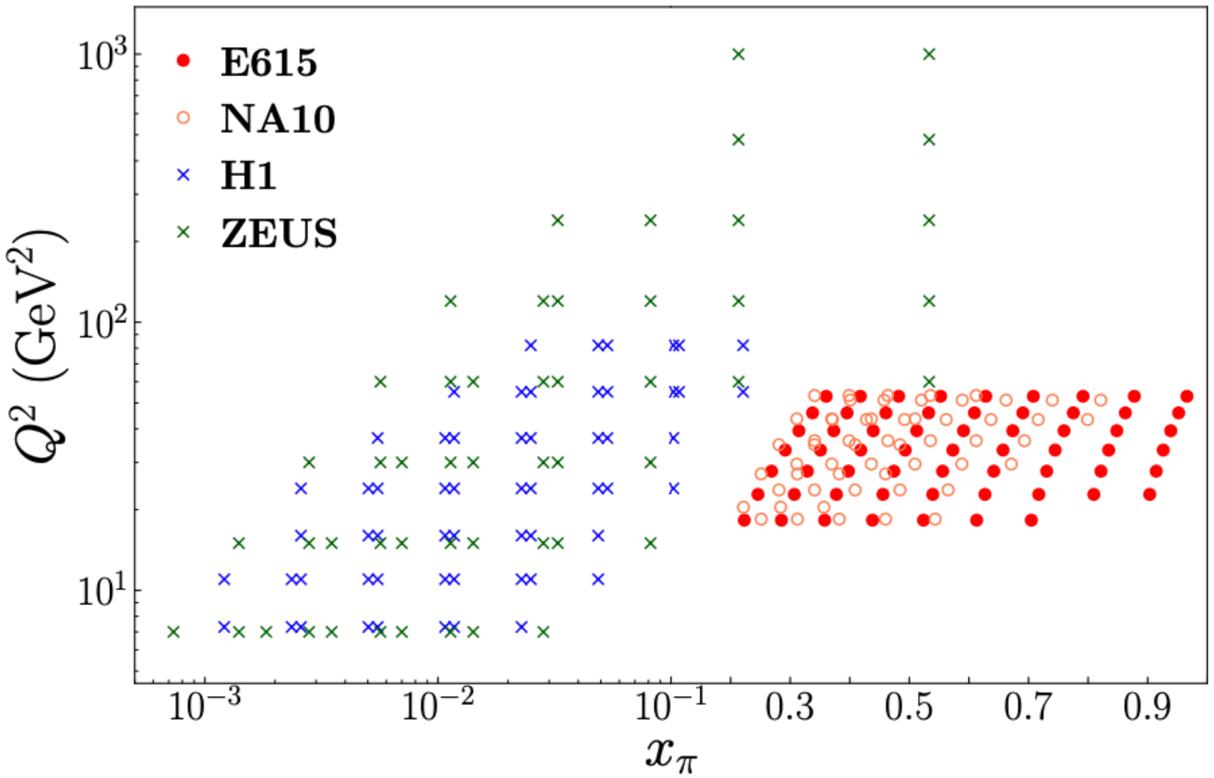
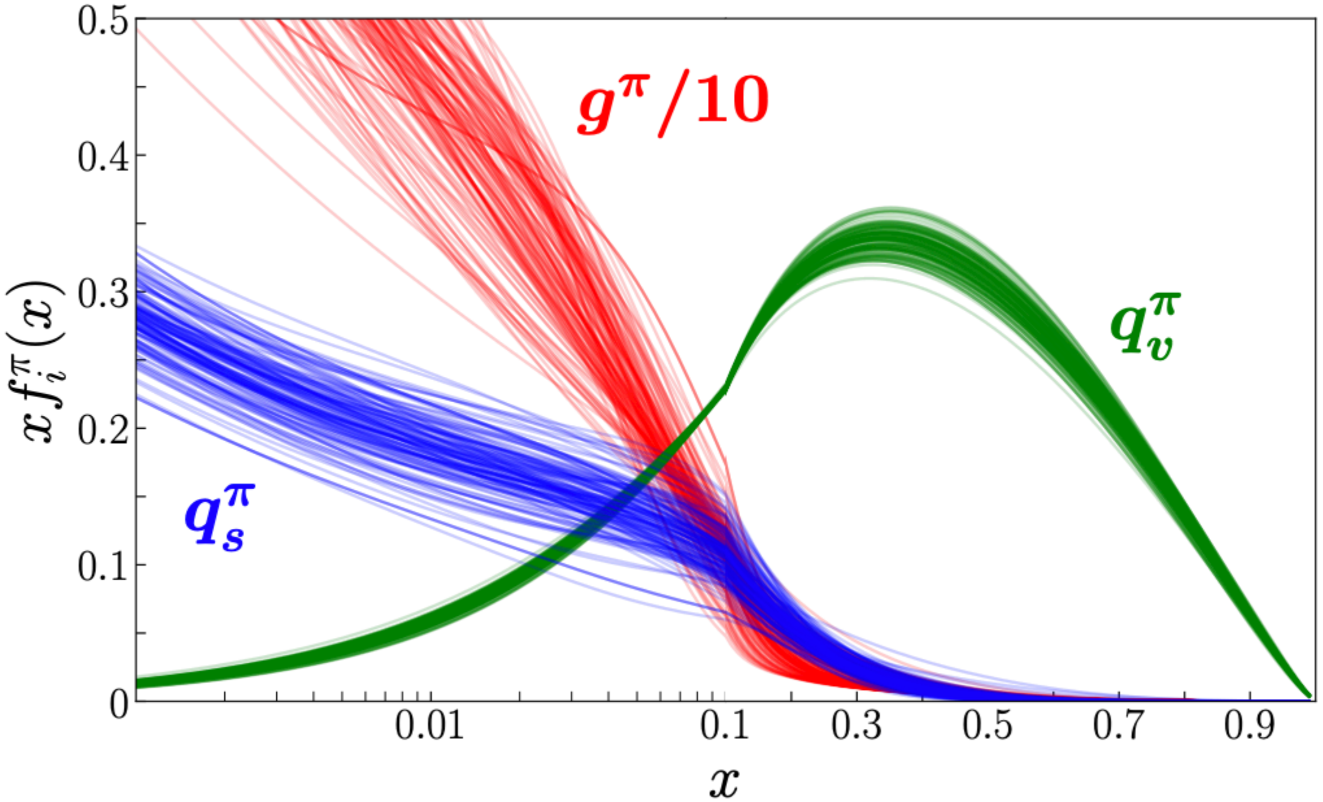




JAM21

Challenge: hard-scattering data with **pion and kaon targets/projectiles** is very scarce!

hence the crucial role to be played by AMBER

NNPDF

The Neural Network Approach to Proton Structure

http://nnpdf.mi.infn.it/

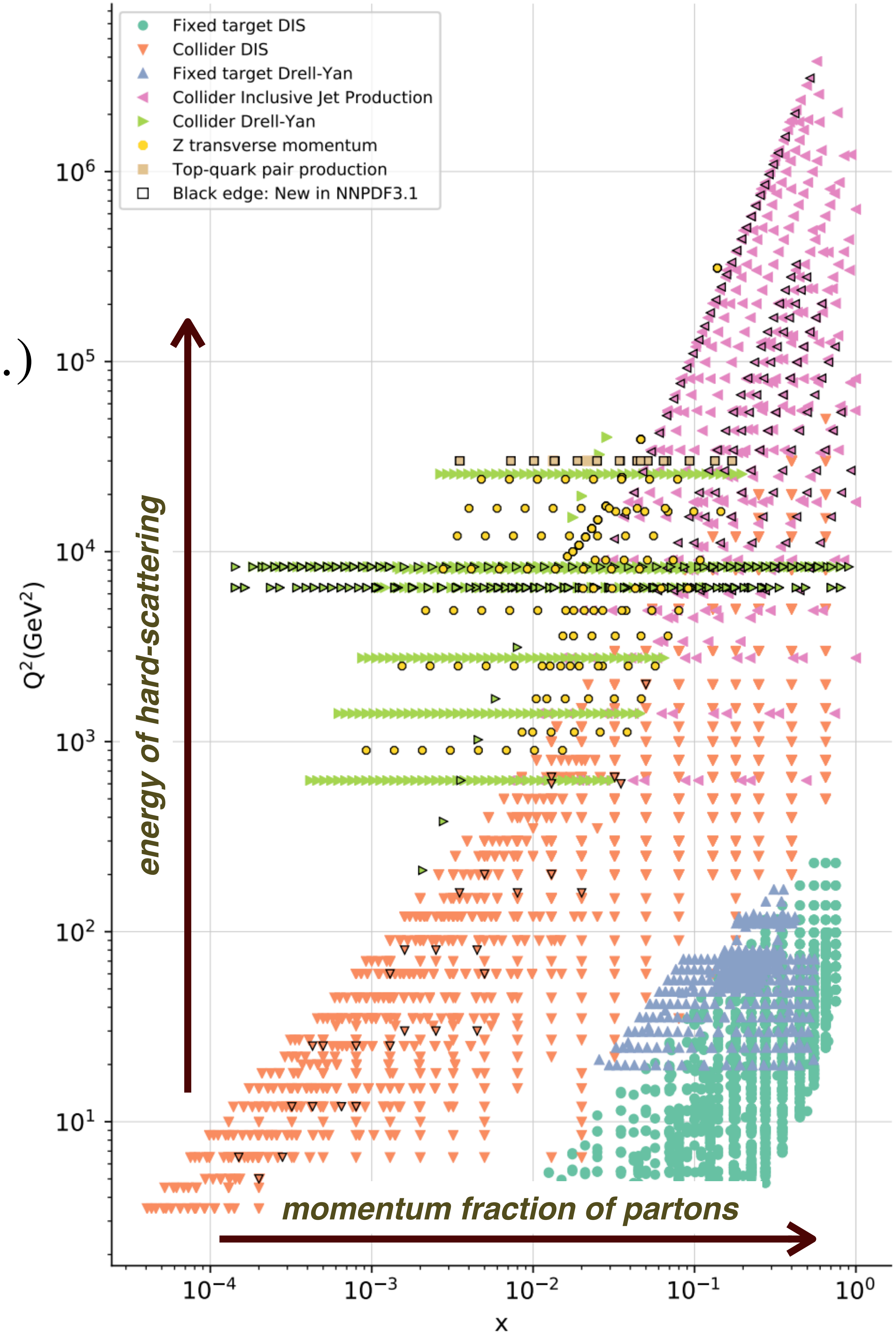
Fitting PDFs

- **Parametrise PDFs at** some low scale Q_0 (around the proton mass, 1 GeV)

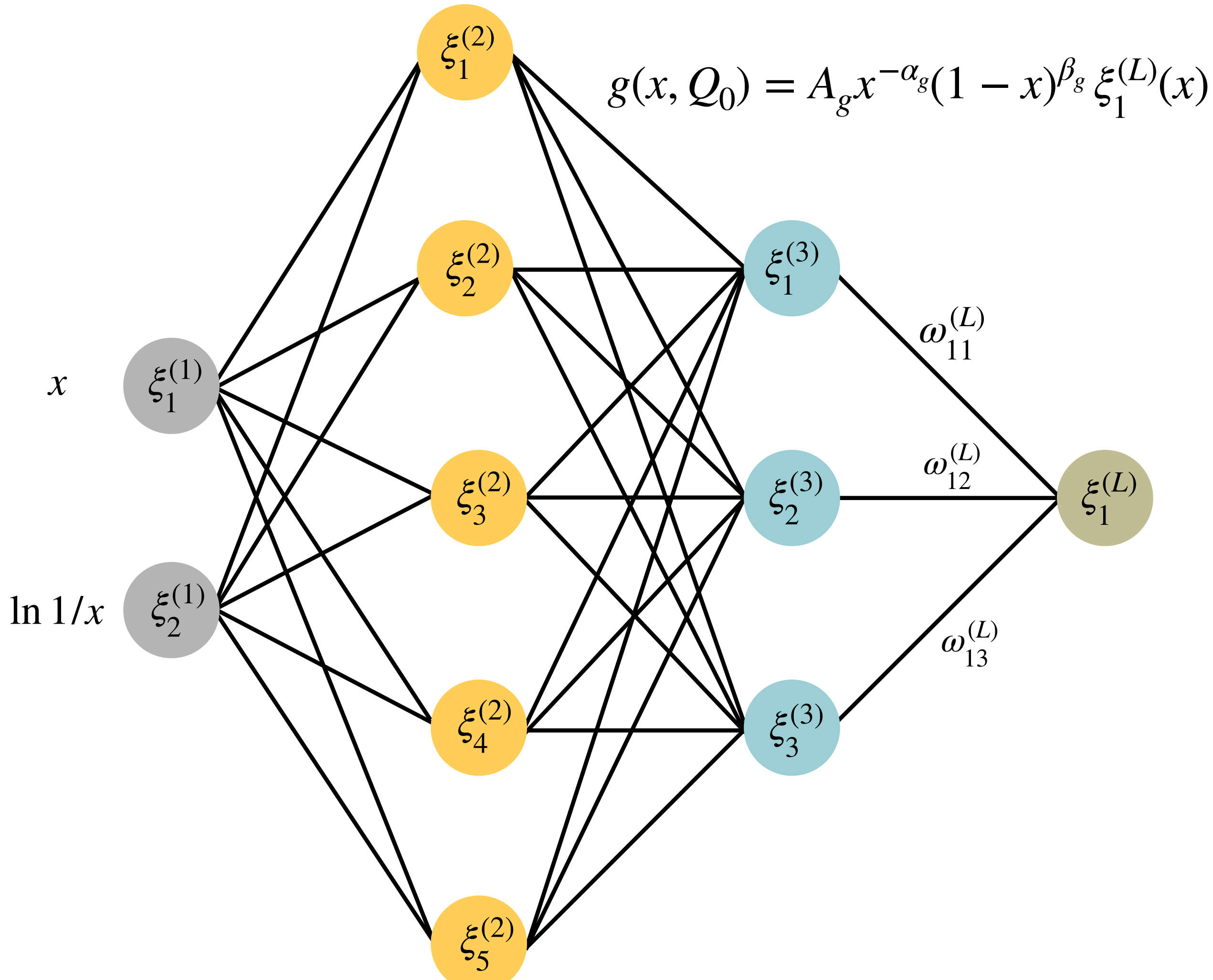
$$g(x, Q_0) \simeq A_g x^{-b_g}(1-x)^{c_g} \times P_g(x, d_g, f_g, \dots)$$

- Fix some parameters from **theory constraints** (e.g. momentum conservation)
- Extract remaining parameters (+ their uncertainties) from global fit to wide dataset

more than **5000 independent cross-section measurements** from **40 different processes**



ML for proton structure



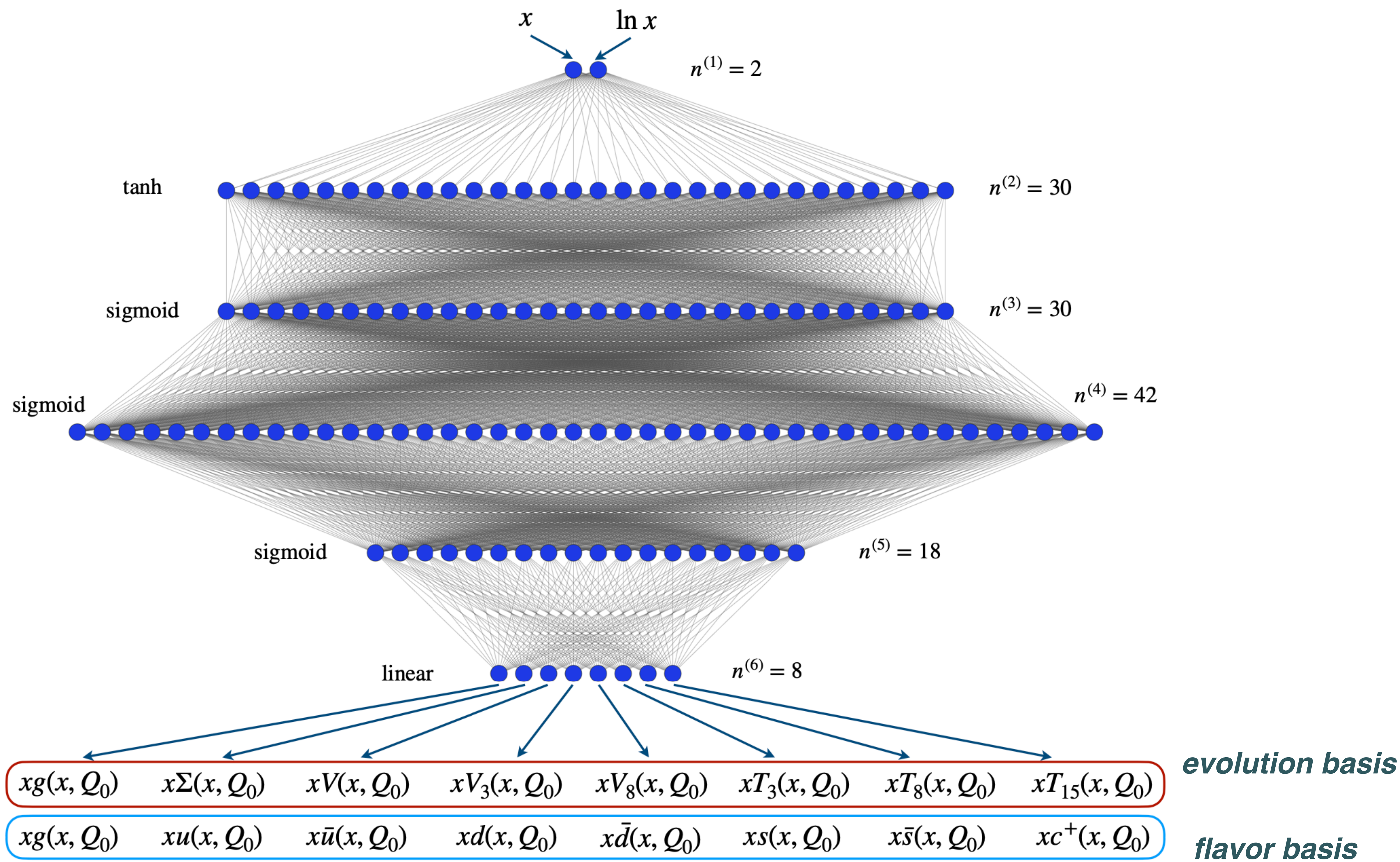
- **Neural Networks** can be used universal unbiased interpolants to **parametrise PDFs**
- Removes model dependence: **unbiased learning** the physical laws from data
- Highly **redundant parametrisation:** identical results if O(10) increase in # free params

	Proton PDFs	***Nuclear PDFs***
Traditional	$g(x) \simeq x^{-b}(1-x)^c$	$R_g(x, A) \simeq (1 + bx + cx^2) \times A^d$
Neural Nets	$g(x) \simeq \mathrm{NN}(x)$	$R_g(x, A) \simeq \mathrm{NN}(x, A)$

x: *proton's **energy fraction** carried by gluons*

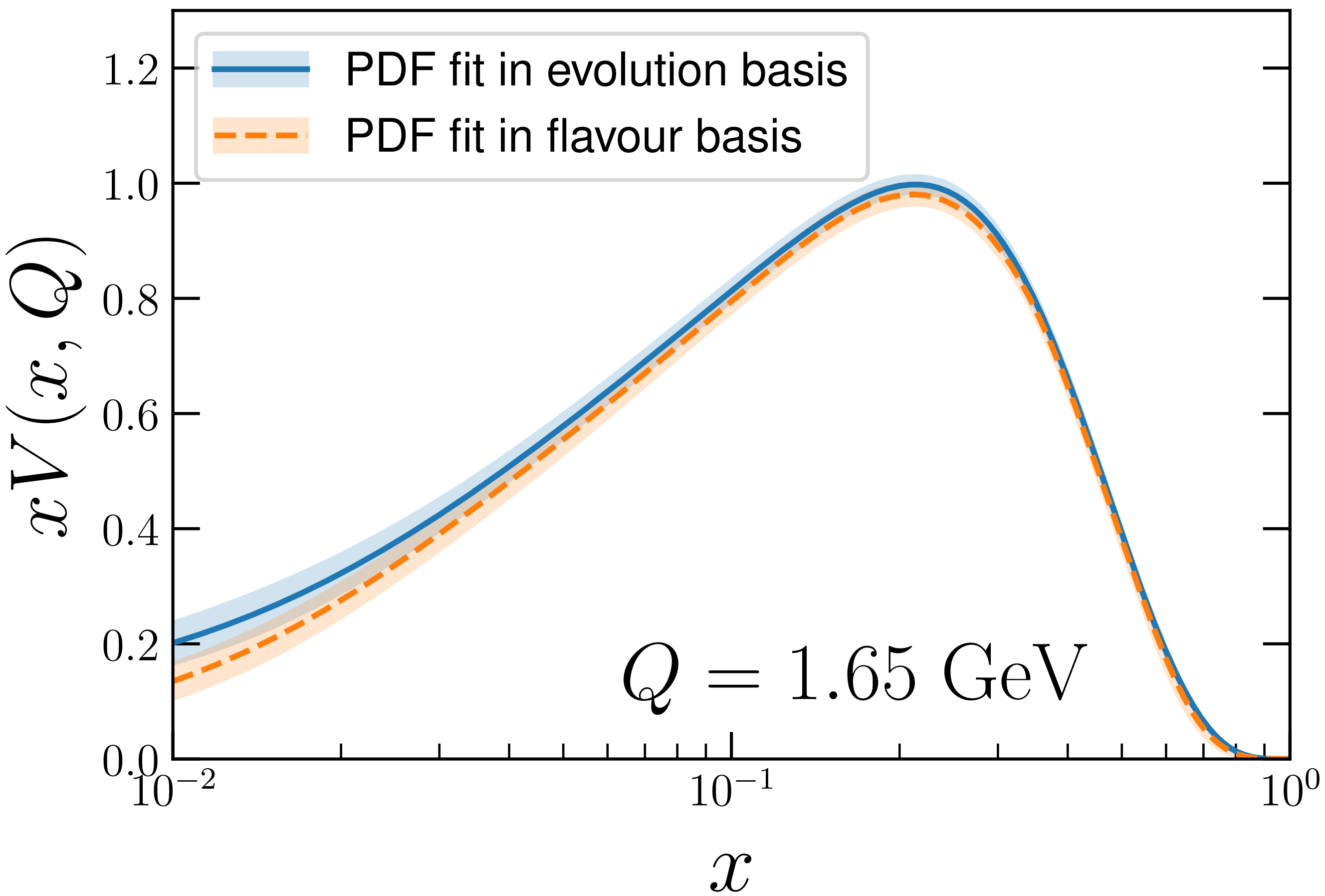
A: *number of protons + neutrons*

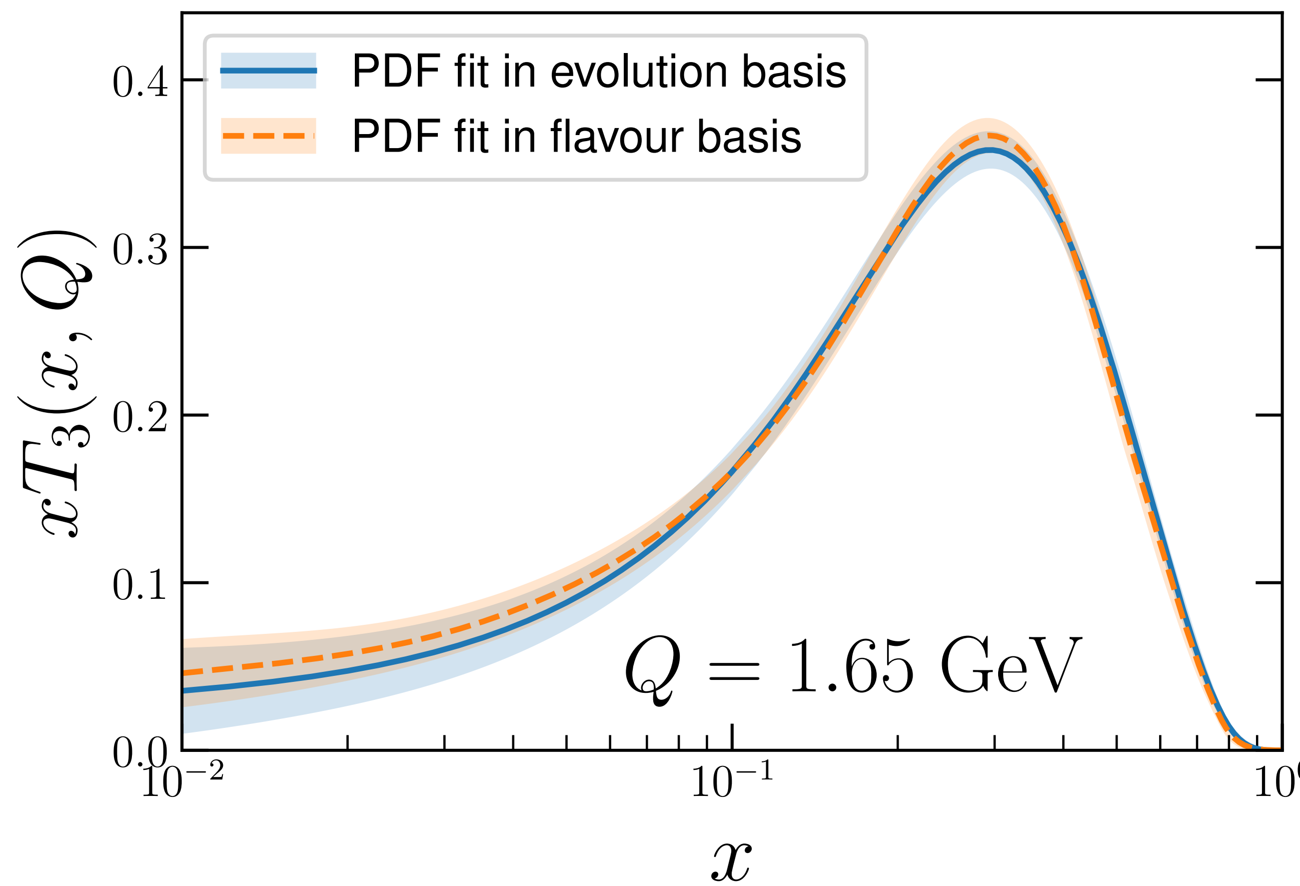
NNPDF4.0 parametrisation



$$f_i(x, Q_0) = x^{-\alpha_i}(1-x)^{\beta_i}\mathrm{NN}_i(x)$$

Parametrisation basis independence





evolution basis PDF parametrisation:

$$xV(x, Q_0) \propto \mathrm{NN}_V(x)$$

$$xT_3(x, Q_0) \propto \mathrm{NN}_{T_3}(x)$$

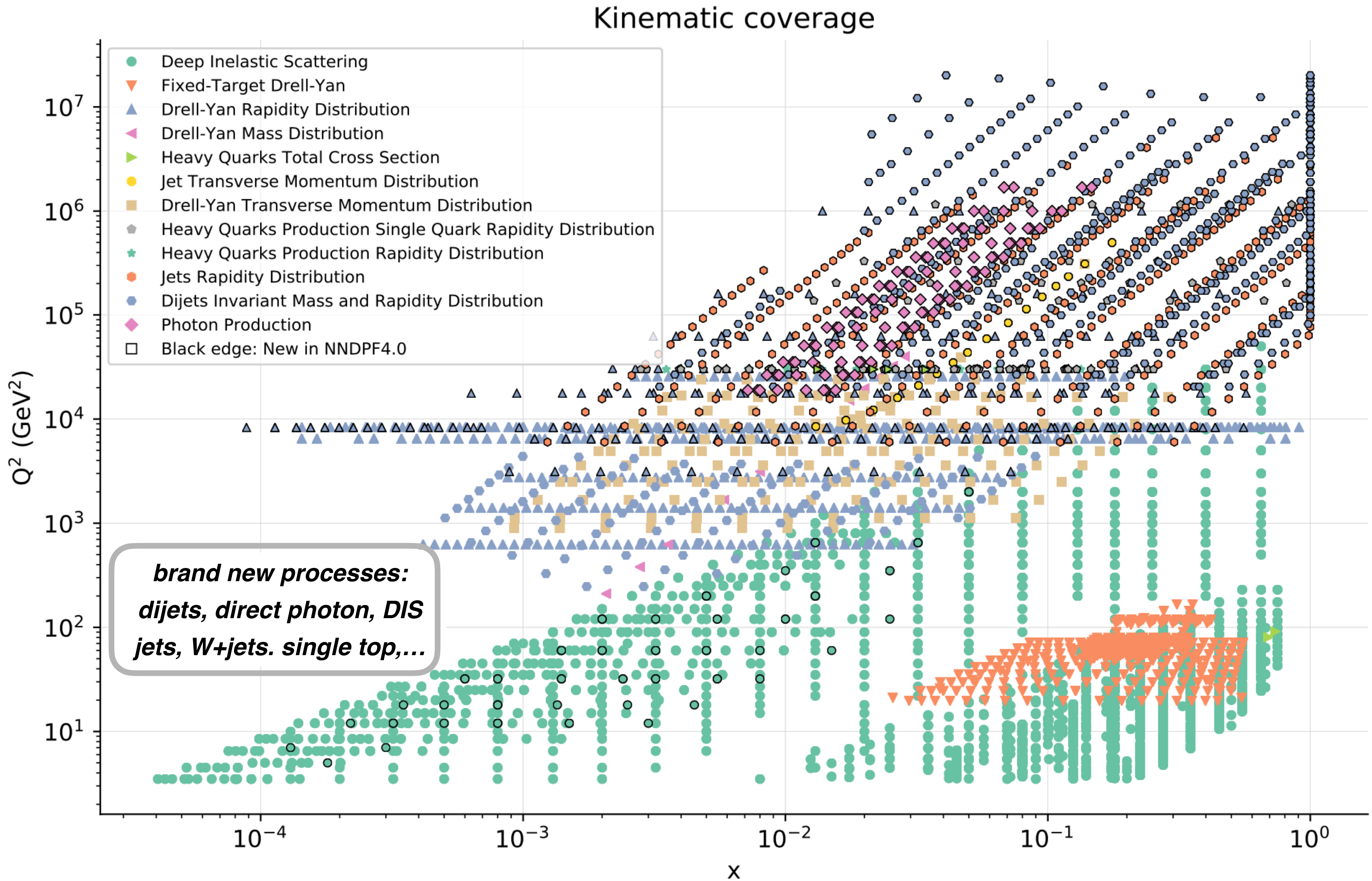
Radically different strategies to parametrize the **quark PDF flavour combinations** lead to identical results: ultimate test of **parametrisation independence**

flavour basis PDF parametrisation:

$$xV(x, Q_0) \propto \left(\mathrm{NN}_u(x) - \mathrm{NN}_{\bar{u}}(x) + \mathrm{NN}_d(x) - \mathrm{NN}_{\bar{d}}(x) + \mathrm{NN}_s(x) - \mathrm{NN}_{\bar{s}}(x)\right)$$

$$xT_3(x, Q_0) \propto \left(\mathrm{NN}_u(x) + \mathrm{NN}_{\bar{u}}(x) - \mathrm{NN}_d(x) - \mathrm{NN}_{\bar{d}}(x)\right)$$

NNPDF4.0: data set extension



$\mathcal{O}(50)$ data sets investigated; $\mathcal{O}(400)$ data points more in NNPDF4.0 than in NNPDF3.1

Monte Carlo replica method

- Generate Monte Carlo **replicas of the original data points** with multi-Gaussian distribution with central values and covariance matrices taken from the input measurements:

$$F_{I,p}^{(\mathrm{art})(k)} = S_{p,N}^{(k)} F_{I,p}^{(\mathrm{exp})} \left(1 + \sum_{l=1}^{N_c} r_{p,l}^{(k)} \sigma_{p,l} + r_p^{(k)} \sigma_{p,s} \right) \ , \ k = 1, \ldots, N_{\mathrm{rep}} \ ,$$

- Train a NN model on each replica from the **minimisation of the log-likelihood**

$$E^{(k)}[\omega] = \frac{1}{N_{\mathrm{dat}}} \sum_{i,j=1}^{N_{\mathrm{dat}}} \left(F_i^{(\mathrm{art})(k)} - F_i^{(\mathrm{net})(k)} \right) \left(\left(\overline{\mathrm{cov}}^{(k)} \right)^{-1} \right)_{ij} \left(F_j^{(\mathrm{art})(k)} - F_j^{(\mathrm{net})(k)} \right) \ ,$$

- We end up with a sampling of the **probability density in the space of NN models,** from which we can compute e.g. the PDF uncertainty for an arbitrary process

$$\sigma_{\mathcal{F}} = \left(\frac{N_{\mathrm{set}}}{N_{\mathrm{set}} - 1} \left(\left\langle \mathcal{F}[\{q\}]^2 \right\rangle - \left\langle \mathcal{F}[\{q\}] \right\rangle^2 \right) \right)^{1/2}$$

Fast Kernel grid technology

- The calculation of hard-scattering cross-sections requires evaluating several nested convolutions (+ DGLAP evolution) of the PDFs at the parametrisation scale: **unfeasibly slow!**

brute-force calculation

$$N(p+\mathrm{Pb}\to\pi+X) \propto \sum_{i,j,k=u,d,g,\ldots}^{n_f} \int dx_1 \int dx_2 \int dz\, \widetilde{\sigma}_{ij\to k+X}(x_1,x_2,z,Q)\Big(f_i(x_1,Q,1)\, f_j(x_2,Q,A_{\mathrm{Pb}})\, f_{k\to\pi}(z,Q,A_{\mathrm{Pb}})\Big)$$

$$f_i(x,A,Q) = \sum_{j=u,d,g,\ldots}^{n_f} \int dQ' \int dz\, \Gamma_{ij}(x/x',Q'/Q_0)\, f_j(x',A,Q_0)$$

NN outputs

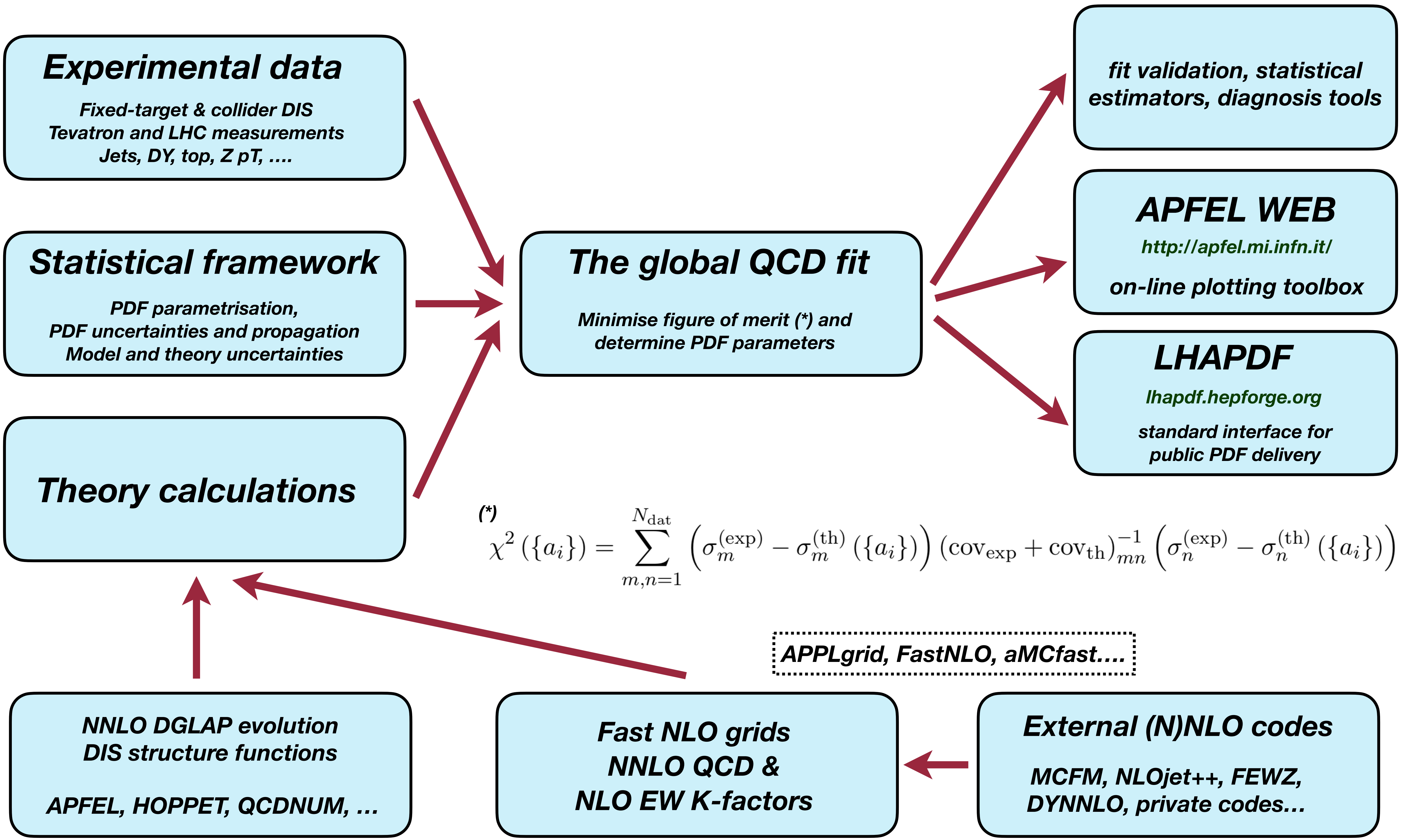
via grid interpolation (NNPDF method)

$$N(p+\mathrm{Pb}\to\pi+X) \propto \sum_{m,n,p=1}^{n_x} \sum_{i,j,k}^{n_f} \left(\mathbf{FK}_{m,n,p,i,j,k}\right) \times \Big(f_i(x_m,Q_0,1)\, f_j(x_n,Q_0,A_{\mathrm{Pb}})\, f_{k\to\pi}(z_p,Q_0,A_{\mathrm{Pb}})\Big)$$

sum over x,z grids *sum over flavour*

- In NNPDF we use an interpolation grid technology (**FastKernel method**) whereby all perturbative information is **precomputed and stored** in grid before the fits
- Now the cross-section is a **matrix multiplication** over a grid of PDFs at the input scale

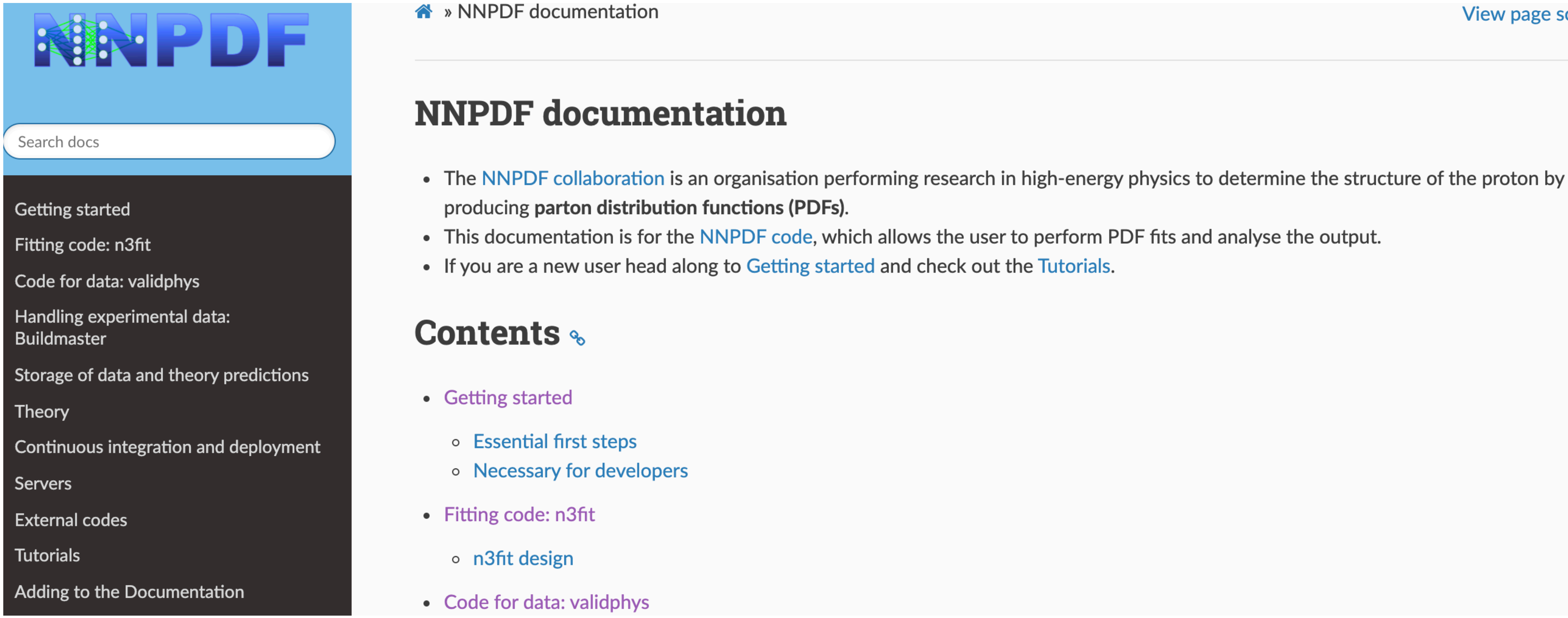
The global PDF fit pipeline



(*)

$$\chi^2\left(\{a_i\}\right)=\sum_{m,n=1}^{N_{\rm dat}}\left(\sigma_m^{(\rm exp)}-\sigma_m^{(\rm th)}\left(\{a_i\}\right)\right)\left({\rm cov}_{\rm exp}+{\rm cov}_{\rm th}\right)^{-1}_{mn}\left(\sigma_n^{(\rm exp)}-\sigma_n^{(\rm th)}\left(\{a_i\}\right)\right)$$

An open-source ML code for QCD fitting



The **NNPDF machine learning fitting framework** will be publicly released **open source,** together with extensive documentation and user-friendly examples, at same time as upcoming NNPDF4.0 paper!

NNPDFs for kaon and proton structure

Drell-Yan with pion and kaon beams

Drell-Yan and charmonium production
The main objective of the proposed Drell-Yan and J/ψ production experiments is to make a major step forward in the determination of the nearly unknown pion and kaon parton distribution functions (PDFs). The planned measurements will provide key benchmarks for testing the most recent predictions of fundamental, non-perturbative QCD calculations, such as lattice QCD and Dyson-Schwinger Equations formalism. At medium and large values of Bjorken-x, a quantitative comparison between the pion and the kaon valence distributions is of utmost importance. At smaller values of Bjorken-x, improved knowledge of the onset of the sea and gluon distributions in the meson will help in explaining the differences between the gluon contents of pions, kaons and nucleons, and hopefully provide clues to understand the mechanism that generates the hadron masses. Furthermore, a comparison between cross sections for

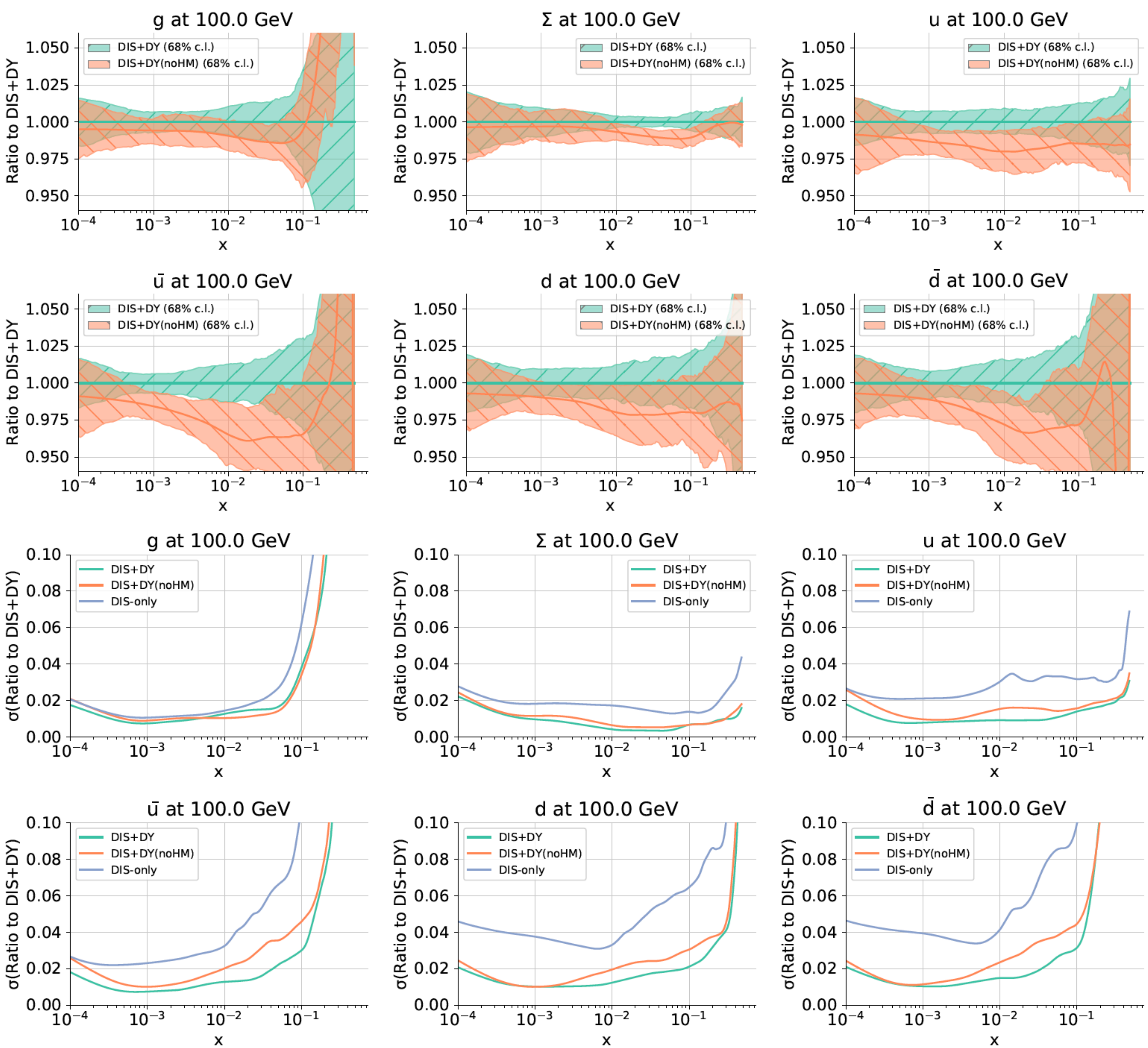
COMPASS++/AMBER LoI

- In global proton PDF fits, **Drell-Yan processes** (both fixed-target and collider) provide instrumental constraints on quark and anti-quark PDF flavour separation

- **Ratios of cross-sections** with **pion or kaon beams over proton beams** specially powerful to cancel out systematics and cleanly probe pion and kaon PDFs

The first part of this programme can be completed using the presently available positive (π^+, K^+, p) and negative (π^-, K^-, $\bar{p}$) hadron beams, in combination with an optimized experimental setup. A detailed

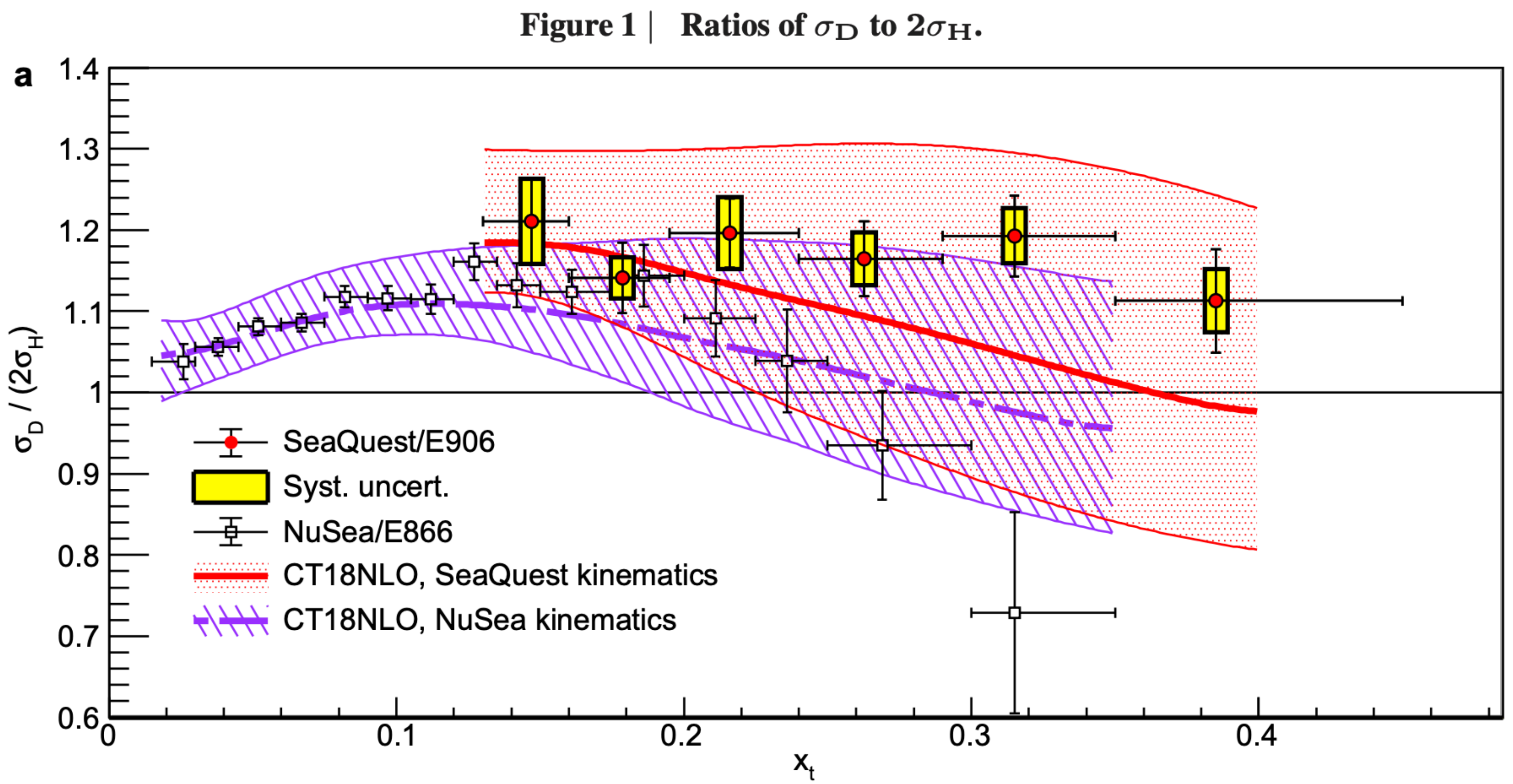
Impact of Drell-Yan data

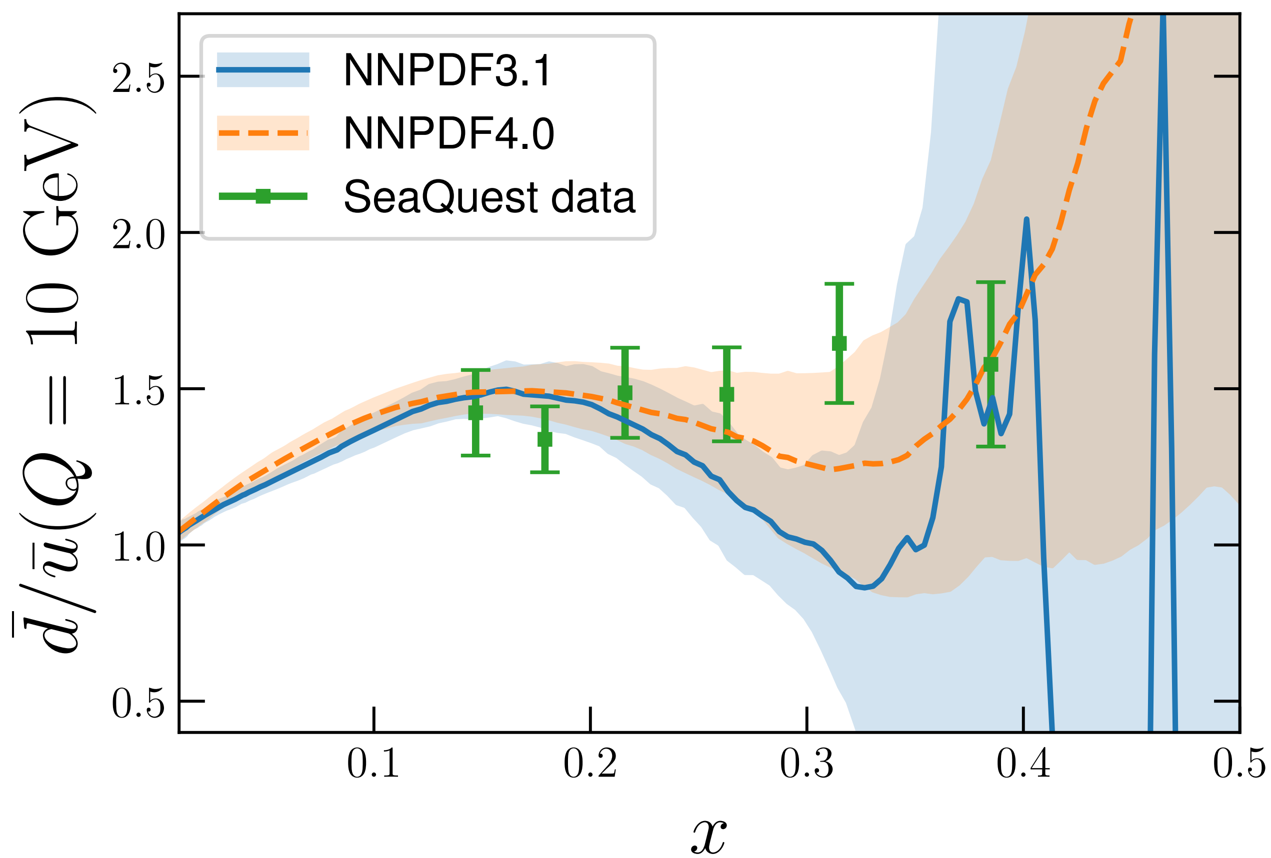


- DY processes add a lot of **extra information** on the PDFs when added to a DIS-only baseline
- Specially important for quark flavour separation
- Little pull on the gluon

Greljo et al 21

Impact of Drell-Yan data





- Recent SeaQuest measurements of **DY ratios** with deuteron and proton targets
- Provide information on the **antiquark asymmetries** in the proton
- Good agreement with the NNPDF3.1 and NNPDF4.0 predictions

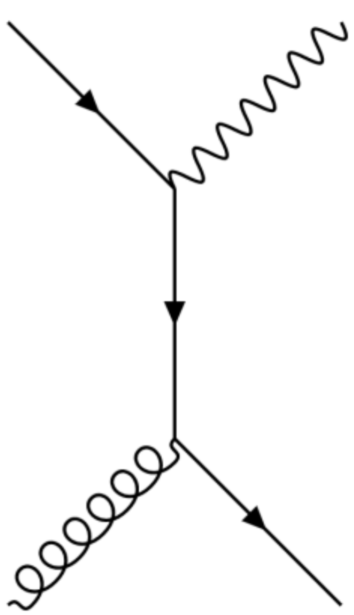
Gluon PDF in pion and kaons

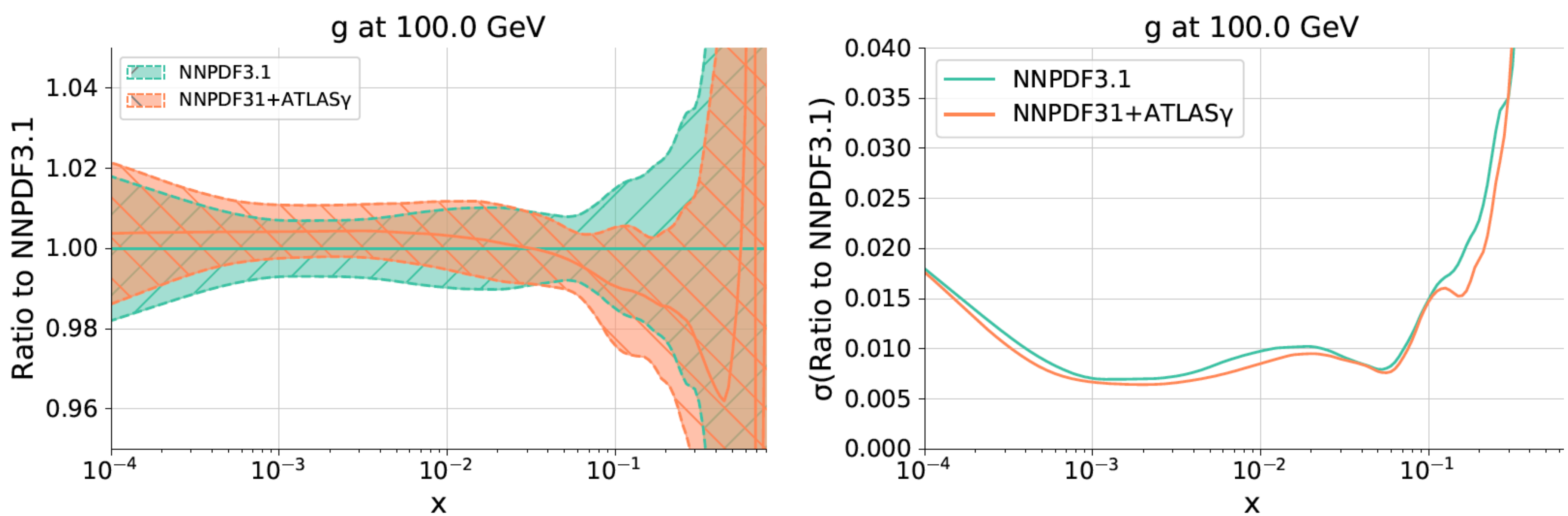
Study of the gluon distribution in the kaon via prompt-photon production

The purpose of this experiment is the study of the gluon content of charged kaons. This is of fundamental importance for understanding the internal structure of light mesons and may also shed light onto the mechanism that generates their mass. In contrast to the well-known gluon distribution of the nucleon, our knowledge on the gluon distribution in light mesons is rather limited. It can be considerably improved by studying prompt-photon production in hadronic collisions using a high-energy meson beam.

- Direct photon production can be evaluated up to NNLO QCD and is known to provide useful information on the **gluon PDF** in the global fit (but jets and top production dominate)

- What about **other final-state probes** of the gluon content of mesons? Open charm (D-meson) production? Jet production? Single-inclusive hadron production?





Campbell et al 18

A NNPDF analysis of meson structure

- Assemble **widest possible dataset**: Drell-Yan data with broad kinematic range (+ ratios with different projectiles), prompt photon production, charm, single-inclusive hadrons …

- Ensure that the **full experimental correlation matrix** is available, with breakup of systematic errors

- Use **state-of-the-art theory calculations and MC simulations** to evaluate acceptance and efficiency corrections, provide measurements both in fiducial region and extrapolated to full phase space

- Determine the flavour combinations to be parametrised, implement **theory constraints,** and eventually account also for lattice QCD information

Use the **NNPDF open-source ML fitting framework** to put everything together and carry out a global determination of pion and kaon structure!

We will be more than happy to provide assistance